Quality and quantity of service in lift groups

Submitted for the Degree of

Doctor of Philosophy

At the University of Northampton

2018

Stefan Gerstenmeyer

Abstract

This research was focused on quality of service experienced by passengers in lift systems where multiple cars are sharing same shafts (multi car lift systems) and destination control. These modern lift systems have opportunities and constraints for control algorithms arising by existing and additional quality of service criteria. These additional criteria have rarely been considered in existing literature, control algorithms or traffic analysis.

The overall aim of the research was to determine and analyse existing and new quality of service criteria for destination control systems and multi car lift systems in terms of traffic handling and developing lift control concepts considering these criteria.

Therefore, the impact on passengers' quality of service was reviewed using psychology of waiting principles. Detailed definition and analysis was done for reverse journeys in destination control systems and departure delays with a focus on multi car lift systems. To develop and analyse control algorithms known event based traffic simulation, round trip time calculation and Monte Carlo simulation were extended and applied.

Traffic control algorithms and concepts were developed to improve passenger experience when using lifts. Additional to dispatching algorithms equations for improved lift kinematics and controlled stopping distances were derived to reduce departure delays in multi car lift systems. Possible improvements were shown in case studies.

Compared to traditional lift systems, special opportunities and constraints of a circulating multi car lift system in traffic handling were explored and analysed. New cycle time calculations for shuttle and local group applications were developed. Results were provided using case studies, and necessary control concepts were addressed.

With the results of this research, better understanding and assessments of multi car lift systems and destination controls are possible. The traffic control algorithms explored help to build better lift controllers, considering passengers perception. The introduced traffic analysis methods for circulating multi car lift systems support lift planning.

Acknowledgement

I am very grateful to my supervisory team at the University of Northampton for their support and guidance. Thank you to Professor Stefan Karczmarczyk for the clear and structured guidance, advice and review. Thank you to Visiting Professor Richard Peters for his encouragement, the time he dedicated to discussing the subject with me, and for reviewing my research. Thank you to Professor Phil Picton for his valued support.

Thank you to thyssenkrupp Elevator for the opportunity and for funding to the research. I am grateful to Patrick Bass for initiating the project. Thank you to Markus Jetter for making things possible, for challenges and listening. Thank you to Kai Egersdörfer and to my colleagues at the tkE R&D department for accepting and compensating my non-availability while I have been focusing on my university research.

Thank you to the staff at Peters Research for sharing their work in support of my research, and for proofreading my written work, including this thesis.

Thank you to my family. Special thanks to my wife Melanie for her love and for taking over extra family responsibilities while I have been studying. And finally, thank you to my children Tobias and David for accepting that their father was home working at times when he could have been spending time with them.

Table of content

1 Introduction 22
1.1 General motivation 22
1.2 Aims and objectives 24
1.3 Overview of the methodology and research tools applied 25
1.4 Structure of the thesis 26
2 Literature review 29
2.1 Traffic analysis/design 29
2.1.1 Quality of service 30
2.1.2 Quantity of service 32
2.1.3 Methods of traffic design and analysis 33
2.1.3.1 Analytical method (calculation) 33
2.1.3.2 Simulation method (event based) 34
2.1.3.3 “Mixed” method (Monte Carlo simulation) 35
2.1.4 Traffic patterns 35
2.1.5 Lift arrangements and traffic concepts 37
2.2 Control systems and algorithms 39
2.2.1 Lift group control types 39
2.2.2 Control algorithms 39
2.2.3 Ideal lift kinematics 42
2.3 Multi car lift systems 44
2.3.1 Two independent cars in one shaft 44
2.3.2 Circulating multi car lift systems 45
2.3.3 Circulating multi car lift system under development 46
2.3.4 Circulating multi car lift system technology 47
2.3.4.1 Propulsion system 47
2.3.4.2 Lightweight car 48
2.3.4.3 Guiding of elevator cars and exchangers 49

2.3.5 Safety distance between multiple lift cars 50
2.3.5.1 Safety distance – safety control levels 50
2.3.5.2 Safety distance theory – certified safety system 51
3 Quality of service and psychology of waiting 54
3.1 Introduction 54
3.2 Lift architecture/environment 55
3.3 User interfaces 56
3.4 Lift control functionality 58
3.4.1 Waiting time versus transit time 58
3.4.2 Reverse journey situations 61
3.4.3 Departure delays 62
3.5 Summary 63
4 Reverse journey in destination control systems 64
4.1 Introduction 64
4.1.1 Background 64
4.1.2 Reversed journey in conventional systems 64
4.1.3 Reverse journey in destination control systems 65
4.1.4 Reverse journey scenarios 65
4.2 Reversals and performance 67
4.3 Reverse journeys in office buildings 68
4.3.1 Morning up peak 68
4.3.2 Lunch peak 69
4.4 Implications of design choices 70
4.4.1 Not all lifts serve all floors 70
4.4.2 Multiple entrance floors 72
4.4.3 Restaurant, meeting and other busy floors 73
4.4.4 Impact of the optimisation method of the ETD algorithm 73
4.5 Design application 74
4.6 User interface 76
4.7 Summary 77

5 Departure delays ... 78
5.1 Introduction ... 78
5.1.1 Background ... 78
5.1.2 Extended door dwell time ... 78
5.1.3 Departure delays in multi car/cabin lift systems ... 79
5.1.4 Departure delays in conventional systems ... 80
5.1.5 Stops without passenger transfer ... 81
5.1.6 Departure delays and quality of service ... 81
5.2 Samples/Records of passenger departure delays ... 82
5.3 Passenger departure delay (open doors) ... 82
5.4 Blind passenger departure delays (closed doors) ... 86
5.5 Cabin departure delay ... 87
5.6 Measures and diagrams ... 88
5.7 Avoidance and reduction of departure delays ... 88
5.8 Summary ... 89
6 Quality of service dispatching ... 91
6.1 Introduction ... 91
6.2 Online survey review ... 91
6.3 Parameters considered by QOS dispatching ... 93
6.4 Dispatching algorithm ... 95
6.4.1 Extended ETD dispatching algorithm ... 95
6.4.2 Simplified QOS dispatching algorithm ... 97
6.4.3 QOS dispatching algorithm ... 98
6.5 Variations ... 100
6.6 Summary ... 101
7 Safety distance control ... 103
7.1 Introduction ... 108
7.2 Definitions ... 110
7.3 Minimum distance ... 111
7.3.1 Minimum distance during normal operation ... 111

7.3.2 Operational distance calculation 114
7.4 Controlled deceleration/controlled stopping distance 116
7.4.1 System reaction time 116
7.4.2 Deceleration with infinite jerk 117
7.4.3 Deceleration with jerk 117
7.4.3.1 Time points 119
7.4.3.2 General equations of the controlled deceleration 121
7.4.3.3 Velocity (v_d) and deceleration (a_d) 123
7.4.3.4 Ideal stopping distance 123
7.4.3.5 Diagrams controlled deceleration 124
7.5 Stopping point or distance during a journey 128
7.6 Constraints (Quantising safe positions) 130
7.7 Summary 133
8 Ideal lift kinematics for multi car lift systems 135
8.1 Introduction 138
8.1.1 General 138
8.1.2 Current situation 138
8.1.3 Approach 140
8.2 Calculations unsymmetrical travelling curve 141
8.2.1 Times 142
8.2.2 General equations (Case A) 143
8.2.3 Adapt rated values 144
8.2.3.1 Adaption of rated acceleration/deceleration 144
8.2.3.2 Condition of case A 145
8.2.3.3 Case B 145
8.2.3.4 Case C 147
8.3 Usage of the unsymmetrical travelling curve 147
8.4 Case study 151
8.4.1 Configuration 152
8.4.2 General calculations 153

8.4.2.1 Handling capacity ... 153
8.4.2.2 Quality of service – additional departure delays ... 153
8.4.3 Spatial plots comparison ... 154
8.4.3.1 Symmetrical travelling curve ... 154
8.4.3.2 Unsymmetrical travelling curve ... 156
8.4.3.3 Effect on handling capacity and quality of service ... 157
8.5 Summary ... 158
9 Circulating multi car lift systems - characteristics ... 159
9.1 Introduction ... 159
9.2 Handling capacity ... 159
9.3 Quality of service ... 161
9.4 User interfaces ... 163
9.5 Lift control types ... 164
9.6 Horizontal passenger transportation ... 166
9.7 Lift arrangements and traffic concept ... 166
9.8 Summary ... 166
10 MCLS as shuttle lift system ... 168
10.1 Introduction ... 169
10.1.1 Single entrance ... 169
10.1.2 Double entrance ... 170
10.2 Minimum possible cycle time ... 174
10.2.1 Cycle time ... 174
10.2.2 Calculation of the minimum possible cycle time ... 175
10.3 Number of cars ... 177
10.4 Handling capacity for shuttle arrangements ... 179
10.4.1 General ... 179
10.4.2 Cabin size ... 179
10.4.3 Double entrance ... 180
10.5 Quality of service for shuttle arrangements ... 180
10.6 Comparison of shuttle lift systems ... 181

10.7 Summary 186
11 MCLS as local group 187
11.1 Introduction 188
11.2 Lift arrangements 188
11.3 Cycle time in local MCLS groups 189
11.3.1 Assumptions 190
11.3.2 Additional cycle time delay 191
11.3.2.1 Delaying stops 191
11.3.2.2 Additional cycle time delay 193
11.3.2.3 Stopping sequences and safe floors 194
11.3.2.4 Comparison of stop sequences 196
11.3.3 Simulation/Calculation 197
11.4 Results 200
11.4.1 $d_{min} < d_{f2f}$ 200
11.4.2 $d_{f2f} < d_{min} < 2\ d_{f2f}$ 203
11.4.3 Express zones 203
11.4.4 3-shaft system 204
11.5 Summary 204
12 Multi car control 206
12.1 Introduction 206
12.2 Call dispatching with multiple loops 206
12.3 Served floors assignment 208
12.4 Synchronisation within a single MCLS loop 211
12.5 Control levels 213
12.6 Summary 215
13 Conclusion 216
13.1 General 216
13.2 Findings and application 216
13.2.1 Quality criteria 216

13.2.2 Traffic control 218
13.2.3 Ropeless lift system 220
13.2.4 Further work 223
13.3 Contribution to knowledge 223
References 225
Appendices 235
Appendix A: List of own publications 235
Appendix B: Operational distance 237
Appendix C: Controlled deceleration with jerk 241
Appendix D: Unsymmetrical travelling curve: times 246

Table of figures

Figure 1-1: General structure of the thesis 26

Figure 2-1: Passengers' time to destination – phases of a journey 30

Figure 2-2: Siikonen full day office traffic pattern 36

Figure 2-3: Comparison of different lift arrangements 38

Figure 2-4: Two levels of (traditional) traffic control 40

Figure 2-5: Three levels of traffic control 41

Figure 2-6: Seven periods (p1..p7) of case A of the ideal lift kinematics 43

Figure 2-7: Lift group with two independent cars sharing the same shaft 45

Figure 2-8: A circulating ropeless MCLS called MULTI (courtesy of thyssenkrupp) 47

Figure 2-9: Light weight car (courtesy of thyssenkrupp) 48

Figure 2-10: Car of a MCLS located at the exchanger unit (courtesy of thyssenkrupp) 49

Figure 2-11: Exchange process of a car in a circulating MCLS (courtesy of thyssenkrupp)........49

Figure 2-12: Real stopping distance in travel direction of an unbalanced system in up and down direction........53

Figure 3-1: Position of destination input devices on a floor........56

Figure 3-2: Reassurance indicator........58

Figure 3-3: Waiting passengers at conventional control lift groups........59

Figure 3-4: Waiting passengers at destination control lift groups........60

Figure 3-5: Lift cars L2 and L3 pass a waiting passenger........61

Figure 4-1: Traffic control levels relevant for reverse journey consideration........64

Figure 4-2: Reverse journey scenarios (A, B, C) of a single lift........66

Figure 4-3: Reverse journey scenario with two lift group........67

Figure 4-4: Comparative performance for sample office building during up peak with and without reverse journeys (RJs) allowed........69

Figure 4-5: Comparative performance for sample office building during lunch traffic with and without reverse journeys (RJs) allowed........70

Figure 4-6: Reverse journeys become more likely when not all lifts serve all floors 71

Figure 4-7: Results showing allowing reverse journeys (RJs) reduces the degradation in performance caused by not all lifts serving all floors........72

Figure 4-8: Results showing the multiple entrance floors are more susceptible to reverse journeys (RJs)........73

Figure 4-9: Comparative performance for sample office building during lunch traffic with and without reverse journeys (RJs) allowed with bias on WT optimisation......74

Figure 4-10: WT (solid line) and time to destination (dotted line) without reverse journeys 75

Figure 4-11: WT (solid line) and time to destination (dotted line) allowing reverse journeys 75

Figure 4-12: Average number of reverse journeys (RJs) by time of day 76

Figure 4-13: Suggested indicator formats to help passengers accept reverse journeys 77

Figure 5-1: Double deck lift with a blind stop for a passenger in the lower cabin 79

Figure 5-2: Delayed departure of the following car in a MCLS 80

Figure 5-3: Experienced departure delays 82

Figure 5-4: Passenger departure delay (normal stop)..83

Figure 5-5: Passenger departure delay (normal stop + traffic caused delay)..........83

Figure 5-6: Short pause in passenger transfer..84

Figure 5-7: Pause in passenger transfer...84

Figure 5-8: Door re-opening and departure delays 85

Figure 5-9: False stop 85

Figure 5-10: False stop + traffic caused delay 85

Figure 5-11: Delayed passenger transfer..86

Figure 5-12: Blind departure delay..86

Figure 5-13: Blind departure delay + additional traffic caused delay.......................87

Figure 5-14: Blind stop..87

Figure 5-15: Histogram of the passenger departure delays (example) 88

Figure 6-1: Traffic control levels – QOS dispatching 91

Figure 6-2: Question 1 part 1 with multiple choice response options (source: peters research (Bird *et al.*, 2016))....92

Figure 6-3: Format of a theoretical journey in Question 2 and 3 (source: peters research (Bird *et al.*, 2016))....92

Figure 6-4: Parameters of a journey to be considered by the different dispatchers 95

Figure 6-5: „time cost" function $C_w(WT)$ 97

Figure 7-1: Unknown required distances between cars 108

Figure 7-2: Unknown required distances between cars (cars stopping at the same floor)....109

Figure 7-3: Dimensions of cars and distances 110

Figure 7-4: Travelling position and real stopping point in down direction 113

Figure 7-5: Jerk, acceleration and velocity of an ideal controlled deceleration starting at tx 118

Figure 7-6: Virtual $tD3$ of an ideal controlled deceleration 120

Figure 7-7: Ideal controlled deceleration starting in period 1of the journey 125

Figure 7-8: Ideal controlled deceleration starting in period 2 of the journey 125

Figure 7-9: Ideal controlled deceleration starting in period 3 of the journey 126

Figure 7-10: Ideal controlled deceleration starting in period 4 of the journey 126

Figure 7-11: Ideal controlled deceleration starting in period 5 of the journey 127

Figure 7-12: Ideal controlled deceleration starting in period 6 of the journey 127

Figure 7-13: Ideal controlled deceleration starting in period 7 of the journey 128

Figure 7-14: Travelling position and ideal stopping point for a controlled deceleration with rated and higher values for deceleration and jerk 129

Figure 7-15: Known required distances between cars 130

Figure 7-16: Known required distances between cars (cars stopping at the same floor)..130

Figure 7-17: Linear motor segmentation 131

Figure 7-18: Modified safety distance due to motor segmentation..132

Figure 7-19: Modified safety distance due to floor segmentation 133

Figure 8-1: Position of two following cars over time (symmetrical travelling curve) 140

Figure 8-2: Distance between leading car and its safe position (symmetrical travelling curve)..140

Figure 8-3: Seven periods (p1..p7) of the ideal unsymmetrical lift kinematics.......142

Figure 8-4: Unsymmetrical travelling curve case B 146

Figure 8-5: Position of two following cars over time (unsymmetrical travelling curve) 149

Figure 8-6: Velocity, acceleration and jerk profile of the following car (unsymmetrical)..149

Figure 8-7: Distance between leading car and its safe position (unsymmetrical travelling curve)..150

Figure 8-8: Traffic control including motion command..151

Figure 8-9: Shaft with two independent lift cars in one shaft 152

Figure 8-10: Round trip of two cars in the same shaft (symmetrical travelling curve) 155

Figure 8-11: Standing time and departure times of two cars (symmetrical travelling curve) 155

Figure 8-12: Roundtrip of two cars in the same shaft (unsymmetrical travelling curve) 156

Figure 8-13: Standing time and departure times of two cars (unsymmetrical travelling curve) 157

Figure 9-1: Circulating MCLS with one way tracks 160

Figure 9-2: Delayed cycle time of subsequent cars 161

Figure 9-3: Allocation to the same shaft door but to different cars 164

Figure 10-1: Options of simplified lift arrangements, including a circulating MCLS as a shuttle with a single entrance floor 170

Figure 10-2: Options of simplified lift arrangements including a circulating MCLS as a shuttle with a double entrance floor 172

Figure 10-3: Spatial plot of two cars with a pair of distributed sky lobbies 173

Figure 10-4: Spatial plot of two cars with two pairs of distributed sky lobbies 173

Figure 10-5: Vertical position of two subsequent cars 175

Figure 10-6: Cycle time at an intermediate floor 177

Figure 10-7: Cycle time, RTT and number of cars 178

Figure 10-8: Cycle time between two pairs of cars 180

Figure 10-9: Comparison of a group of circulating multi car systems with a double deck group 182

Figure 10-10: Comparison MCLS vs. double deck depending on travel height: velocity 183

Figure 10-11: Comparison MCLS vs. double deck depending on travel height: number of cabins 183

Figure 10-12: Comparison MCLS vs. double deck depending on travel height: HC 184

Figure 10-13: Comparison MCLS vs. double deck depending on travel height: interval 184

Figure 10-14: Comparison MCLS vs. double deck depending on travel height: average WT and average TT 185

Figure 11-1: Arrangements of a MCLS as local group 189

Figure 11-2: Spatial plot with the stopping sequence of two subsequent cars violating the safety distance 191

Figure 11-3: Spatial plot with the stopping sequence of two subsequent cars with an additional cycle time delay 192

Figure 11-4: Adapted speed to avoid an additional cycle time delay and violation of safety distances 193

Figure 11-5: Algorithm to calculate the delaying stops 196

Figure 11-6: Structure of the Monte Carlo simulation to calculate the average cycle time 197

Figure 11-7: Monte Carlo simulation - sequence of operations 199

Figure 11-8: Screenshot of the software to calculate the average cycle time and handling capacity of a local circulating MCLS 200

Figure 11-9: Average incoming HC5 for one local circulating MCLS loop 201

Figure 11-10: Average delaying stops for one local circulating MCLS depending on number of floors 202

Figure 11-11: Average delaying stops for one local circulating MCLS depending on passengers per car 202

Figure 11-12: HC depending on the safety distance constraints 203

Figure 12-1: HC in 5 minutes per MCLS loop if multiple loops are operated as one group 207

Figure 12-2: HC in 5 minutes gain if multiple MCLS loops are operated as one group 207

Figure 12-3: Alternating floor assignment of multiple MCLS loops 209

Figure 12-4: Effect of served floor assignment 210

Figure 12-5: Alternating floor assignment of multiple MCLS loops with a double entrance lobby 211

Figure 12-6: Spatial plot of three cars in MCLS 212

Figure 12-7: Traffic control levels of a MCLS 214

Figure 13-1: Overview quality criteria 217

Figure 13-2: Traffic control levels considering QOS criteria 219

General definitions

The following terms in this thesis are sometimes used in the lift industry but are defined here for clarity.

Multi car lift system
: Multiple independent running lift cars sharing one or more of the same shaft(s). This can be a circulating multi car lift system or two independent cars in one shaft.

Circulating multi car lift system
: A multi car lift system with shafts mostly used as one-way tracks. Horizontal exchange of lift cars between shafts is possible and necessary.

Multi car lift system loop
: A circulating multi car lift system with two or three shafts.

Cycle time
: Time between two subsequent lift cars departing from the main entrance floor in a circulating multi car lift system.

Car vs. cabin
: A lift car can be moved independent from other lift cars within shafts. Mutual interaction between multiple cars in one shaft is possible. Single deck lift cars have one cabin that can be loaded by lift passengers. Double deck lifts have one car with two mechanically connected cabins, one above the other.

Abbreviations

Abbreviations used across this thesis are listed here. Abbreviations only used in particular chapters or section are explained where they are used.

ETD	Estimated time to destination [s]
HC	Handling capacity (quantity of service) [persons or % building population per unit of time]
HC5	Handling capacity in 5 minutes
MCLS	Multi car lift system
QOS	Quality of service experienced by lift passengers
RTT	Round trip time [s]
TT	Transit time [s]
TTD	Time to destination [s]
WT	Waiting time [s]

List of symbols

Generally used parameters – these are also used with indices and explained where applied.

a	Acceleration and deceleration [m/s²]
$A(t)$	Acceleration at time t [m/s²]
d	Distance [m]
$D(t)$	Distance travelled at time t [m]
h	Height [m]
j	Jerk [m/s³]

$J(t)$	Jerk at time t [m/s³]
t	Time [s]
v	Velocity [m/s]
$V(t)$	Velocity at time t [m/s]

1 Introduction

1.1 General motivation

Ongoing urbanization demands more places to live and work in cities. Limited space requires higher buildings. As buildings get taller, vertical transportation of passengers in buildings has become increasingly important. Efficient lift systems in buildings need to transport passengers vertically, whilst providing appropriate handling capacity (HC), a good quality of service (QOS) and considering energy and space required for vertical transportation.

Levitt said: “Products are consumed, services are experienced” (Maister, 1985). Although lifts are sold by manufacturers as products their lift systems are providing a service for people in buildings – vertical transportation. The lifts are transporting people with real feelings and emotions. If lifts transported solely boxes and goods the science of designing lift controls would be different and less exciting. Therefore, the overall experience for lift passengers and the service quality is an important factor for vertical transportation in buildings. It is necessary that all vertical transportation concepts keep in mind passengers’ experience. This includes lift arrangements, passenger traffic flow concepts, control systems and lift types.

The existing QOS criteria, mostly based on waiting time, cover passenger transportation in traditional lift systems were multiple lifts, each running in its own and exclusive shaft, are operated in lift groups to serve the passengers transportation requests. Lift arrangements and traffic flow concepts are developed through traffic design and planning for buildings. These need to be adapted to building circumstances to improve efficiency of vertical transportation systems in buildings (Siikonen, 1997a, Barney, 2003, Strakosch and Caporale, 2010). Examples include dedicated lifts for building zones or special floors and shuttle lifts with transfer floors. Control and dispatching algorithms help to improve QOS, HC and energy consumption (Barney, 2003). Particular advanced group control types like destination control help to improve HC of lift groups especially in up peak situations. As the traffic handling of the lifts with destination control is different to conventional group control, additional constraints and situations need to be considered related to QOS.

Beyond traditional lift systems, lift systems with multiple lift cars sharing shafts and double deck lifts can improve shaft efficiency, especially in tall buildings with long shafts. Double deck lifts with two cabins mechanically connected above each other and operate together as one car propelled by one motor are well known (Vogel, 1889). A lift system where two independent single deck cars are operated in one shaft increases shaft efficiency and flexibility (Thumm, 2004). These multi car or cabin systems require and enable additional traffic concepts with double entrance lobbies to improve performance and efficiency of lift groups. Even concepts and ideas of circulating multi car lift systems (MCLSs) exist, where multiple ropeless lift cars, propelled by linear motors, are moving independently sharing two or more shafts. These are being currently developed (ThyssenKrupp Elevator AG, 2014). A MCLS with multiple independent moving cars requires additional safety means to avoid collisions. Control systems need to operate the cars efficiently without any collision. Interaction between cars limits the freedom to move compared to one lift car in one shaft. This can affect HC and QOS experienced by lift passengers.

Modern lift systems with destination control, double deck lift systems and MCLS have additional opportunities but also constraints for control algorithms arisen from existing and additional QOS criteria. The QOS criteria in combination with modern lift systems including MCLS have rarely been considered in existing literature, control algorithms or traffic analysis. Delayed departures of cars and reverse journeys of passengers linked to user interfaces and expected lift behaviour need to be applied to control and dispatching algorithms. Control and dispatching algorithms of modern destination control and MCLS need to be explored and developed based on existing and additional QOS criteria.

1.2 Aims and objectives

The overall aim of the research is to determine and analyse existing and new quality of service (QOS) criteria for destination control systems and multi car lift systems (MCLSs) in terms of traffic handling and developing lift control algorithms/concepts to consider these QOS criteria. This includes circulating multi car lift groups, lift control functionality and call dispatching strategies.

The identification of QOS criteria in MCLSs with multiple cars in one or more shafts represents a complex problem and should be associated with the psychology of waiting.

The main objectives are:

1. Explore existing and define new QOS criteria relevant for MCLSs and destination control systems to meet passengers' perception.
2. Explore and develop lift control strategies including dispatching algorithms for destination control systems considering new and existing QOS criteria.
3. Explore and develop control algorithms including kinematic equations to optimize speed patterns in terms of QOS and HC in MCLSs considering safety distance constraints.
4. Explore and develop traffic concepts and analysis for circulating MCLSs considering QOS criteria.

Without considering the safety distance constrains it is not possible to optimize control algorithms and speed patterns in a MCLS. For that reason analysis and calculation of safety distances and stopping distances of cars are also conducted in the research work.

Some of the concepts for MCLSs can be applied to double deck lifts systems.

1.3 Overview of the methodology and research tools applied

Existing QOS criteria in the area of traffic analysis of lift groups are based on conventional/traditional lift systems. New QOS criteria that are relevant for destination control systems and MCLSs are necessary. Psychology of waiting aspects were used to review and analyse situations and introduce additional QOS parameters for lift passengers, especially in destination control systems and MCLSs. This is supported by results of an online survey asking about passengers preferences (Bird *et al.*, 2016) and input from traffic analysis experts in the lift industry.

To analyse the effect of reverse journeys used as a QOS criterion in destination control systems, the lift traffic simulation software ELEVATE was used (Peters Research Ltd., 2014). An existing C++ implementation of a dispatching algorithm was modified and expanded using software development environment (Microsoft Corporation, 2007). Different traffic types and demands were applied. To evaluate the effects, the results of the defined QOS criteria were compared.

Round trip time (RTT) calculations (Barney, 2003, CIBSE, 2015) were used to calculate the performance of roped shuttle lifts. Based on the RTT calculation method, a cycle time calculation was developed for ciculating MCLSs to evaluate the HC and number of cars necessary.

To analyse the HC of a circulating MCLS when it is used as a local group the analytical method of the cycle time calculation was expanded with an additional cycle time delay to consider different stop sequences. Similar to RTT calculations for conventional lift systems, this was combined with the numerical concpet of the Monte Carlo simulation (Al-Sharif *et al.*, 2012). This was implemented by using a C++ software development environment (Microsoft Corporation, 2007). Additionally, the passenger traffic generator of ELEVATE (Peters Research Ltd., 2014) was used.

If there are multiple lift cars sharing the same shafts, then the control system needs to consider safety distance constraints. To reduce departure delays, known speed profile (kinematics) needs to be adapted and modified. Therefore, equations for controlled stopping distances and ideal, unsymetrical lift kinematics were derived by using mathematical software (PTC Inc., 2013).

1.4 Structure of the thesis

This thesis covers a wide range of aspects related to the quality and quantity of service in lift groups where multiple lift cars are sharing the same shafts and lift groups with destination control. This brief overview of the chapters in this thesis highlights peer reviewed papers and articles published during the research (see list of own publications in the appendix).

The general structure of the thesis is shown in Figure 1-1. The main body has three major blocks: Quality of service, traffic control algorithms and MCLS traffic analysis. The “Quality of service” block analyses and defines QOS criteria. “Traffic control algorithms” describes and analyses traffic control algorithms considering QOS criteria. In “MCLS traffic analysis” an analysis for a circulating MCLS is established considering QOS.

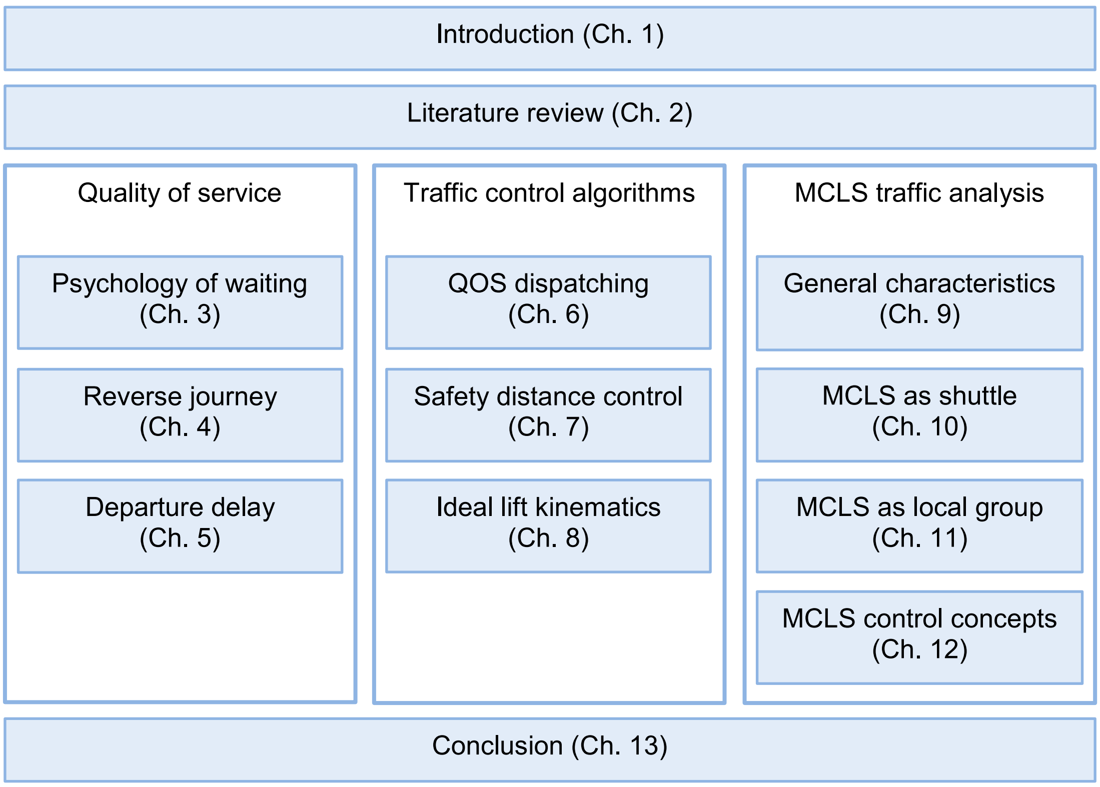


Figure 1-1: General structure of the thesis

Chapter 2 summarises the literature review about relevant topics that need to be considered for analysing and improving QOS in MCLS and destination control systems. The topics are split into three groups: “traffic analysis and design”, “control systems and algorithms” and “multi car lift systems”.

Chapter 3 explores the relevance of the psychology of waiting to the overall lift design and its QOS aspects. This includes the lift architecture, user interfaces and lift control functionality which contains reverse journeys and departure delays (Smith and Gerstenmeyer, 2013).

Chapter 4 introduces reverse journeys as quality criterion. It explores reverse journey situations in destination control systems, and how they affect the average waiting times (WTs) and implications for lift group designs (Gerstenmeyer and Peters, 2014).

Chapter 5 defines departure delays for lift systems, where they come from and how they can be measured in simulation and real installations. It also explains situations in which they can occur (Gerstenmeyer et al., 2017).

Chapter 6 applies existing and new QOS parameters to the cost function of a call dispatching algorithm. The transit time is split into different phases. Reverse journeys and departure delays during stops are considered.

Chapter 7 explores safety distance constraints if multiple cars are sharing the same shafts. It calculates minimum car to car distances and stopping distances of cars. This is necessary to develop an optimised interaction between multiple cars sharing same shafts (Gerstenmeyer and Peters, 2016a).

Chapter 8 derives equations for an unsymmetrical travelling curve to be used for multiple cars sharing the same shafts. A comparison in a double lobby express shuttle arrangement with symmetrical travelling curves considering safety distance constrains shows the positive effect to QOS through reduced departure delays experienced by passengers.

Chapter 9 explains the general characteristics of ropeless circulating MCLSs and explores the aspects that need to be considered in lift applications and control systems (Gerstenmeyer and Peters, 2016b).

Chapter 10 focuses on a circulating MCLS as an express shuttle. Next to possible lift arrangements, traffic design principles are established by introducing cycle time calculations. Lift performance is compared with conventional shuttle lifts (Gerstenmeyer and Peters, 2015, Gerstenmeyer and Peters, 2017, Jetter and Gerstenmeyer, 2015, Choleau et al., 2016).

Chapter 11 focuses on traffic analysis for circulating MCLSs used as local groups. A method to calculate necessary additional average cycle time and avoiding “traffic jams” and departure delays is introduced. Monte Carlo simulation is used to calculate the average HC of a local MCLS group for pure incoming traffic.

Chapter 12 shows the positive effect of dispatchers if multiple MCLS loops are operated as one common group. Controller concepts to operate and coordinate cars within MCLS loops are explained based on different control levels (Gerstenmeyer and Peters, 2016b).

2 Literature review

This literature review covers the wide range of aspects linked to the research of quality and quantity of service in lift groups and their control algorithms:

- Traffic analysis/design:
  This covers and describes existing measures for quality and quantity of service and methods used for traffic analysis and design. Current lift arrangements and traffic concepts for tall buildings are reviewed.
- Control systems and algorithms:
  This looks into current control strategies and designs and how they consider overall lift performance and quality of service (QOS) criteria. Lift groups with single car and multi car/cabin shafts are reviewed.
- Multi car lift systems:
  Existing and proposed multi car lift systems (MCLSs) where multiple lift cars are sharing same shafts are reviewed. In particular, a ropeless lift system with circulating multiple lift cars under development has been considered. Existing safety distance theories and concepts, especially of certified safety systems for MLCS are reviewed, as they need to be considered in control algorithms.

2.1 Traffic analysis/design

Traffic analysis is the “determination of statistical characteristics of passenger movements in an elevator […] system” (CIBSE, 2015). It is used in vertical transportation planning, traffic design, traffic studies and the assessments of passenger vertical transportation in buildings. Vertical transportation concepts for buildings are measured against performance criteria like QOS, quantity of service, energy efficiency and core space needed for lift systems in buildings. It considers building parameters like heights and number of entrances, building types and usages (office, residential, hotel, etc.), passenger demands and traffic flows. A major impact to the vertical transportation performance has the lift systems itself: number of cars and shafts, cabin sizes, lift performance times and others affect the results. Control types like destination control and conventional control, user interfaces and control algorithms need to be considered in a detailed analysis as well.

2.1.1 Quality of service

A passenger's journey consists of two different phases (see Figure 2-1), waiting for the lift at the arrival floor, known as waiting time (WT) and the travelling time inside the car, known as transit time (TT). The sum of WT and TT is called time to destination (TTD) (CIBSE, 2015).

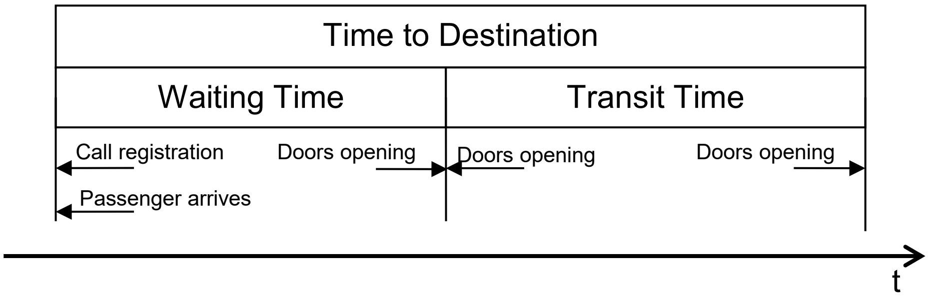


Figure 2-1: Passengers' time to destination – phases of a journey

QOS in terms of traffic handling is mostly defined by WT (Barney, 2003, Strakosch and Caporale, 2010, CIBSE, 2015). Traditionally, the interval also gives an indication of quality (Barney, 2003). Other definitions of QOS exist e.g. like system response time (Barney, 2003), the majority being based solely on interval or WT. Another factor is the TT. One QOS rating, based on the modern office templates, includes average WT, average TT but also the capacity factor by area for up-peak and lunch-peak traffic (CIBSE, 2010).

QOS in terms of traffic handling is linked to "waiting for a service" in general. Passengers may wait for the lift to arrive, and wait while transported inside the lift to the passengers' destination. So QOS very much depends on the psychology of waiting and the experience passengers have while using the lifts for vertical transportation. To understand QOS, it is valuable to look to research previously conducted on the psychology of waiting in lines (R. Smith, 2013). Waiting in lines research is most commonly linked to amusement parks, fast food restaurants and food stores.

In 1985 the following key concepts of the psychology of waiting lines were published (Maister, 1985):

1. Occupied time feels shorter than unoccupied time

2. People want to get started
3. Anxiety makes waits seem longer
4. Uncertain waits are longer than known, finite waits
5. Unexplained waits are longer than explained waits
6. Unfair waits are longer than equitable waits
7. The more valuable the service, the longer the customer will wait
8. Solo waits feel longer than group waits

In 2008 eight design principles for waiting lines were presented (Norman, 2008):

1. Emotions dominate
2. Eliminate confusion: provide a conceptual model, feedback and explanation
3. The wait must be appropriate
4. Set expectations, then meet or exceed them
5. Keep people occupied: filled time passes more quickly than unfilled time
6. Be fair
7. End Strong, start strong
8. Memory of an event is more important than the experiences

Many of these sixteen concepts apply to waiting and riding in lifts and are considered in current lift concepts. These are reviewed in chapter 3 and need to be considered for MCLSs as well.

TT may seem longer to passengers as, psychologically, they may feel time passes slower inside an elevator car (Lin *et al.*, 2013). Long TTs are associated with high anxiety levels. However, it is assumed that WT is more painful than TT (R. Smith and Peters, 2004); this is consistent with Maister’s suggestion that waiting people want to get started on their journey and high anxiety levels make the wait seem longer (Maister, 1985). There is a limit to the amount of time passengers will wait (WT) and travel (TT) before they become impatient, which is dependent on individual factors (Strakosch and Caporale, 2010). If there are too many intermediate stops for passengers before they reach their destination they become impatient and intolerant (Barney, 2003).

Another aspect of QOS and its psychological effects is the reverse journey situation, which is undesirable (Levy *et al.*, 1977). In a reverse journey situation, a passenger is initially taken up when the call is in down direction or vice versa.

The quality criteria were originally defined for traditional lift systems. They need to be reviewed for new lift systems were multiple cars and cabins are operated in the same shafts and for destination control systems (see chapter 3).

2.1.2 Quantity of service

Quantity of service is defined as the handling capacity (HC) of a lift installation (CIBSE, 2015). It is the number of passengers a lift system can transport in a specific period of time. Often it is expressed as percentage of building population but can be also given as an absolute number of passengers and is measured typically in 5-minute periods (HC5). It is often used as total number of passengers a lift system can transport in an up peak traffic condition with a specified car loading, usually taken as 80% of the rated cabin capacity (CIBSE, 2015). For a lift group with conventional control the HC5 for a pure up-peak traffic situation can be calculated as shown in equation (2-1) (Barney, 2003):

$$UPPHC = \frac{300s}{UPINT} P \qquad (2\text{-}1)$$

where

$UPPHC$	The up-peak HC in 5 minutes
$UPINT$	The up-peak interval is the average time between successive lift car arrivals at the main terminal floor
P	The average number of passengers carried

During other traffic conditions the HC5 is compared to up-peak:
down-peak: 160%; interfloor: 140%; lunch-traffic: 130% (Barney, 2003).

However, Smith argues that the relative HC compared to the up-peak HC varies from system to system (R. Smith, 2011). Thus the HC also depends on the dispatching algorithm. It is related to the lift performance time (Peters, 2012) and special building and traffic flow situations. To provide a good QOS sufficient HC is needed. So it is valuable to improve the HC in different traffic conditions by applying different strategies.

If the passenger demand exceeds the maximum possible handling capacity provided by a lift group, the lift group saturates. In saturation the average queue length of waiting passengers grows over time (R. Smith, 2011).

2.1.3 Methods of traffic design and analysis

Lift traffic design aims to determine the lift group configuration that meets the traffic requirements of a building during the planning phase (Al-Sharif *et al.*, 2012). In lift traffic design and analysis, different methods exist and are used. In general there are two categories: calculation and simulation (Al-Sharif and Al-Adem, 2014).

2.1.3.1 Analytical method (calculation)

The classical method is an analytical, equation-based calculation – the round trip time (RTT) calculation (Barney, 2003, CIBSE, 2015). The RTT calculation is based on pure up peak traffic conditions. Inputs to calculate the RTT for a single car are an average highest reversal floor, the probable number of stops, average number of passengers in the car, their transfer times and lift performance times including door times and car moving times. The average up peak interval of lifts departing from the main terminal floor depends on the RTT and number of lifts in a group. The interval as a result is used as a measure for the QOS. This is a lift metric rather than a quality criteria experienced by passengers. The relationship between interval and WT is complex (Peters, 2013a).

The RTT calculation has limitations as it is based on assumptions and simplifications. The main assumptions are equal floor population, equal floor heights, rated velocity is reached for every trip and a single entrance lobby (Al-Sharif *et al.*, 2012). Modifications of the classical RTT calculation are necessary to address limitations analytically. These can be complex and especially combinations of addressed limitations become complicated (Al-Sharif *et al.*, 2012).

Extensions to the classical RTT calculations overcome limitations (Al-Sharif and Abu Alqumsan, 2015). General Analysis overcomes most of the limitation of the classical RTT calculations (Peters, 1990). It introduces complex equations that enable analytical analysis with mixed traffic conditions and requires an iterative calculation.

These methods (RTT calculation and General Analysis) were extended to analyse double deck lift systems (Peters *et al.*, 1996, Siikonen, 2000, Al-Sharif *et al.*, 2017). For MCLSs with multiple independent cars sharing the same single shaft, a RTT calculation is proposed based on all independent cars that are serving the same entrance floors (Sakita, 2010). That does not fit to the proposed zoning concept of two independent cars in one shaft with a double entrance lobby (Müller, 2014). For two independent cars in one shaft, lift traffic simulations are used (Peters Research Ltd., 2014). The analytical method also does not consider individual dispatching and control algorithms of the lift system.

2.1.3.2 Simulation method (event based)

Lift traffic simulations are discrete event based or time-slice (timer-event-based) simulations. The whole process of passenger arrivals and transportation in lift cars is simulated including the lift functionality. As traffic simulation is closer to “real life” it has some advantages compared to RTT calculations (CIBSE, 2015): it models the lift control system; it enables more realistic passenger arrivals rather than constant passenger arrival like assumed in the RTT calculation and it enables various types of results that can be analysed. The passenger waiting and transit time results are the main measure for QOS, but other analysis are possible. Traffic simulation covers different kind of building configurations, traffic types, lift configurations and types of lifts systems. But lift traffic simulations are more complex and time consuming compared to analytical calculations (Peters, 2013a, Al-Sharif *et al.*, 2014). If a traffic simulation is configured according to the assumptions of a RTT calculation it can be shown that results are consistent (Peters, 2013a). ELEVATE is a lift traffic simulation software (Peters Research Ltd., 2014) that is widely used in the lift industry for traffic design and analysis. It enables to connect proprietary dispatchers for known roped lift systems (Peters, 2002). It was shown that simulation results are consistent with real world results and it is suitable to be used as research tool (R. Smith, 2011).

2.1.3.3 "Mixed" method (Monte Carlo simulation)

A kind of a "mixed" traffic design method uses the Monte Carlo simulation method to evaluate the RTT of a lift in up peak traffic condition (Al-Sharif *et al.*, 2012). If the building configuration becomes complicated it helps to overcome combinations of the mentioned limitations of the RTT calculation method. A random passenger generator generates the passenger's destinations for each round trip. The probability of the destination floors is based on the building population for each floor. To cover multiple entrance floors the arrival floor of the passengers is also generated based on the arrival probability for each entrance floor. A round trip calculator calculates each RTT. It uses a kinematic calculator to consider unequal floor heights and trips where the rated velocity is not reached. If the number of samples is 1000 it was shown that the accuracy of the results is <+/- 0.3% (Al-Sharif *et al.*, 2011). This is a good method if equations for the analytical calculation become complex.

2.1.4 Traffic patterns

For more detailed traffic design and traffic analysis, traffic patterns in buildings need to be considered and applied. The RTT calculation uses constant, pure incoming traffic. This kind of traffic does not exist in real buildings. But as a worst case scenario, for conventional lift groups this may be feasible for planning. For advanced methods like simulation and General Analysis enhanced traffic patterns can be used and are required (CIBSE, 2015).

Similar to the HC the passenger demand or arrival rate is often given relative to the building population as a percentage for a 5 minutes period. The passenger demand or arrival rate can also be expressed as an absolute number of arriving passengers.

In general there are two ways to define enhanced traffic patterns. A simple method to define traffic in a building is based on a traffic mix between incoming, outgoing and interfloor traffic (CIBSE, 2015). Incoming passengers arrive at the main entrance floor with a destination in the upper floors. Outgoing passengers arrive in upper floors with the destination of the main entrance lobby. Interfloor passengers are between other floors than the main entrance lobby. The traffic mix is given as percentage of the total demand. For more detailed traffic definition an origin destination matrix with an arrival rate per floor and a probability of destination floors for each arrival floor is required. Both traffic definitions can be configured with the ELEVATE traffic simulation (Peters Research Ltd., 2014). Traffic patterns are usually defined in 5 minute periods.

For reliable traffic analysis, the knowledge of traffic patterns in buildings is necessary (CIBSE, 2015). The arrival rate and traffic mix in buildings is affected by the building type and varies by time of day. Additional variations will be caused by aspects like culture, location of the building or if it is a multi or single tenant office building.

As a definition of traffic patterns in buildings is important they can be generated from real lift installations by manual traffic surveys (Peters and Evans, 2008) or automated counting systems (Siikonen and Roschier, 1995, Batey and Kontturi, 2016). Traffic patterns have changed over years (R. Smith, 2011). Modern traffic pattern for office buildings are available. An example of a full day office traffic pattern is shown in Figure 2-2 (Siikonen, 2000). Other analysis showed similar results (Peters *et al.*, 2011). Also traffic patterns for hotels and residential building (Siikonen, 2013) are available.

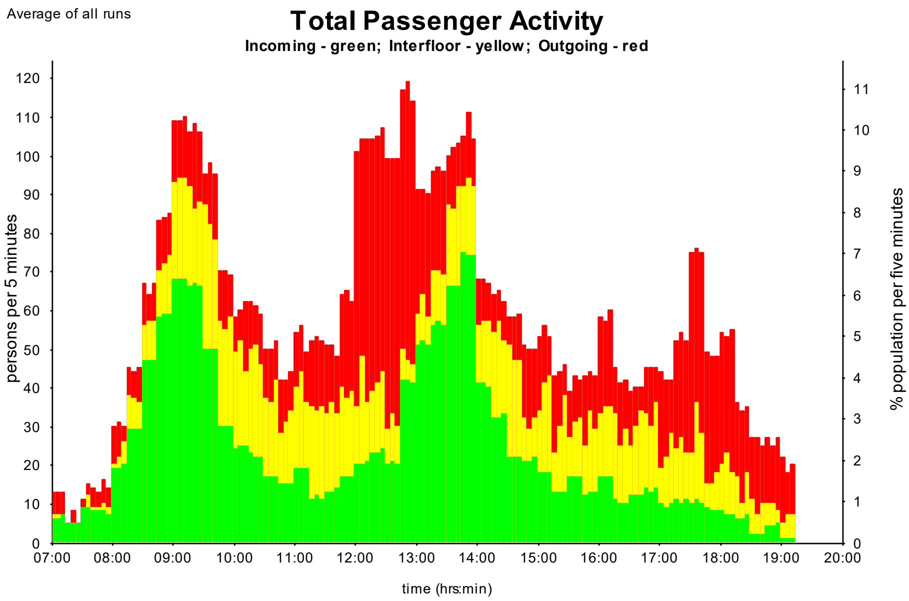


Figure 2-2: Siikonen full day office traffic pattern

For traffic planning different templates of theoretical traffic patterns exists (CIBSE, 2015). Constant arrival rates and step profiles for different traffic types (up peak, lunch peak) and different traffic mixes are used. A typical incoming traffic mix is (incoming[%] / outgoing[%] / interfloor[%]) 85/10/5. A typical average lunch time traffic mix is 45/45/10 (it starts with higher outgoing 30/60/10 and ends with higher incoming 60/30/10 traffic). For planning purposes with simulation a constant arrival rate over 2h excluding the results of passengers arriving the first 15 minutes and the last 5 minutes is proposed (CIBSE, 2015). In earlier expert discussions it was proposed that passengers of the first and last 5 minutes should be excluded of a minimum of 1h simulation (CIBSE Lifts Group, 2013).

2.1.5 Lift arrangements and traffic concepts

For good building efficiency in tall buildings it is important to keep the footprint necessary for vertical transportation to a minimum without compromises in HC (Müller, 2014). A classical approach in high-rise buildings to reduce the footprint of lift equipment is to divide the building in different zones (see Figure 2-3 (a)). Each zone is served by a lift group dedicated to a specific zone. If all lifts do not serve all of the floors in the building, core space can be reduced in the upper zone and low rise lifts can be provided at lower velocities (Barney, 2003, Strakosch and Caporale, 2010). Dedicating lift groups to zones reduces the number of probable stops. Based on the RTT calculations; reducing the number of stops reduces the RTT (CIBSE, 2010); this can reduce the total number of necessary lifts. Lift groups for upper zones can have an express zone. Fast lifts are necessary to travel long distances and achieve necessary group HCs, WTs, and TTDs. Additionally, an installation with double entrance lobbies reduces the necessary footprints for lifts. Double deck lift cars and two independent cars in one shaft make it possible to improve shaft efficiency. Double deck lifts are operated in odd/even mode in order to reduce number of stops (Siikonen, 2000). But that limits interfloor traffic between odd and even floors. Two independent cars in one shaft (Thumm, 2004) provide higher individual flexibility and can be seen as lift groups of two zones, located within the same shaft. A major advantage of double entrance lobbies is the parallel loading and unloading of passengers in two entrance levels rather than loading and unloading all passengers with one bigger cabin. Regardless, there are limits in vertical transportation planning if no interzone transfer floors are used (Müller, 2014).

A state-of-the-art approach includes using sky lobbies as transfer floors into the vertical transportation planning (see Figure 2-3 (b)). Local groups serving dedicated zones from a sky lobby are stacked, and express shuttle lifts serve the passenger demand between the entrance floors and the sky lobbies. Vertical transportation concepts with interzone transfer floors can save lift shaft space (Siikonen, 1997b, Barney, 2003, Strakosch and Caporale, 2010) and the shuttle arrangements can be realized with single or with double entrance floors. The latter requires the use of two cabins in one shaft, mechanically coupled as double decker or with two independent single deck cars. Also, escalators connecting between the entrance floors may be necessary. Local groups can be single car shafts or multi car/cabin shafts.

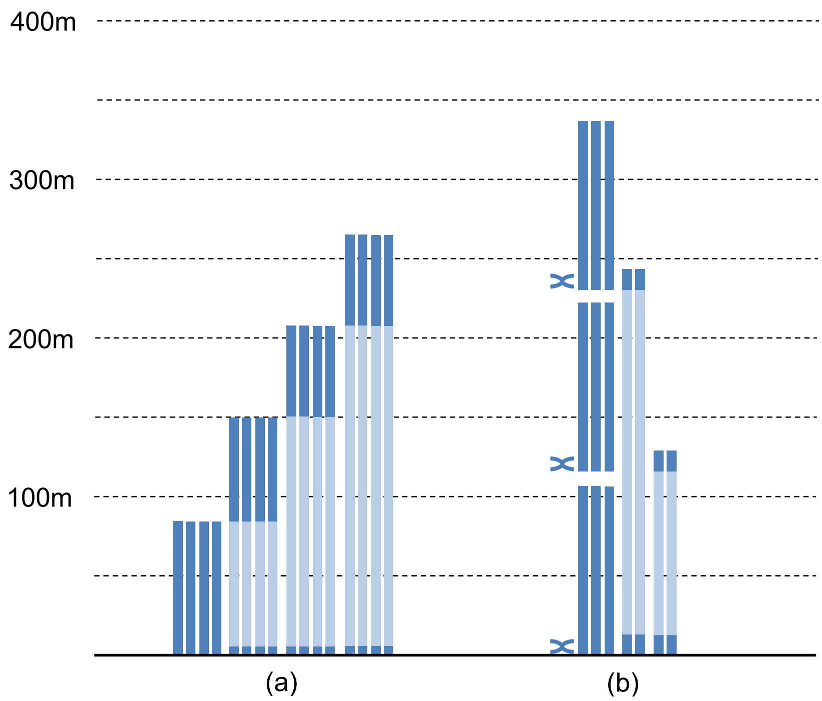


Figure 2-3: Comparison of different lift arrangements

Shuttle and sky lobby arrangements using traditional single or double deck lifts do have limits and disadvantages in shaft efficiency. Still, only one or two cars use a long single lift shaft. In mega high-rise buildings, lifts are getting faster to keep the journey time to a minimum and to provide an adequate HC and QOS with a minimum number of shuttle lifts. Limits in speed are related to human comfort regarding differential ear pressure. Limits in travel height are related to the maximum possible length of hoist cables.

2.2 Control systems and algorithms

The lift control system defines the behaviour of the lift system. The control system has impact on performance of lift systems including QOS. Thinking of a MCLS, interaction between cars and the movement of cars needs to be considered.

2.2.1 Lift group control types

If more than one lift is necessary to provide the required HC for lift passengers in a building the control of the lifts shall be interconnected to operate as groups (Barney, 2003, CIBSE, 2015). In conventional lift groups up-/down landing call push buttons are shared and group control dispatchers allocates cars to landing calls. Destinations of passengers are registered in the cabin. For destination control systems (R. Smith and Peters, 2002, Sorsa *et al.*, 2005, Lauener, 2007) also named as “hall call allocation” (Barney, 2003) the destinations of passengers are registered at the lobby and an instant allocation of a car/cabin is indicated to the passengers. This is achieved by directing the passenger to a shaft door. Destination control algorithms improve up-peak performance (Peters, 2006). Passengers with the same destination are grouped together and are allocated to the same lift, however, a drawback to destination control systems is the fact that reallocation of a call is not possible. Mixed systems combine destination control and conventional control. At heavy traffic floors, mainly at the main entrance floors, destination input stations are installed and other floors are equipped with up-/down- landing call push buttons. This adds the up peak performance improvements to a conventional group control system.

2.2.2 Control algorithms

In general, for traditional lift systems with one car per shaft, the control of a group of lift cars to serve registered landing and car calls can be divided into two levels (Sorsa *et al.*, 2009). The levels are illustrated in Figure 2-4. The higher level (call dispatching/group control) lift dispatching problem can be considered as an assignment problem. One example of a dispatching algorithm strategy is genetic algorithms. Another example of a dispatching algorithm strategy is the estimated time to destination (ETD) algorithm (R. Smith and Peters, 2002).

The lower level (call control) is self-contained, can be treated as a travelling salesman problem and is traditionally solved with collective control (Barney, 2003). There is an accepted set of rules and constraints of lift behaviour (Closs, 1970, Levy *et al.*, 1977, Siikonen, 1997b, Barney, 2003). Summarised they are:

1. Do not bypass a car call/destination of a passenger.
2. Do not transport passengers away from their destination.
3. Only stop at a floor because of a car call or landing call.

These “rules of call control” alleviate the psychological aspects passengers feel by avoiding reversed journeys and unnecessary (blind) stops.

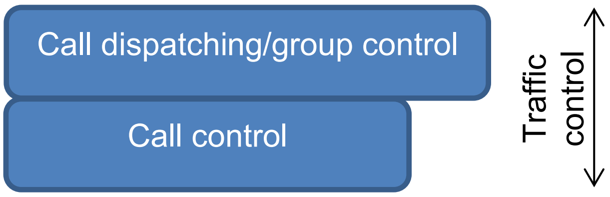


Figure 2-4: Two levels of (traditional) traffic control

QOS consideration in control algorithms: Dispatching types like destination control systems, conventional up-down button systems or mixed systems affect the HC and QOS. But also group control algorithms play a key role in improving the HC and QOS of lift groups. The estimated time of arrival (ETA) algorithm considers the arrival of lift cars to passengers waiting at the floors (Barney, 2003). The basic concept of the ETD algorithm is to optimise passenger’s TTD by allocating a lift car with the lowest time to destination cost (R. Smith and Peters, 2002). The cost for an allocation of a landing or destination call to a lift car can be described with equation (2-2).

$$ETDC = TDC + \sum_{p=1}^{p_{exist}} (TDDC_p) \qquad (2\text{-}2)$$

where

$ETDC$ Cost function of the ETD algorithm

TDC Time to destination cost of the call to be allocated

$TDDC_p$ Time to destination degradation cost of existing and affected calls/passengers (p)

Control and dispatching algorithms can consider psychology aspects. An extension of the ETD algorithm describes the split of passenger's TTD into WT and TT (R. Smith and Peters, 2004). It uses factors or functions (pain index over waiting or transit time) to consider passengers perceived times by introducing a pain index. A linear pain index function equals a constant factor. A psychology factor can be used to consider the perceived WT and TT in the dispatching control algorithm (Lin *et al.*, 2013). The psychology factor is the ration between the WT people feel to the real time people are waiting.

Multi cabin/car algorithms: Group control algorithms like genetic algorithms (Tyni and Ylinen, 2001) and the ETD algorithm are known for different dispatching types and lift types, for example, double decker lifts (Sorsa *et al.*, 2003) or two independent lift cars in one shaft (R. Smith and Peters, 2004). To coordinate multiple independent cars sharing the same shaft additionally a "system control" needs to be applied as part of the traffic control system, see Figure 2-5. Other studies of control algorithms for multiple cars sharing the same shaft with are published based on genetic algorithms (Ikeda *et al.*, 2007, Yu *et al.*, 2011) and focus on avoiding collisions (Tanaka and Watanabe, 2009).

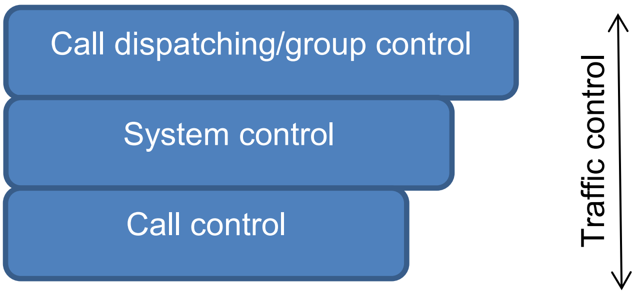


Figure 2-5: Three levels of traffic control

Door command/control: Usually the door command for a lift car considers door dwell times based on door protection means and the type of calls (landing or car call). The door is opening and closing based on a fixed configuration.

Motion command/control: Usually the motion command for lift car journeys uses the rated values of a symmetrical travelling curve. Different speed profiles may be selected because of “spare” torque available (R. Smith and Peters, 2004) or energy saving aspects (Peters and Mehta, 1998, Pletschen *et al.*, 2011). This may affect HC and WTs but is not necessarily considered as a means of traffic control for multiple lift cars sharing the same shaft.

2.2.3 Ideal lift kinematics

Equations for ideal lift kinematics were published (Peters, 1996). The equations of a symmetrical travelling curve (all jerk rates have the same absolute value and acceleration and deceleration have the same absolute values) can be used for up direction (positive values for v, a, j and d) and down travelling (negative values for v, a, j and d). Three different cases are considered.

- Case A: rated velocity and acceleration reached
- Case B: rated velocity not reached but rated acceleration reached
- Case C: rated velocity and rated acceleration are not reached

Case A is shown in Figure 2-6. The journey is split into 7 periods (p1..p7).

- Period 1: increase acceleration, constant positive jerk
- Period 2: constant acceleration
- Period 3: decrease acceleration, constant negative jerk
- Period 4: constant velocity
- Period 5: increase deceleration, constant negative jerk
- Period 6: constant deceleration
- Period 7: decrease deceleration, constant positive jerk

Depending on the parameters v, a, j and d the duration of period p2, p4 and p6 can be 0 seconds. Maximum rated values for acceleration/deceleration and jerk are limited by passenger comfort and expectations (CIBSE, 2015).

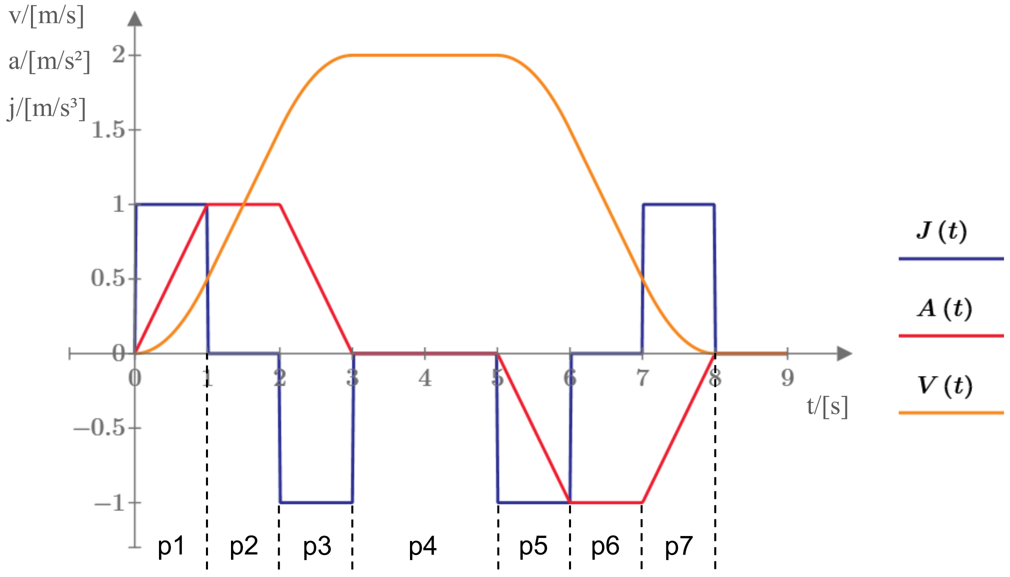


Figure 2-6: Seven periods (p1..p7) of case A of the ideal lift kinematics

There are conditions for each case (Peters, 1996). A configuration where the rated velocity is reached and rated acceleration is not reached is excluded since this would be an illogical design. For that case the rated acceleration can be adapted with equation (2-3) (Motz, 1976, Motz, 1991).

$$a = \sqrt[2]{v\,j} \tag{2-3}$$

The maximum velocity of a journey with case B (short journeys) can be calculated with the equation (2-4) (Andrew and Kaczmarczyk, 2011).

$$v = \sqrt{\frac{a^4}{4j^2} + d\,a} - \frac{a^2}{2j} \tag{2-4}$$

The maximum velocity and the maximum acceleration of a journey with case C (very short journeys) can be calculated with the equations (2-5) and (2-6) (Motz, 1976, Motz, 1991, Andrew and Kaczmarczyk, 2011).

$$v = \sqrt[3]{\frac{j\,d^2}{4}} \tag{2-5}$$

$$a = \sqrt[3]{\frac{j^2\,d}{2}} \qquad (2\text{-}6)$$

With the adaption of velocity and acceleration for case B and C all cases can be calculated with the equations of case A.

2.3 Multi car lift systems

Multiple independent lift cars increase the shaft efficiency especially in tall buildings as the same shaft is used by multiple lift cars. That includes roped lift systems and ropeless lift systems. To ensure high performance including QOS and develop control strategies it is necessary to understand the technology of these systems.

2.3.1 Two independent cars in one shaft

Two independent cars in one shaft are known in existing lift systems (Thumm, 2004). Figure 2-7 shows an example of a lift group with two independent cars per shaft. Both cars move independently using traditional lift technology. Each has its own counterweight, safety components, drive and control system. The suspension ropes of the lower car need to be diverted around the upper car. The cars use the same guide rails and stop at the same landing doors. A control and dispatching system of two independent cars in one shaft exists as an extension of the ETD dispatching strategy (R. Smith and Peters, 2004). Other control strategies exist e.g. using genetic network programming (Lu Yu *et al.*, 2009). The control strategies need to consider the safety distances of the cars to avoid collisions.

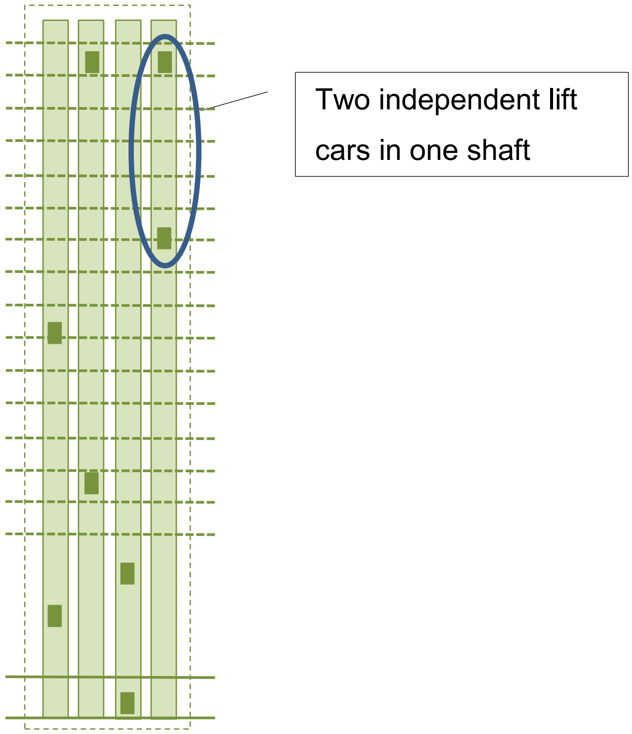


Figure 2-7: Lift group with two independent cars sharing the same shaft

2.3.2 Circulating multi car lift systems

Traffic handling efficiency is limited by putting more than two cars with traditional roped technology in one shaft as it becomes more difficult for all cars to serve the main entrance floors. Using a shaft for both up and down travel means that the cars need to wait until all of the cars have reversed their direction of travel, which is a constraint to improving performance. Instead of waiting to reverse direction in the same shaft it is beneficial to travelling in the opposite direction in another shaft.

Having multiple cars running in at least two shafts circulating with one shaft being used for travelling in the up direction and the other shaft for travelling in the down direction enables improvements in performance and efficient shaft usage. An early example is the paternoster which was the first realisation of a circulating lift system (Elevator World, 2015). The continuous slowly circulating chain of open cabins, with no cabin or shaft doors has limitations in travelling time, safety and transportation of handicapped passengers. Assuming a cabin to cabin distance of 3 metres, a velocity of about 0.3 m/s (Strakosch and Caporale, 2010) and two passengers per cabin the HC5 of a paternoster is about 60 passengers/5 minutes. The paternoster generates short WTs, but long TTs for high travel heights because of the slow movement.

The concept and idea of a circulating MCLS with independent moving cars is not new in the lift industry (Elevator World, 1996). Simple traffic calculations of a circulating lift system were published based on technical assumptions as there were unanswered technical and economic questions (Jappsen, 2002). Cars without ropes propelled by linear motors installed in the hoistway are moving independently. Exchanger units enable the cars to move between vertical shafts horizontally (ThyssenKrupp Elevator AG, 2014). Also, advanced two dimensional traffic systems that include horizontal passenger movement were analysed (So *et al.*, 2014, So *et al.*, 2015). Even concepts and ideas applying vertical trains and curved car guidance exist (Godwin, 2010, King *et al.*, 2014).

To realise a circulating MCLS different technical challenges needs to be solved. A propulsion system to propel multiple independent moving cars in multiple shafts is necessary as well as a guiding system for the cars including exchanger units to move cars between shafts horizontally. Lightweight car designs enable an economical system. A certified safety system including safety brakes needs to ensure that there is no collision.

If multiple cars in multiple shafts are using the same hoistway and are stopping at the same floors it is important to have a control system that coordinates the operation of the cars. To ensure an optimized operation the control system needs to control the distance between cars and other moving parts in the hoistway. The control system needs to consider also passengers expectations while riding lifts.

There are additional advantages of a ropeless lift system. Vibration of tall buildings e.g. excited by strong winds can excite lift ropes sway especially if natural frequencies coincide. Rope sway with large amplitudes may cause major problems and damage (Kaczmarczyk, 2008). With ropeless lifts these problems do not exist.

2.3.3 Circulating multi car lift system under development

In 2014, a ropeless elevator system called MULTI (ThyssenKrupp Elevator AG, 2014) was unveiled. Multiple lift cars using the same shafts are able to change vertical shafts horizontally. A 1:3 scaled mockup of the system is running in Spain

(A. Smith, 2016, Scott, 2016) and a full scale model is running in the new thyssenkrupp elevator test tower in Rottweil/Germany (Baldwin, 2017). The MULTI system enables multiple, independent lift cars circulating safely in multiple shafts propelled by linear motors (see Figure 2-8).

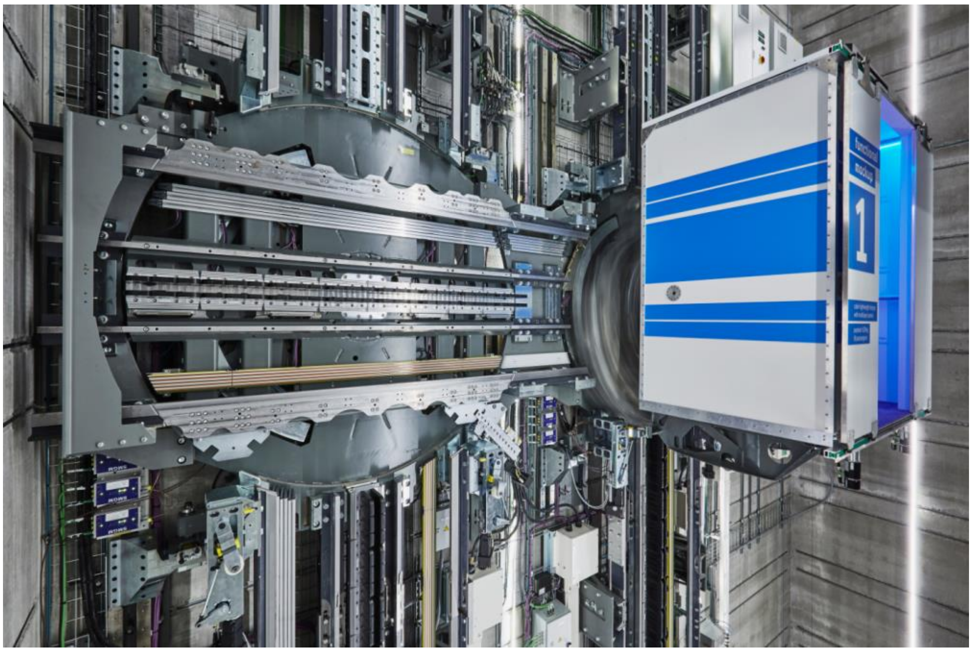


Figure 2-8: A circulating ropeless MCLS called MULTI (courtesy of thyssenkrupp)

2.3.4 Circulating multi car lift system technology

Different technical innovations and solutions solve technical challenges to realise a circulating MCLS are necessary. The technological aspects are briefly described in this section based on that design (Jetter, 2015).

2.3.4.1 Propulsion system

For many years the linear drive was considered feasible to implement lift ropeless lift cars (Jessenberger, 1998). The concept of a long stator synchronous linear drive is applied for the MCLS. The MCLS shafts are equipped with coil units and multiple frequency inverters, and the magnet yokes are mounted on the cars. Multiple redundancies in the propulsion system ensure high reliability. During down travelling of cars regenerated energy can be fed back to the grid or can be directly used internally within the system.

To build an economical propulsion system, it is important to limit the weight of cars and the loads transported.

2.3.4.2 Lightweight car

A ropeless lift system with linear motors as a propulsion system does not have a counterweight like traditional lifts. Therefore a low total car weight is necessary to realize an economical linear motor propulsion system. A conventional car design, using mainly steel as material, would be far too heavy. New and optimized design and manufacturing technologies, together with the use of new materials such as carbon composites make it possible to achieve a low car weight target. Topology optimization helps to minimize car weight (see Figure 2-9). Beyond the optimized mechanical design of the car, all devices on the car necessary for the elevator controller, electrical power, safety, guiding, and the interior of the cabin are optimized in weight. Each car is capable of carrying eight passengers.

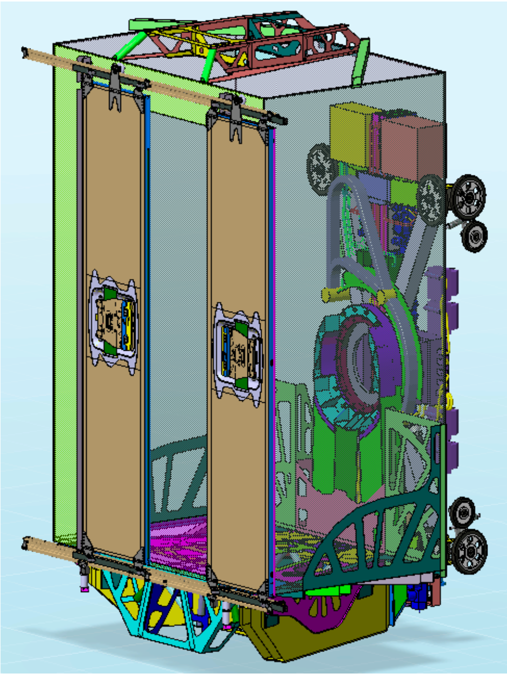


Figure 2-9: Light weight car (courtesy of thyssenkrupp)

2.3.4.3 Guiding of elevator cars and exchangers

To guide lift cars in the shafts through vertical and horizontal movement, changing between different shafts needs to be considered. A backpack solution with guidance and integrated linear motor is the flexible design applied to realize a ropeless, circulating lift system. To exchange cars between vertical shafts, shaft guidance elements rotate by 90° enabling horizontal movement using the same shaft elements. During the rotation process of the shaft elements, the cabin of the car is held in the upright position (see Figure 2-10). Passengers can load and unload the cabin during the rotation process (see Figure 2-11). This guidance and exchanger concept enables an exchanger unit at every position in the shaft. It also enables an extended horizontal movement between more than two shafts and longer travel distances.

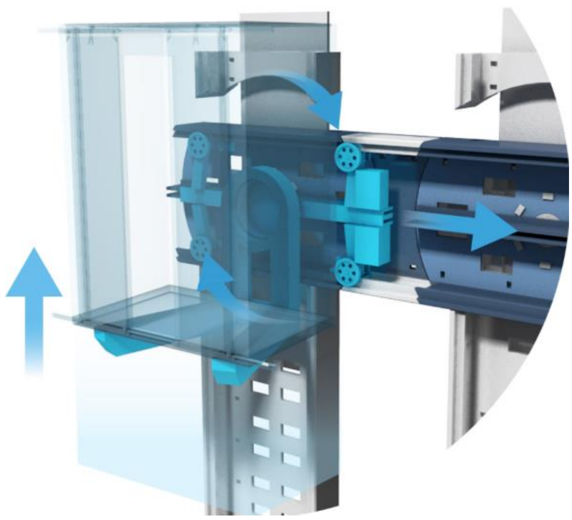


Figure 2-10: Car of a MCLS located at the exchanger unit
(courtesy of thyssenkrupp)

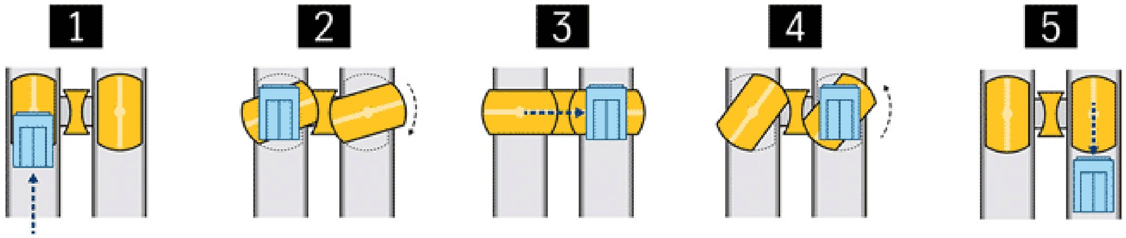


Figure 2-11: Exchange process of a car in a circulating MCLS
(courtesy of thyssenkrupp)

2.3.5 Safety distance between multiple lift cars

2.3.5.1 Safety distance – safety control levels

Thumm describes a four level safety concept for a lift system with two independent cars in one shaft (Thumm, 2004). Triggering levels three (emergency stop) and four (safety gear) are realized by a single mechanical system which activates if level one and two fail. Nuebling describes an electrical safety device which replaces the mechanical solution, triggering the emergency stop and the safety gear based on current speed and distances (Nuebling, 2006).

From a controller point of view, the emergency stop and safety gear operation are both an uncontrolled deceleration. Therefore, level three and four can be seen as one combined certified safety system that ensures a minimum safety distance triggered by level three. The philosophy of the three-level safety concept can also be adapted for circulating MCLSs.

Level two of the safety concept triggers a controlled slowdown of a car before level three needs to trigger an uncontrolled deceleration. It is triggered by their being too short a distance between cars, which is dependent on current travelling speed and the positions of the cars. The controlled stopping distance needs to be known at any time and compared with current distance between cars. The controlled stopping of a car can be achieved with the rated values or with higher deceleration values to realize a shorter controlled stopping distance.

Level one implements control strategies that ensures that level two does not need to trigger a controlled deceleration. That may include intelligent call assignment (Thumm, 2004) as well as holding cars back from departure if another car will be in the way (R. Smith and Peters, 2004). Other but similar control strategies exist to avoid any collision of cars (Tanaka and Watanabe, 2009). The control strategies described do not explain how certified safety systems and controlled stopping distances are calculated and considered. These are important and need to be considered in order to implement working control strategies. The control strategies only consider fixed configured speed profiles without any adaption of the parameters and without the usage of unsymmetrical travelling curves.

2.3.5.2 Safety distance theory – certified safety system

A certified safety system prevents collision between cars. It monitors the position, speed and acceleration of all the cars as well as the status of additional shaft elements for horizontal transportation of the cars. In case of any potential safety distance violation, the safety system is able to stop the cars by triggering a first braking system similar to an emergency stop for an uncontrolled deceleration or an equivalent stopping mechanisms which avoids injuring passengers and causing any car collision. A second braking system similar to safety gear can be triggered in case the first braking system does not stop the car within the limit of a required minimum safety distance. A maximum deceleration of 1g (9.81 m/s²) is allowed by EN 81-20 (EN 81-20:2014, 2014).

The real stopping distance after triggering an emergency stop in case of a failure depends on details of the lift system. There is a delay between the time a critical situation is detected and the actual braking force being applied (system reaction time). This includes processing time of software systems and mechanical delays such as brake activation times. Considering the technical probable worst case behaviour of the lift system after occurrence of the failure is important. Cars can be accelerated by the propulsion system in the direction of travelling. The acceleration rates are dependent on the maximum power of the propulsion system and the masses that are accelerated. Worst case scenarios are also different for different types of lift systems, balanced rope lifts with counterweight and lifts propelled by linear motors without counterweights.

Balanced rope lifts with counterweight: Balanced rope lifts with counterweights such as the known system with two independent cars in one shaft have the same worst case scenarios in both directions. The same is true for horizontal movement for circulating MCLSs if braking systems behave the same way in both directions. An example of how this can be calculated for two independent cars in one shaft is published (Nuebling, 2006). The calculation is based on a real stopping distance (named as critical distance) when an emergency stop needs to be triggered to avoid compromising a minimum safety distance.

Equation (2-7) is the quadratic equation for the real stopping distance ($d_{URSB}(v_{tr})$).

$$d_{URSB}(v_{tr}) = \frac{v_{tr}^2}{2\,a_{UD}} + v_{tr}\,t_{sr} \qquad (2\text{-}7)$$

where

v_{tr}	Velocity [m/s] when an unexpected, uncontrolled deceleration is triggered
a_{UD}	Deceleration value [m/s²] of the uncontrolled deceleration process
t_{sr}	System reaction time [s] - time between detection of the failure until deceleration process of car starts

Equation (2-7) does not consider an acceleration of the car during the system reaction time in case of a failure. This could be considered by adapting v_{tr}. The difference in the moving direction is not relevant since the car and counterweight are balanced.

Typical and realistic values for the system reaction time are 200 - 400 ms and 1.8 – 2.0 m/s² for deceleration (Altenburger, 2015).

Lifts propelled by linear motors: The real, uncontrolled stopping distance for ropeless lifts with linear motors can be described with quadratic equations. The real stopping distances for these systems without ropes and counterweights are additionally affected by the direction the car is moving. Acceleration by mistake in either up or down direction is considered. It is influenced by gravity and may be in or against the moving direction. That means that in each travelling direction there are two real stopping distances, one with the failure acceleration in travelling direction another one with the failure acceleration against the travelling direction. For these scenarios the worst case conditions need to be considered, including car loading. The worst case stopping distance in travelling direction is considered here for the stopping distance.

For a sample configuration of a system propelled by linear motors the quadratic equations (2-8) and (2-9) can be assumed as follows (Steinhauer, 2015):

$$d_{URSUU}(v_{tr}) = 0.051\,v_{tr}^2 + 0.24\,v_{tr} + 0.141 \qquad (2\text{-}8)$$

$$d_{URSLD}(v_{tr}) = -0.085\, v_{tr}^2 + 0.61\, v_{tr} - 0.69 \qquad (2\text{-}9)$$

where

$d_{URSUU}(v_{tr})$	Upper real stopping distance in up direction [m]: car is moving upwards and failure acceleration is in up direction
$d_{URSLD}(v_{tr})$	Lower real stopping distance in down direction [m]: car is moving downwards and failure acceleration is in down direction
v_{tr}	Velocity [m/s] when an unexpected, uncontrolled deceleration is triggered

Equations (2-8) and (2-9) are true for open brakes. There is a real stopping distance also with $v_{tr} = 0$. Acceleration by mistake and a system reaction time is considered.

Figure 2-12 shows the real stopping distance $d_{URST}(v_{tr})$ over velocity the uncontrolled deceleration is triggered. This is the upper real stopping distance in up direction (positive velocity) and the lower real stopping distance in down direction (negative velocity) (real stopping distances in travelling direction).

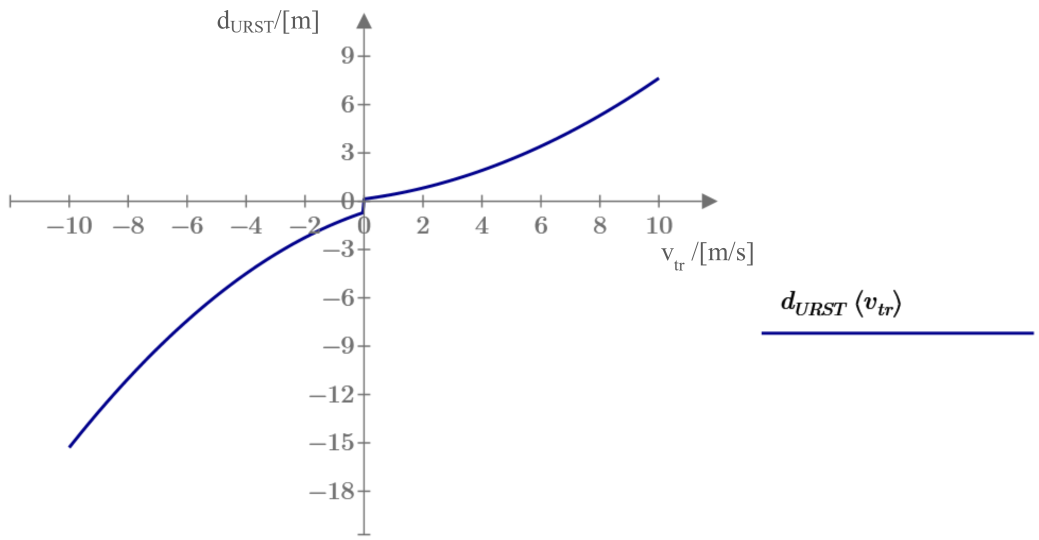


Figure 2-12: Real stopping distance in travel direction of an unbalanced system in up and down direction

3 Quality of service and psychology of waiting

3.1 Introduction

Waiting time (WT) is the main quality metric for lift systems in buildings, and quality of service (QOS) is linked to the concepts of psychology of waiting (see section 2.1.1). The real and measurable waits and how those waits are experienced need to be considered (Maister, 1985). As a “first law of service” the satisfaction of a service can be explained with a simple equation (3-1):

$$Satisfaction = Perception - Expectation \tag{3-1}$$

If the perception in a situation exceeds expectation, there is a high satisfaction. Perception and expectation, representing experience, are psychology phenomena and are not reality but may have a connection to it. All three attributes perception, expectation and reality (what is really done for a waiting person) can be managed (Maister, 1985). The similarity between the iceberg model of humans mind (Johnston, 1984) and the “psychology phenomena vs. reality” support the importance of the non-reality experience passengers have during using lifts.

The waiting for a service must be appropriate (Norman, 2008) and linked to the value of the service (Maister, 1985). There are different targets of average WTs and average times to destinations (TTDs) for morning peak and lunch traffic in office buildings (CIBSE, 2015). The targets may assume that the passengers’ expectations are lower during the lunch traffic or that the quality levels are simply adapted to performance capability of lift groups. The quality targets are different depending on the building usage (office, residential, hotel, etc.) and are different depending on the standard level of buildings (luxury, normal, etc.). Also expectations depend on culture.

To manage the overall passengers’ satisfaction three different aspects of the lift design needs to be considered:

- Lift architecture
- User interfaces
- Lift control functionality

These lift design aspects can be analysed by using the psychology of waiting lines concepts (Maister, 1985, Norman, 2008).

The *lift architecture* includes the lobby design, cabin design, fixture design and everything that creates or affects the lift usage environment including additional services not directly linked to lifts.

The *user interfaces* include all the input devices used to call the lift or to register a destination as well as output devices such as call registered lights or directions to use a particular lift. Additionally, displays and announcements can be used to inform passengers about lift status and service status. The use of special user interfaces and feedback information can affect the options of the lift control and dispatcher strategies.

The *lift control functionality* includes the lift behaviour and the dispatcher functionality. The control functionality should consider the psychology of waiting and the QOS. Passengers need to be transported in a good and pleasant manner. The dispatcher and the overall lift performance are responsible for providing the necessary handling capacity (HC) that is needed to achieve good QOS.

3.2 Lift architecture/environment

Architectural elements of the lift design and additional services can have a significant effect on the experience of lift passengers. Therefore, lift designers should pay attention to psychology aspects while designing lifts.

Keeping people occupied while waiting for and using a lift is an effective concept. Simple architectural elements are mirrors. It was shown that mirrors in lobbies reduce complaints although the actual WT was unchanged (Maister, 1985). Mirrors animate passengers to check their hair or clothing while they are waiting and so they are kept occupied. People are also occupied if infotainment is provided inside the lift cabins or in the lift lobbies. In-car information displays have become very common. The displays present a mix of news, weather, stock prices and advertising. An additional advantage is that the building owner can receive revenue from the advertising. Wi-Fi access for lift passengers ensures a good internet access enabling personal infotainment and communication via e-mail and other services like social networks (LinkedIn, 2017, facebook, 2017).

The position of destination control input devices can reduce passengers' perceived WT. The destination input devices in destination control systems are often located outside the lobby. This is shown in Figure 3-1. Passengers can register their destination before they enter the lift lobby and a lift is allocated directly. The walking time to the lobby is part of the WT. This is occupied WT and passengers already get started since their journey time starts after the call registration with the process of walking to the lift (lobby). It is helpful if the walking distance is not too far. Passengers may forget their car assignment. A maximum walking distance to the lift lobby of 10 m is reasonable.

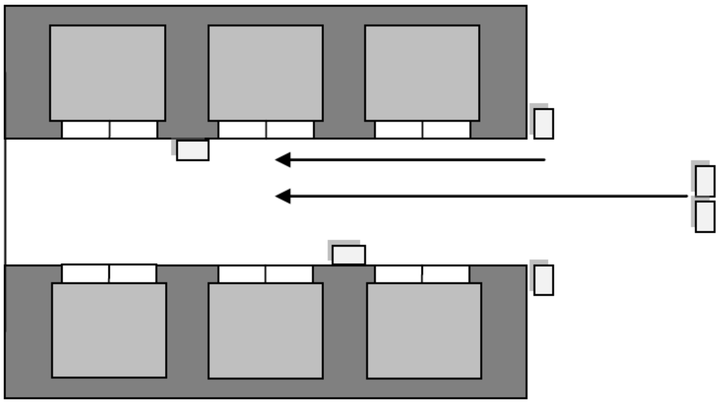


Figure 3-1: Position of destination input devices on a floor

Space for lift passengers in the lobbies and cabins increases the comfort and supports a positive experience using lifts. Also, mirrors in lift cabins make the lift appear larger and therefore more comfortable. A clean, modern, appealing/friendly appearance and environment supports positive emotions. Rides in panoramic lifts are fascinating for people (at least for those without fear of heights). Long rides in lifts will appear shorter as lift passengers have a higher value and good experience.

3.3 User interfaces

Good user interfaces are necessary to manage passengers' expectation and perception. If they provide a clear conceptual model, give feedback and explanation, they can help to avoid confusion, reduce anxiety and uncertainty (Norman, 2008). User interfaces can also affect opportunities and constrains for lift controllers.

The landing call push buttons of current conventional group control systems include call registered lights as an acknowledgement that a call is accepted. It indicates that the lift is working and reduces anxiety and uncertainty. However, people often press a lighted push button as anxiety still exists about whether a lift is coming or not. Systems with early call announcement (ECA) directly allocate a lift. This is indicated with an illuminating hall lantern. This may reduce anxiety as the passenger knows the lift he/she is waiting for. Additionally, the walking time to the allocated lift is occupied WT (compare with destination control input stations in section 3.2). But a fixed direct allocation stops the dispatcher to reallocate the call to another lift for further optimisation if the traffic condition changes. If calls are reallocated with ECA constant flashing hall lanterns confuses passengers (R. Smith, 2014). Destination control systems require the registration of the passengers' destination in the lobby. The systems directly allocate a destination call to a fixed lift. As the passengers register their destination directly when calling the lift, they may sense that they have already stated their journey which will reduce perceived WT.

To reduce the anxiety while waiting, indicators showing the arrival time of lifts can help. Destination control systems can show the current estimated arrival time as additional information to the allocated lift. Countdown indicators can continuously show the remaining time until a lift arrives. These kinds of indicators are known from other transportation systems such as trains and metros indicating the next arriving train. The indicators provide feedback to passengers and keep them occupied by watching the displays. But if expectations are set they need to be met or exceeded. This is evident in lift groups, as the traffic situation for each lift changes consciously by new allocated landing and destination calls, reallocations or new car calls. This can delay the arrival time of lifts and makes arrival time indicators difficult in lift applications compared to trains that are operated with a fixed schedule.

For destination control systems, "reassurance indicators" can reduce anxiety. These can be installed inside the cabins and in the lobbies e.g. above each landing door. Waiting passengers can see their destination floor registered at the allocated lift/landing door to confirm the allocation, especially for longer WTs. Inside the cabin current registered destination floors can be shown to confirm passengers' destinations. An example is shown in Figure 3-2. Floor 8 and 10 are registered destinations.

Figure 3-2: Reassurance indicator

Smartphones can be used as individual and personal user interface if the lift system provides a wireless server that can be connected. In every case user interfaces for lift groups need to avoid confusion by providing necessary information and feedback about lift to the passenger. They need to support a good passenger experience.

3.4 Lift control functionality

The lift behaviour and control functionality is strongly associated with the real WT, but also plays a key role in the passengers' experience using lifts. The widely accepted and applied "rules of call control" for a single lift control serving allocated calls (see section 2.2.2) cover and generate passengers' expectation of lift behaviour at the same time.

The concepts of the psychology of waiting lines (see section 2.1.1) can be used as guidelines to review the lift behaviour especially with destination control and multi car/cabin lift systems.

3.4.1 Waiting time versus transit time

Destination control systems have shorter average times to destination (TTD) compared to conventional systems but with longer average WT (R. Smith and Peters, 2002). WT is assumed to be more "painful" than transit time (TT). This can be explained by the psychology of waiting lines: people want to get started and anxiety makes waits seem longer. Once passengers are in the lift there is no further anxiety about when the lift will arrive. Considering the WT more than TT can increase the perceived level of service for lift passengers (R. Smith and Peters, 2004).

The optimisation of the estimated time to destination (ETD) dispatching algorithm considers WT and TT of passengers (see section 2.2.2). In these systems, (especially ones with destination control), situations for passengers can be observed, which are critical in regard to the psychology of waiting aspects.

1. “Last come - first serve”:
   In lift groups with conventional control there is a common landing call for all waiting passengers with the same travel direction request. The same lift answers the landing call for all the waiting passengers (see Figure 3-3).

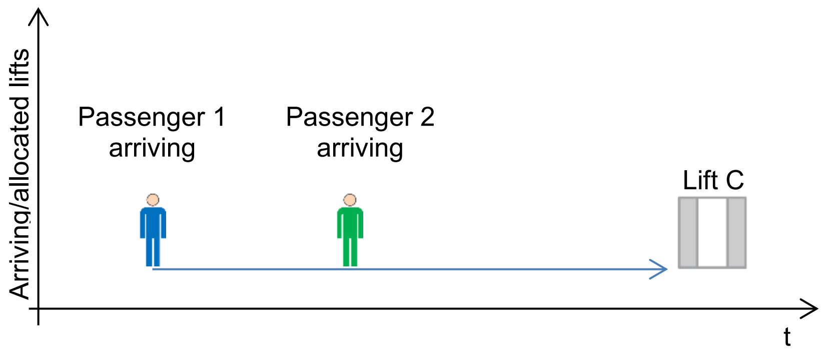


Figure 3-3: Waiting passengers at conventional control lift groups

In destination control systems, passengers are allocated to individual lifts. This can be the same lift, or a different lift. This is done to optimise time to destination and boost up peak performance.
Depending on the overall traffic situation it can happen that the call for a later arriving passenger is answered first (last come – first serve). This is illustrated in Figure 3-4. This can be frustrating for passengers arriving first and can be seen as unfair. This also increases the perceived WT according to the principle of the psychology of waiting. If destination control systems are optimising on WT, this effect is reduced and passengers waiting in the same lobby aiming to travel in the same direction are allocated more likely to the same lift.

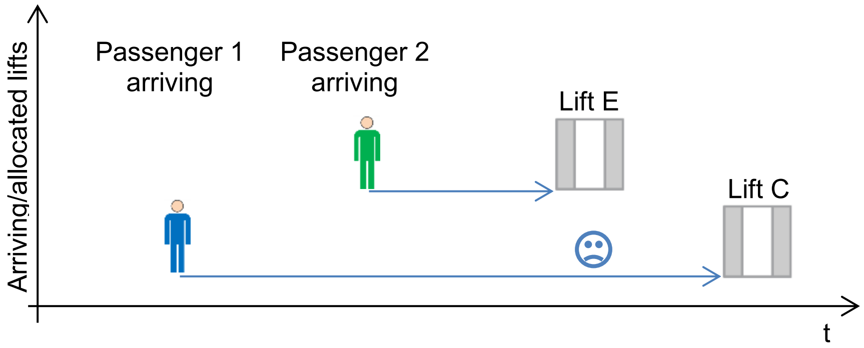
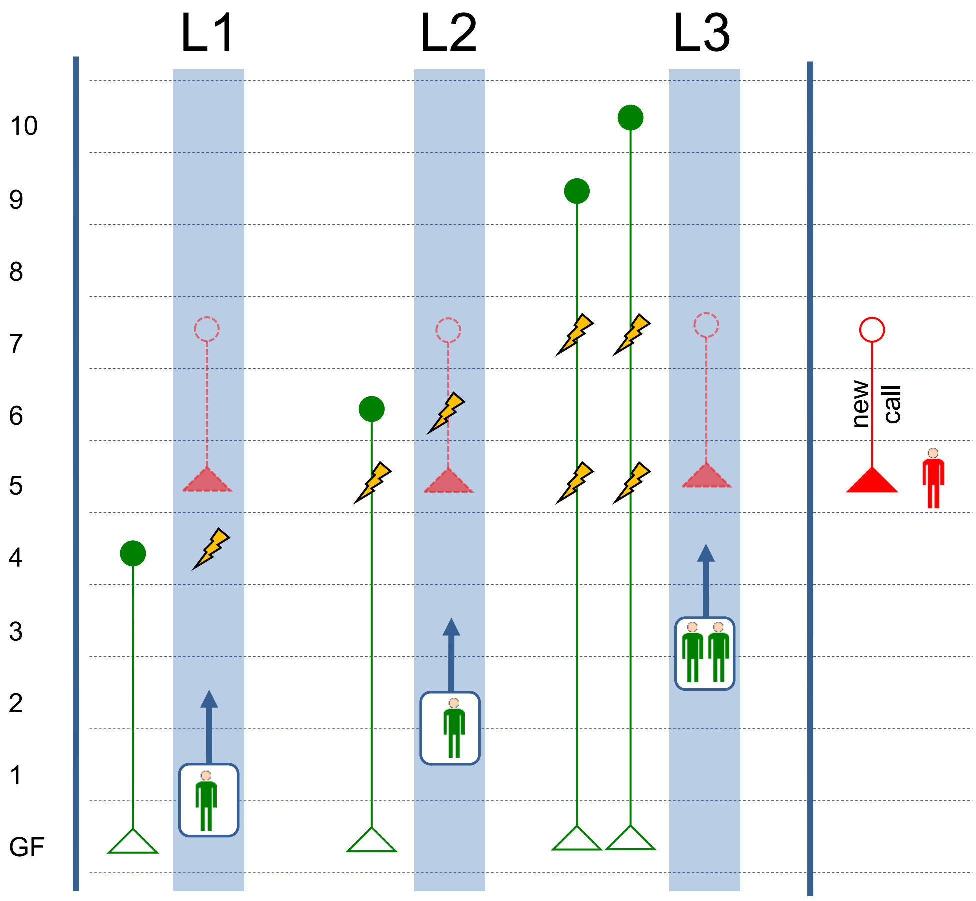


Figure 3-4: Waiting passengers at destination control lift groups

2. “Another lift car passing while waiting”:
   Another scenario is that lift cars pass waiting passengers in the direction of the waiting passengers’ requested direction. That can be observed especially with destination control systems and systems optimising on TTD. An example comparing different dispatching strategies illustrates that behaviour (R. Smith and Peters, 2002). Figure 3-5 shows a similar example. Lift 2 and lift 3 will pass the waiting passenger before the allocated lift 1 arrives. In systems with position indicators of the cars in the lobbies and lifts with transparent shaft doors waiting passengers can be frustrated as this may be seen as unfair what increases the perceived WT. If destination control systems are optimising on WT this effect is reduced and cars passes less likely.



Test call			
WTC:	8s+10s*	6s	4s
TTC:	12s**	12s**+10s*	12s**
Existing calls			
TTDC:	-	10s*	4 x 10s*
Total cost:	30s	38s	56s

* Time consumed when making a stop is 10s

** Travel time from floor 5 to floor 7 is 6 s

Standing time is 6 s

WTC: Waiting time cost [s]

TTC: Transit time cost [s]

TTDC: Transit time degradation cost [s]

Figure 3-5: Lift cars L2 and L3 pass a waiting passenger

3.4.2 Reverse journey situations

When a passenger gets into a lift, he or she expects to be taken in the direction of their destination. This is consistent with the “rules of call control” for the lift behaviour described in section 2.2.2. A reverse journey, where the passenger is initially taken up when the call is in the down direction, or vice versa can be disconcerting what increases the perceived TTD.

In conventional control systems, reverse journeys happen when passengers do not recognise direction indicators or if they deliberately choose a reverse journey. Reverse journeys can be avoided with destination control, but only if the system is allowed to refuse calls. Refusing calls, with a “no lift available, please try again later” message or indication is frustrating for passengers.

Chapter 4 of this thesis explores why destination control systems are susceptible to reverse journeys and how lift planning affects this issue. Where accepting a reverse journey is the best compromise, appropriate indication can help to avoid passenger confusion. Allowing reverse journeys has an impact on other QOS criteria.

3.4.3 Departure delays

As described in section 2.3 there is a range of lift systems with more than one car or cabin per shaft. Double deck lifts have a car with two attached cabins, serving adjacent floors at the same time. Other systems enable two independent cars to share the same shaft. The next generation ropeless lifts will allow many cars to share the same shafts.

In these systems the interaction between the cars and cabins affects the experience for passengers travelling in lifts. Departure delays occur when passenger loading and unloading times or the sequence of stops required to serve passengers is not the same. The consequence is that cars and cabins delay each other’s departure. Departure delays can also occur in lift systems with a single car per shaft, for example as a consequence of destination calls which are registered at a significant distance from the lift lobby. The delays are confusing for lift passengers as passengers expect the lift to depart after the process of passenger transfer in and out has finished.

To include departure delay in an assessment of QOS, a definition of passenger and cabin departure delays and a method to measure these delays is required. Chapter 5 describes the different types of departure delays and their causes. It proposes a way to measure these delays.

3.5 Summary

Overall, lift design needs to consider and manage reality and non-reality aspects of waiting. Both the lift architecture and user interfaces focus more on the psychological, non-reality aspects perception and expectations. These need to be supported by the lift traffic control functionality which is mainly focused on the measurable reality. Beyond WT and TTD, traffic control needs to consider perception and experience of lift passengers. Specific lift allocations can be experienced by passengers as unfair (last come – first serve, lifts pass waiting passengers). Reverse journeys in destination control systems can confuse passengers. Especially in lift groups where multiple lift cars are sharing same shafts, departure delays affect passengers' satisfaction.

Chapter 4 describes and analyses reverse journeys in destination control systems. In chapter 5 departure delays are described and defined. To control reverse journeys and departure delays different control levels are affected. This includes the dispatching (see chapter 6) and system control/motion commands (see chapter 7 and 8). Traffic analysis for circulating MCLS as introduced in chapter 9, 10 and 11 considers departure delays.

4 Reverse journey in destination control systems

4.1 Introduction

4.1.1 Background

Reverse journeys happen if passengers enter a lift car and they are first taken away from their destination floor or if a car bypasses a destination of a passenger inside the lift car. The widely accepted and applied “rules of call control” (see section 2.2.2) cover and shall prevent this kind of passenger transportation. This considers psychological aspects and avoids confusion for passengers. However, the dispatcher/group control needs to consider the reverse journey situation during a call allocation. Therefore, the dispatching/group control and call control level needs to be considered if reverse journeys are analysed (see Figure 4-1).

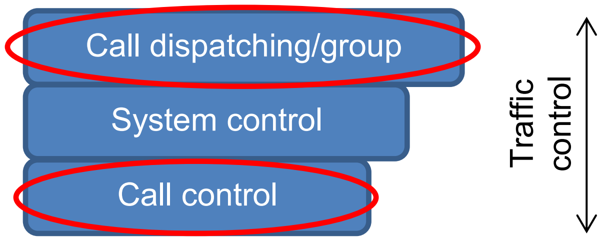


Figure 4-1: Traffic control levels relevant for reverse journey consideration

Conventional group control and destination control manage reverse journey situations differently. Destination control systems are more susceptible to reverse journey situation compared to conventional control. It has an impact on the lift group performance if reverse journeys are allowed in destination control systems. Both the traffic type and the lift design in buildings have an impact on number of reverse journey scenarios. These factors are investigated in this chapter using simulation.

4.1.2 Reversed journey in conventional systems

Reverse journeys are not difficult to avoid with conventional collective control where there are up and down landing call buttons. EN 81-70 requires direction indicators for conventional control systems (EN 81-70:2003, 2003). In most cases, the car allocation is only revealed shortly before a car arrives at the landing: passengers travelling up get into the car when the lift stops on its way up with the up indicator lit;

passengers travelling down get into the car when the lift stops on its way down with the down indicator lit. This means that the same car can be allocated both an up and a down call on the same floor without resulting in reverse journeys.

Reverse journeys do occur, but only when passengers do not recognize the announcement, or if they deliberately choose a reverse journey. Sometimes choosing a reverse journey can result in a shorter time to destination (TTD) and passengers' recognition of this has been observed in heavily loaded systems. Some passengers press both pushbuttons with the hope of a faster car arrival. Sometimes passengers enter a lift although it announces the opposite direction. In these cases, passengers get into the lift knowing that they will ultimately get to their destination, or do not see/understand the announcement.

4.1.3 Reverse journey in destination control systems

In destination control systems the passenger selects the floor he or she is travelling to, and is told immediately which car to use. Each lift entrance needs to be individually marked and needs to be easily identified (EN 81-70:2003, 2003). When the car arrives, no direction information is provided. Since the passengers are waiting in front of the allocated lift, hall gongs and lanterns are not needed (Strakosch and Caporale, 2010). Some installations include indicators to reassure passengers that they are waiting in front of the correct car for their destination (see section 3.3). When the car arrives, it is normal to have an in-car indication of the planned stops.

Reverse journeys can be avoided with destination control, but only if the system is allowed to refuse calls (Peters, 2013b). Refusing calls, with a "no lift available, please try again later" message or indication is frustrating for passengers. It can also lead to a significant increase in waiting times (WTs). For these reasons people designing and configuring destination control dispatchers sometimes allow reverse journeys.

4.1.4 Reverse journey scenarios

Figure 4-2 illustrates three separate scenarios where accepting a new allocation will cause a reverse journey. In scenario A and C, the new call causes a reverse journey for existing passengers. Scenario B causes a reverse journey for the new call. In scenario C the reverse journey is caused by the combination of three calls.

Some systems may stop twice at the same floor. For example, in scenario A the lift could stop at the entrance floor in both the down, and then up direction. However, as passengers enter the allocated lift when it opens the doors independent from any direction indicators, in practice the second stop is not required and can be avoided. This needs to be considered by the call control of the single lift. The dispatcher/group control needs to consider the call control behaviour during the allocation. However, space in the car for passengers who start their travel time in the wrong direction should be considered. For the simulations in section 4.3 and 4.4 the second stop is avoided in reverse journey situations.

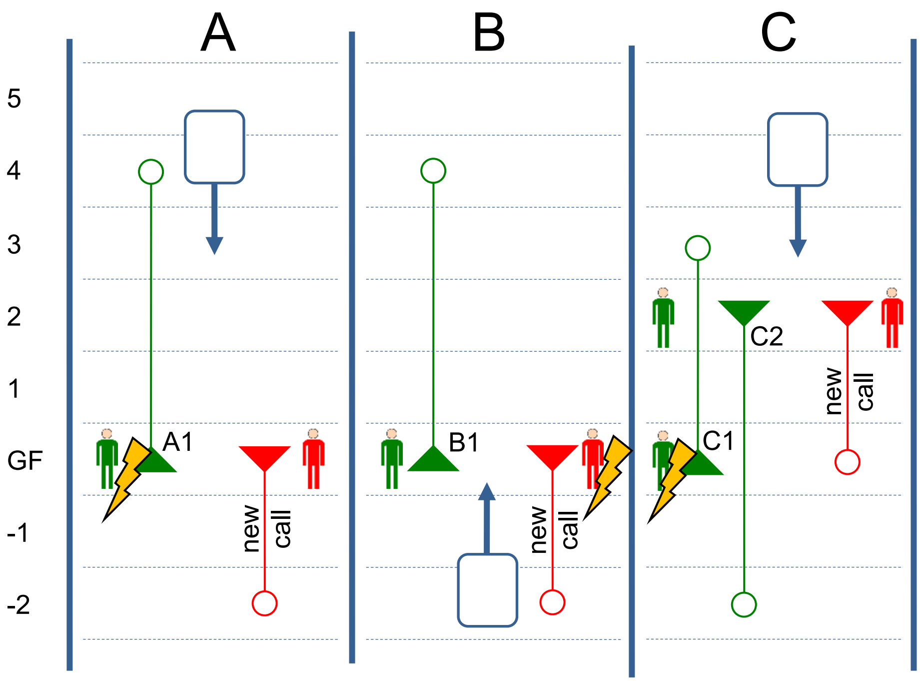


Figure 4-2: Reverse journey scenarios (A, B, C) of a single lift

Table 4-1: Stopping order of reverse journey scenarios

Scenario	**Order of stops**	
	Without new call	**With new call**
A	GF → 4	GF → -2 → 4 (reversal for A1 at GF)
B	GF → 4	GF → 4 → -2 (reversal for new passenger)
C	2 → -2 → GF → 3	2 → GF → -2 → 3 (reversal for C1 at GF)

In many cases the reverse journey can be avoided simply by choosing another car. However, a combination of the scenarios described happening together results in their being times where the choice is to accept the reverse journey, or to refuse calls with a “no lift available, please try again later” message. This is illustrated for two lifts in Figure 4-3, but also occurs with larger groups when there are more calls.

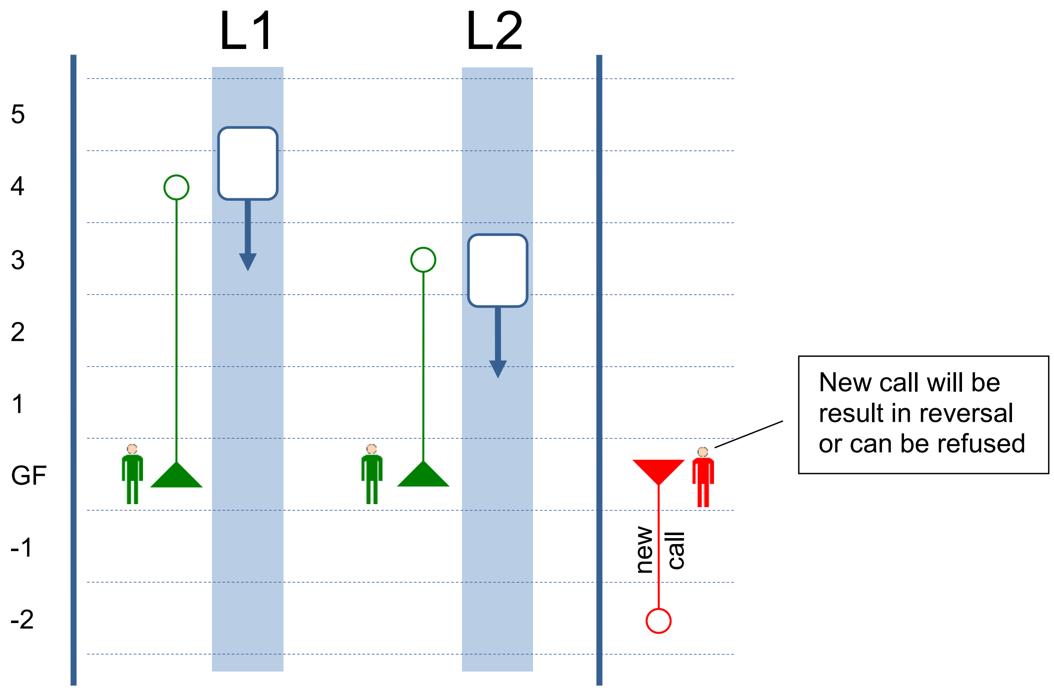


Figure 4-3: Reverse journey scenario with two lift group

4.2 Reversals and performance

When destination control systems are saturated, not all passengers receive an immediate allocation (Finschi, 2010) and the system refuses calls (R. Smith and Peters, 2009). Excluding allocations that cause reverse journeys limit the dispatcher’s options and makes refusals more likely at lower levels of demand, prior to saturation. Refusals are more irritating to passengers than reverse journeys (Peters, 2013b). So, the option to allow reverse journeys should be considered.

Lift performance was compared in destination control systems where reverse journeys are and are not permitted; it was shown that the results for the average time to destination are better (Tanaka *et al.*, 2005) if reverse journeys are allowed. However, the work was based on a single car operation and does not discuss the dispatching problem. Revere journeys were also considered in a system with two independent cars in on shaft (Tanaka and Watanabe, 2010).

The effect on the lift group performance with allowing or refusing allocations causing reverse journeys in destination control systems is unknown and is investigated in section 4.3. The effect combined with different lift group design choices is shown in section 4.4.

4.3 Reverse journeys in office buildings

The effect of reverse journeys on a lift group is investigated with the event based traffic simulation software ELEVATE (Peters Research Ltd., 2014) applying the estimated time to destination (ETD) algorithm (R. Smith and Peters, 2002). The ETD algorithm was modified to allow reverse journeys. The call control was modified to avoid the second stop in reverse journey scenarios. The ETD algorithm optimises per default on TTD.

The sample building has 6 1600 kg lifts @ 2.5 m/s serving 14 floors above the entrance level(s), with a population of 60 persons per floor (20 persons on top floor). For simplicity, the initial results are based on a four hour simulation with constant passenger demand of 12% of population per five minutes (results of the first and the last 5 minutes excluded).

4.3.1 Morning up peak

In an office building during the morning up peak, the typically traffic mix is 85% incoming, 10% outgoing and 5% interfloor (CIBSE, 2010). For the sample office building with a single entrance, Figure 4-4 compares average WT and TT results with and without reverse journeys allowed. Where reverse journeys are allowed, the number of reverse journeys per five minutes is also plotted.

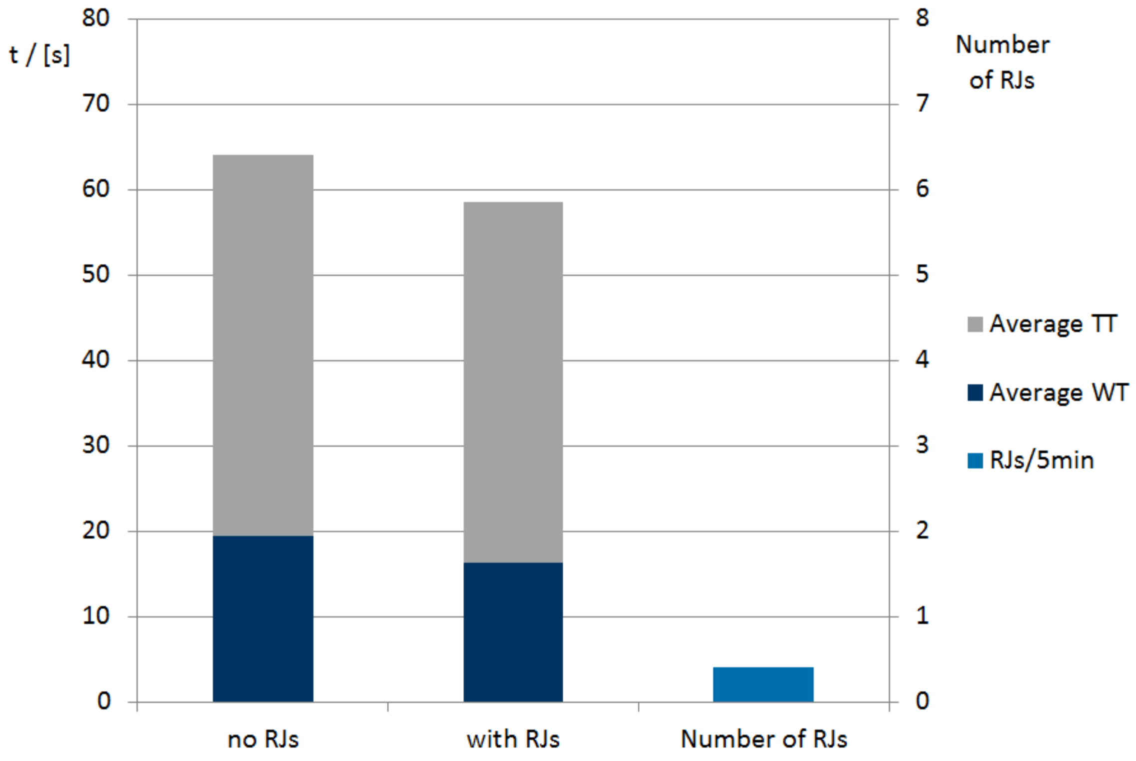


Figure 4-4: Comparative performance for sample office building during up peak with and without reverse journeys (RJs) allowed

4.3.2 Lunch peak

During the lunch period, a typical traffic mix is 45% incoming, 45% outgoing and 10% interfloor (CIBSE, 2010). Figure 4-5 shows simulation results for this lunch time traffic mix, with and without reverse journeys. As would be expected intuitively, with the traffic more evenly divided in the up and down directions, there are more reverse journeys (if allowed). As the dispatcher optimisation process only chooses a reverse journey when it improves the TTD, the performance improvements are more significant than for up peak traffic.

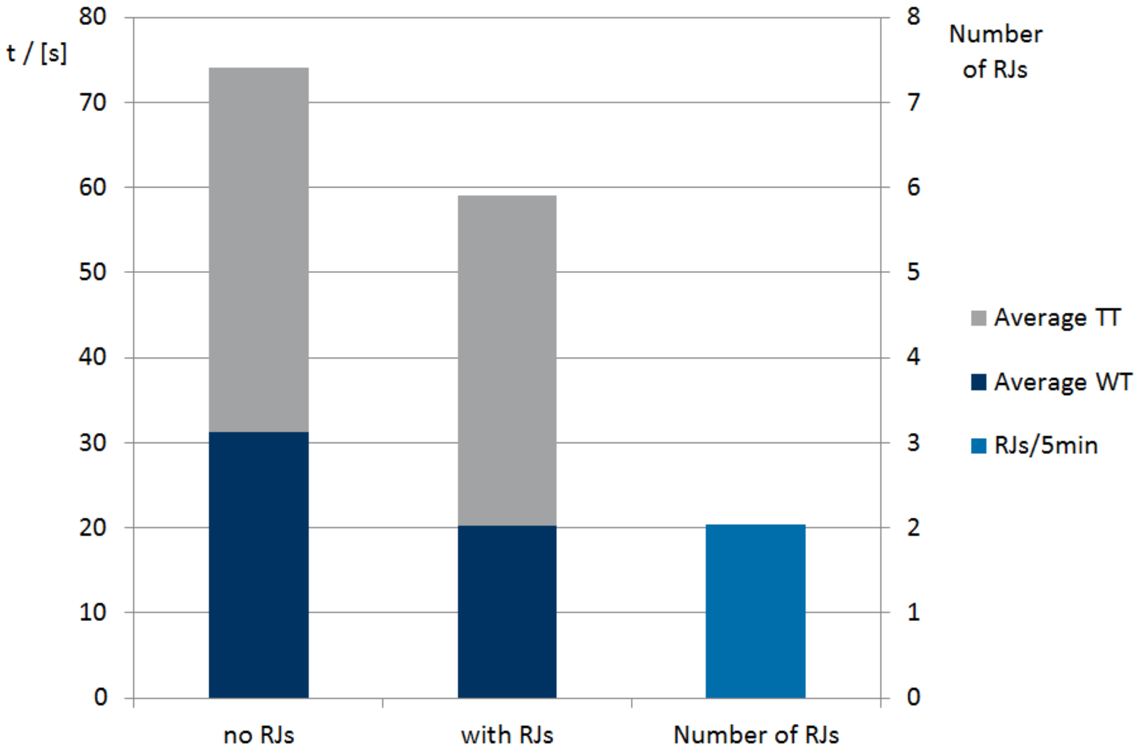


Figure 4-5: Comparative performance for sample office building during lunch traffic with and without reverse journeys (RJs) allowed

4.4 Implications of design choices

4.4.1 Not all lifts serve all floors

A common sense rule of group lift designs is that all lifts in a group should serve the same floors (Strakosch and Caporale, 2010). Ignoring this rule is generally a false economy. If it is - for some reason - not possible to let all lifts serve all floors, it is a good choice to use a destination control system as the system knows which lift serves a passenger's arrival and destination floor (Peters, 2013b). However, reverse journey situations are more likely because less lifts are available for some trips. An example is given in Figure 4-6. The new call can only be served by L3. An allocation of the new call causes a reverse journey for the passenger waiting on floor 2. If the control system excludes allocations with reverse journeys, the call must be refused.

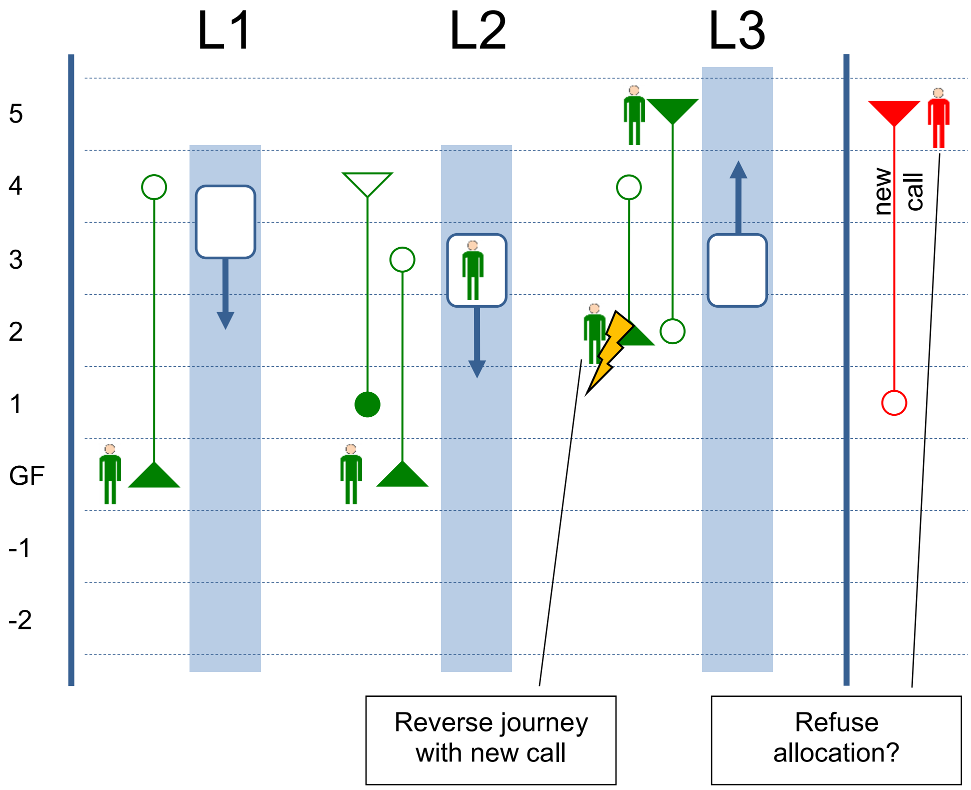


Figure 4-6: Reverse journeys become more likely when not all lifts serve all floors

To demonstrate the effect of one lift not serving the top floor, the simulation yielding results in Figure 4-5 was repeated with only one lift serving the top floor. The results in Figure 4-7 demonstrate the impact on performance by not having all lifts serve all floors. However, by allowing reverse journeys the degradation of performance is reduced.

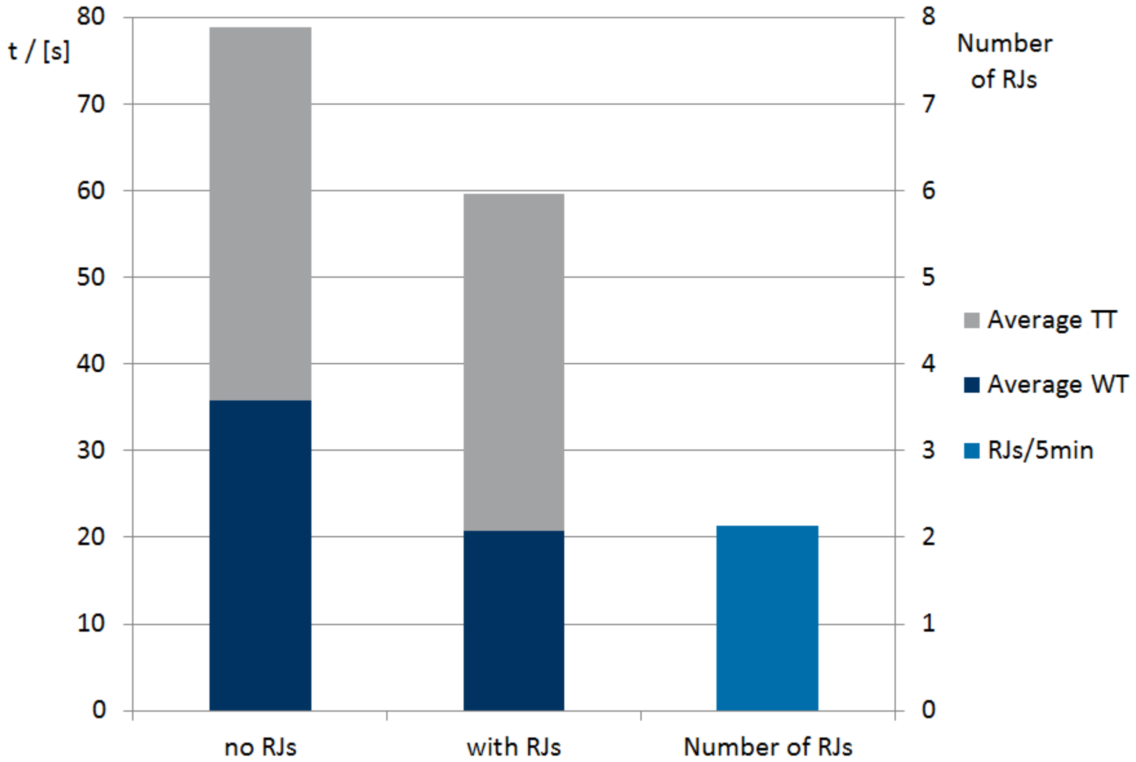


Figure 4-7: Results showing allowing reverse journeys (RJs) reduces the degradation in performance caused by not all lifts serving all floors

4.4.2 Multiple entrance floors

Some buildings have multiple entrance floors. These multiple entrance floors can be at different street levels or serve car parks in basement floors below the main entrance lobby. An entrance floor becomes relevant if there is a significant number of passengers boarding and alighting the lifts. Multiple entrance floors result in additional stops which have an effect on the round trip time, impacting both QOS and handling capacity (HC). Shuttle lifts or escalators carrying people from the basement floors to main entrance help to eliminate these additional stops (Strakosch and Caporale, 2010).

Buildings with multiple entrance floors with mixed traffic are particularly susceptible to reverse journeys at peak times. This is because any lift stopping at an upper entrance for a passenger to alight is also likely to have been allocated an up call from this entrance. Figure 4-8 shows the number of reverse journeys for the sample building with a single and double entrance. For the double entrance simulation, the entrance bias was 50% to each floor. The traffic mix is 45% incoming, 45% outgoing and 10% interfloor. If reverse journeys are not allowed, there is a corresponding increase in WT.

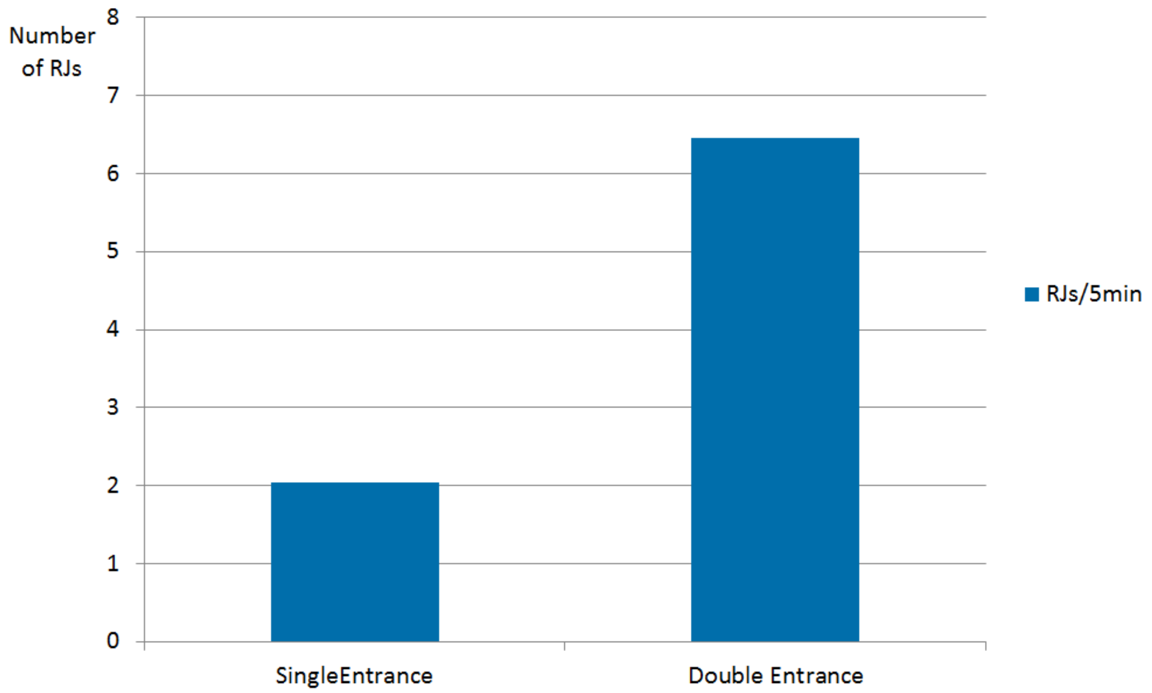


Figure 4-8: Results showing the multiple entrance floors are more susceptible to reverse journeys (RJs)

4.4.3 Restaurant, meeting and other busy floors

Many office buildings have dedicated staff restaurants (Peters *et al.*, 2011) that affect the morning and the lunch traffic. Restaurants, meeting rooms, and other busy floors should preferably be located in the basement or on the second floor and should be served separately by escalators or shuttle lifts. The traffic of restaurants floors can be treated as additional entrance floors (Strakosch and Caporale, 2010). Strakosch recommends never locating a restaurant/cafeteria at an intermediate floor of a lift group (Strakosch and Caporale, 2010). As with multiple entrance floors, these busy floors are particularly susceptible to reverse journeys at peak times.

4.4.4 Impact of the optimisation method of the ETD algorithm

The optimisation function of the ETD algorithm can split the passengers' time to destination into WT and TT with different/individual factors (see section 2.2.2). The ETD algorithm can be operated with an optimisation function where WT is three times more important than the TT. The results of a one hour traffic simulation during constant lunch traffic conditions (results of the first and the last 5 minutes excluded) are shown in Figure 4-9. As expected it shows shorter average WT compared to TTD optimisation. But if allowed around 2.5 times more reverse journeys occur compared to the TTD optimisation (compare with Figure 4-5). Longer TTs are less important and therefor reverse journeys are more likely.

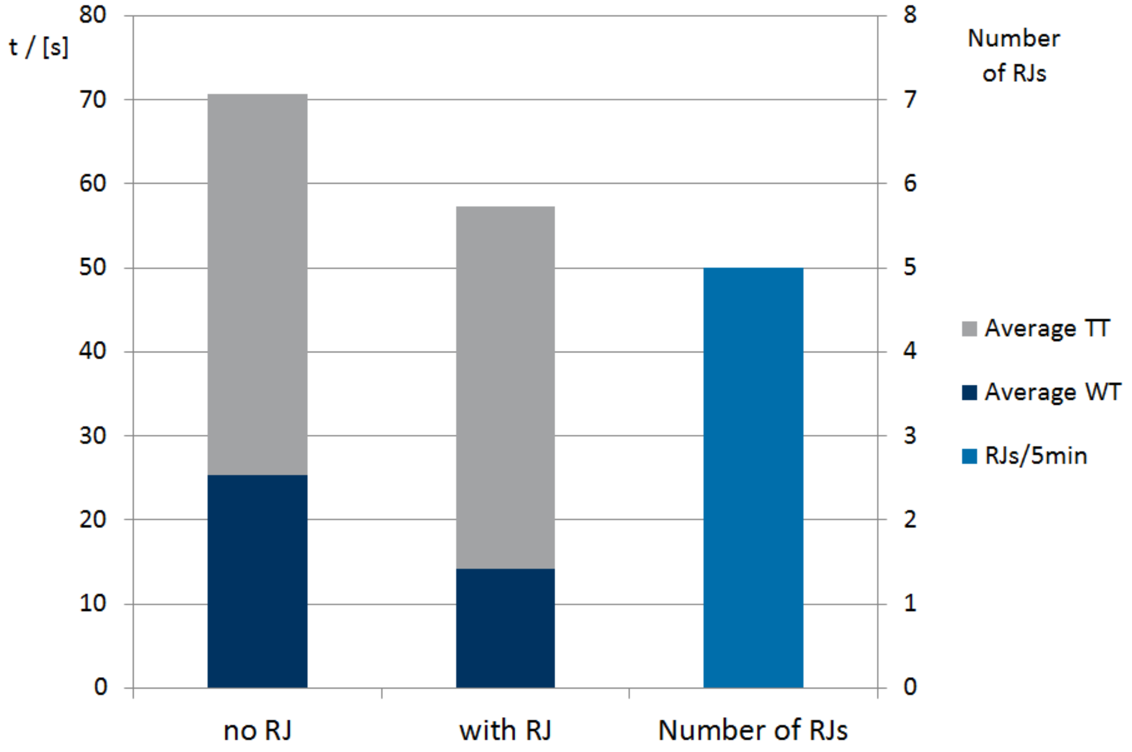


Figure 4-9: Comparative performance for sample office building during lunch traffic with and without reverse journeys (RJs) allowed with bias on WT optimisation

4.5 Design application

The simulation in earlier sections are indicative of what factors affect the number of reverse journeys that occur if allowed, or the impact on WT and TT if they are not. However, it is difficult to generalise these results as there are many parameters, and the performance of lift systems is not linear. For building specific advice, demand templates based on actual passenger demand are more useful. Figure 2-2 in section 2.1.4 provides a sample office building demand template (Siikonen, 2000). This has been applied to a 6 car lift group serving 14 floors above two entrance levels (average of 4 runs).

Without reverse journeys, the WT and TTD plotted throughout the working day are as indicated in Figure 4-10.

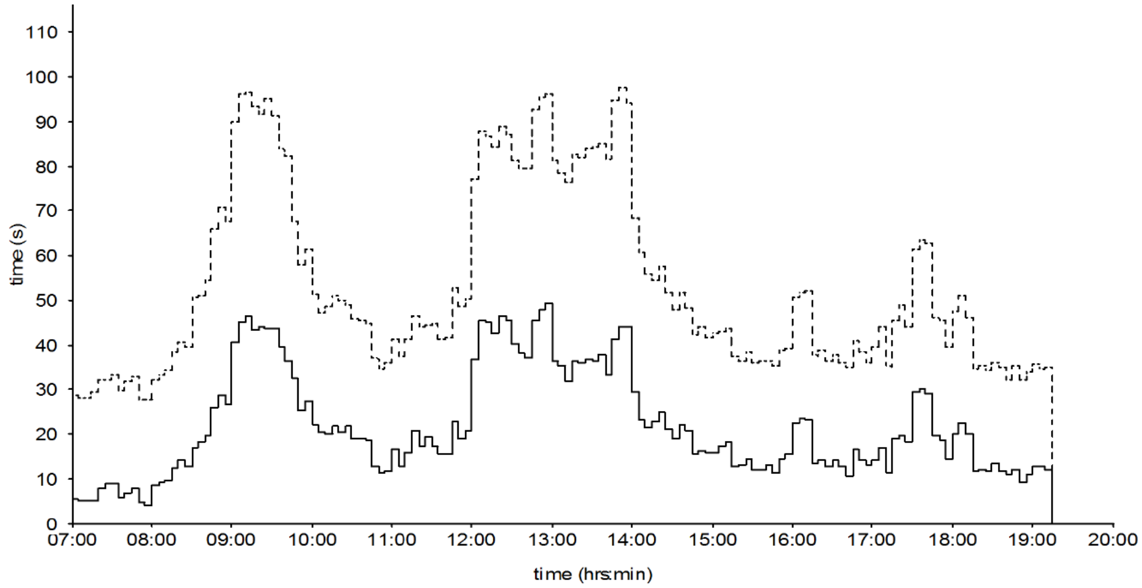


Figure 4-10: WT (solid line) and time to destination (dotted line) without reverse journeys

Allowing reverse journeys, the waiting and time to destination plotted throughout the working day are as indicated in Figure 4-11. The number of reverse journeys plotted by time of day is given in Figure 4-12.

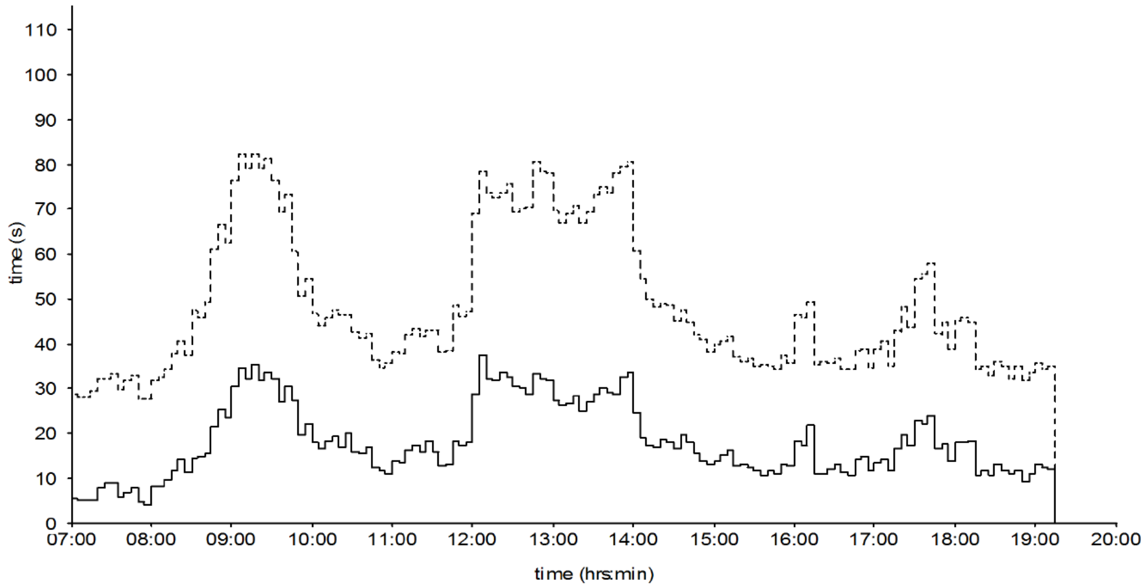


Figure 4-11: WT (solid line) and time to destination (dotted line) allowing reverse journeys

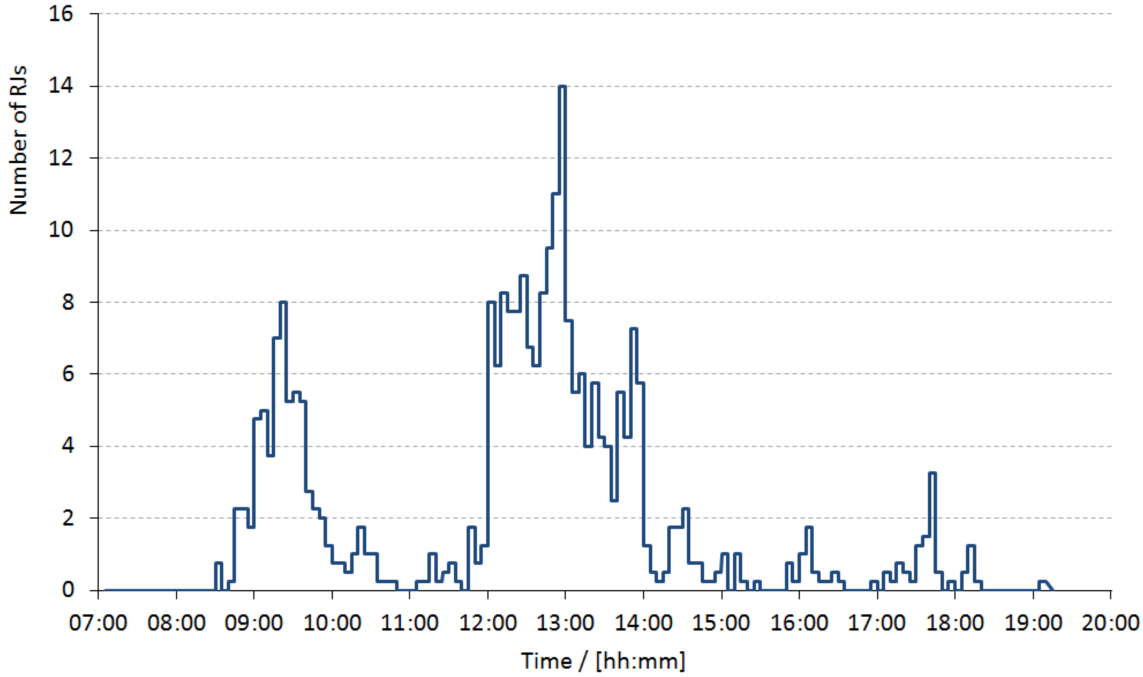


Figure 4-12: Average number of reverse journeys (RJs) by time of day

Allowing reverse journeys reduces the peak average WT (for the worst five minutes) by over 10 seconds. The results also show that reverse journeys are more frequent during busy times.

4.6 User interface

If reverse journeys are allowed the user interface needs to be considered in terms of QOS (see section 3.3). If passenger travel begins in the wrong direction (reverse journey) reassurance indicators reduces the anxiety of passengers and can explain that the reverse journey is not a system fault. Reducing the anxiety will make waits feel shorter (Maister, 1985). Also, the quality of the user interface and the how the information is displayed is important to provide clear information from the lift system. Current displays do not show the stopping order; if they did reverse journeys are easier to understand and are more likely to gain acceptance by the passengers. Suggested formats for displays are given in Figure 4-13.

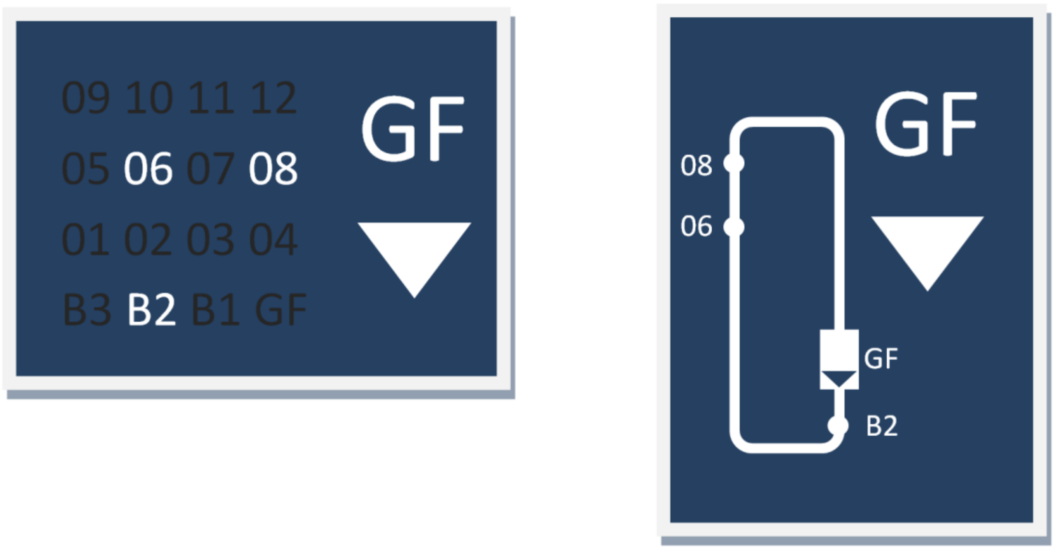


Figure 4-13: Suggested indicator formats to help passengers accept reverse journeys

4.7 Summary

Reverse journeys violate the widely accepted “rules of call control”. They have a negative effect on the passengers experience travelling in lifts as they are not expected. Reverse journeys can be avoided with destination control, but only if the system is allowed to refuse calls. Refusing calls is even more frustrating for passengers. Reverse journeys (or longer WT resulting from not accepting reverse journeys), are particularly prevalent: (a) with mixed traffic, (b) at peak times, (c) with multiple entrance floors, (d) where not all lifts serve all floor, (e) with restaurants and other busy floors, (f) in under-lifted buildings.

Allowing reverse journeys reduces average WT and TTD, but may confuse passengers. Improved indication can mitigate this problem.

Reverse journeys are not desirable, but sometimes represent the best compromise. Therefore, the choice the dispatcher makes whether or not to accept a reverse journey needs to consider more than just the optimisation of a combination of WT and TT. The acceptance of reverse journeys will be added as a consideration with the dispatcher algorithm to provide improvements in QOS based on best understanding of the psychology of waiting and travelling in lifts as analysed in chapter 3. A QOS dispatching algorithm is described and defined in chapter 6.

5 Departure delays

Abbreviation

Additional abbreviations used in this chapter:

PDD	Passenger departure delay [s]
BPDD	Blind passenger departure delay (with closed doors) [s]
CDD	Cabin departure delay [s]
BCDD	Blind cabin departure delay (with closed doors) [s]
PTPT	Passenger transfer pause threshold [s]

5.1 Introduction

5.1.1 Background

A lift stands with its doors open at a landing to allow passenger transfer. After the transfer of passengers has finished, the door closing and the departure of the car may be delayed by the control system. There are known delays caused by door dwell times and start delays of cars before the next journey. But additional delays are possible. Lift systems with more than one car or cabin per shaft are susceptible to additional departure delays. These traffic caused delays are confusing for lift passengers as passengers expect the lift to depart after the process of passenger transfer in and out has finished. Different types of departure delays are described and a way to measure these delays in both simulation and real systems is proposed in this chapter. A metric is provided which can be applied in lift planning and dispatcher design.

5.1.2 Extended door dwell time

Most modern lift controllers have intelligent door dwell time algorithms. The presence of passengers is detected by the photoelectric door protection devices. If the door beams are interrupted, the control system assumes that passenger transfer is occurring and the doors remain open.

Extended door dwell time (sometimes known as door closing delay) is the time after the passenger detection beams of the doors are cleared before the lift door starts closing. Door dwell time before or during passenger transfer is not part of the extended door dwell time. The extended door dwell time can override the door dwell time.

The extended door dwell time is a delay experienced by passengers inside the cabin. This includes passengers who have just entered the cabin and passengers who are already inside the cabin having an intermediate stop. During the extended door dwell time, nothing happens for the passengers. It can be observed that regular lift users often press the door close button in the cabin rather than waiting for the doors to start closing for themselves after the extended door dwell time. Extended door dwell time is experienced as departure delay.

5.1.3 Departure delays in multi car/cabin lift systems

Departure delays in lift systems with more than one car or cabin per shaft occur when the loading/unloading times of the cabins are different, the number of stops is not equal, or one car blocks the way of another. An example of a stop with a different loading and unloading situation in the upper and lower cabin of a double deck lift car is illustrated in Figure 5-1. Figure 5-2 shows a simple example of a leading car ($D1(t)$) delaying a following car ($D2(t)$) because of stops. In a multi car lift system (MCLS) cars may delay a departure to avoid collision (R. Smith and Peters, 2004, Tanaka and Watanabe, 2009).

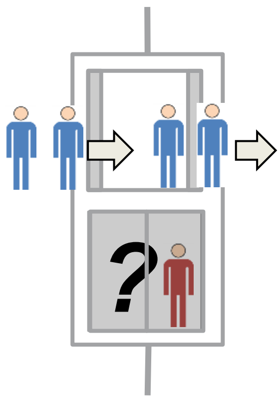


Figure 5-1: Double deck lift with a blind stop for a passenger in the lower cabin

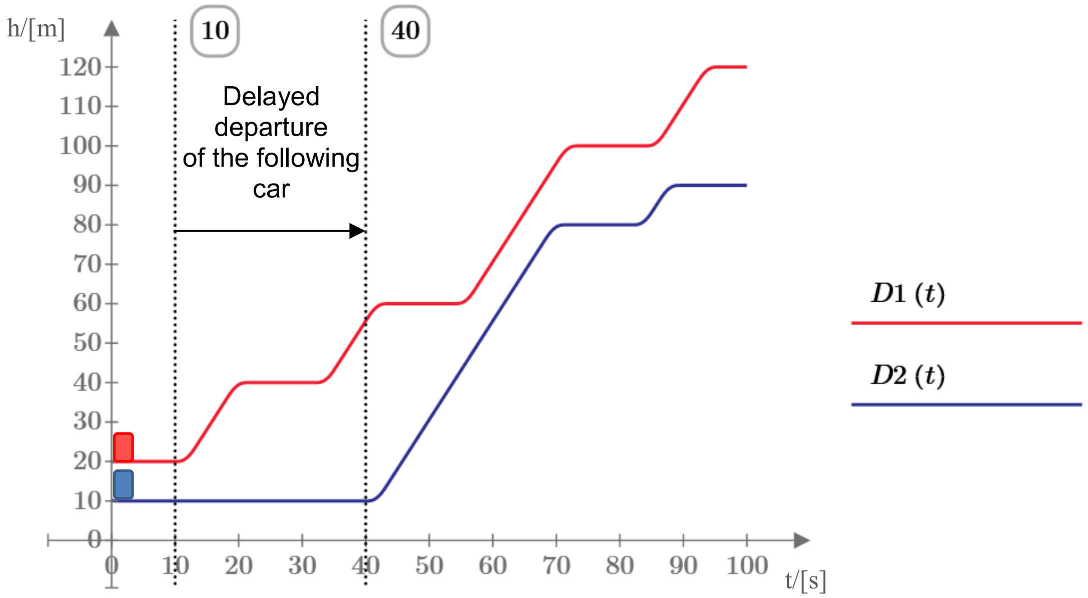


Figure 5-2: Delayed departure of the following car in a MCLS

5.1.4 Departure delays in conventional systems

Up peak: Departure delays are sometimes initiated by the dispatcher. In up-peak traffic conditions it can be beneficial to delay a car's departure from the lobby to wait for additional arriving passengers so that the cabin is filled to a higher capacity (Barney, 2003, Strakosch and Caporale, 2010). It is recommended that passengers should not be held at the lobby for more that 10 to 15 s (Strakosch and Caporale, 2010).

Walking times: Delays may occur if passengers need to walk to an allocated and arriving lift car. In destination control systems, the walking time from a call input station to the allocated car (see Figure 3-1 in section 3.2) is part of the waiting time (WT) of a passenger if the car has not yet arrived. However, a passenger walking from a call input station to a car that is already standing with open doors at the arrival floor delays the departure of the lift and any passengers who are already inside the car.

Door dwell time in conventional systems may need to be lengthened due to the arrangement of the lifts. In buildings built before lifts were automatic, it was common to place six or even eight lifts in a row. When these lifts were modernized, the dwell time needed to be long enough to permit passengers to walk from one end of the lobby to the other. Lift shafts may be arranged in line or opposite each other. Lift group layouts and lift lobby sizes affect the walking time. Long walking distances will delay the closure of car doors and will cause departure delays of cars (CIBSE, 2015). Also crowded lobbies can affect passenger transfer and cause delays.

5.1.5 Stops without passenger transfer

False stop: A false stop is a stop where the doors open and close without any passenger transfer (see Figure 5-9). A false stop occurs if a waiting passenger walks away before the lift arrives. The door dwell time during a false stop is a departure delay for passengers already inside the car. False stops can occur in MCLSs if an empty car is shunted (moved out of the way) with a car call initiated by the lift control system to allow another car to reach its destination. No passenger is affected, so there is no contribution to departure delay.

Blind stop: A blind stop is a stop of a cabin with no door operation (see Figure 5-14). In general, blind stops should only occur without passengers inside the cabin (see “rules of call control” in section 2.2.2). Passengers who are inside the cabin are confused by blind stop situations.

In a conventional system, a blind stop occurs if a lift does not have an allocated call and the car is parked at a floor. Passengers are not affected by this kind of blind stop. In double deck lift systems, blind stops can occur if only one of the two cabins have passengers transferring. In multi car lift systems with independent cabins in the same shafts, blind stops with passengers inside the cabin should be rare.

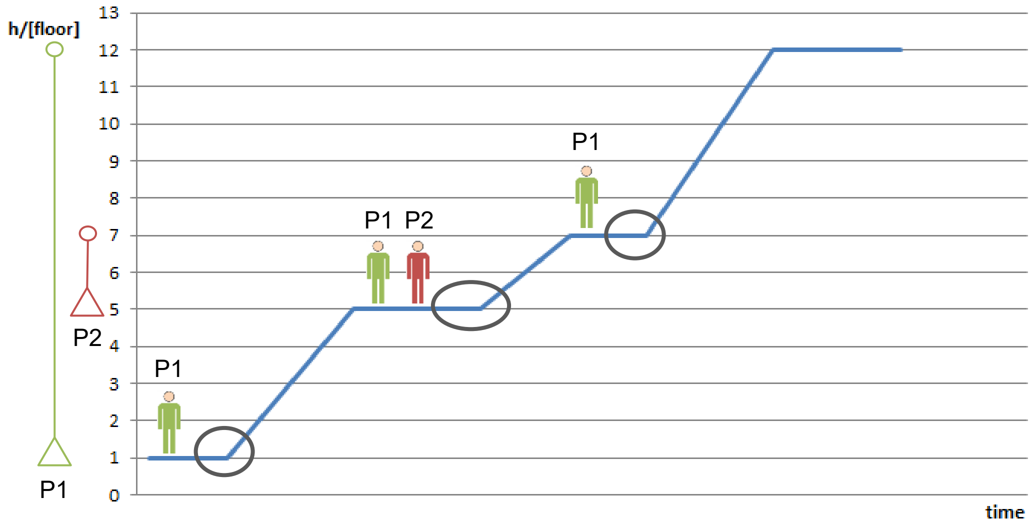
5.1.6 Departure delays and quality of service

Departure delays are confusing for lift passengers and reduce the experienced quality of service (QOS). A blind stop or any other departure delay should be explained to the passengers because unexplained waits seem longer than explained waits (Maister, 1985). The use of a display in double deck cabins that states “serving other deck” when a blind stop occurs is recommended (Fortune, 1995). For all types of departure delays, information about a departure delay can reduce passenger’s anxiety about their service. However, even explained departure delays can be annoying for passengers if they are too long as waiting needs to be appropriate (Norman, 2008).

There is a difference in the departure delay experienced by passengers if doors are opened or closed. A departure delay with the doors closed is known as a blind departure delay.

5.2 Samples/Records of passenger departure delays

During a journey, passengers experience different stop times including departure delays. The first stop time is the arrival of the cabin at the passenger's floor before it starts moving. Additional stop times during transit occur at the intermediate stops. The stop at the destination floor of the passenger is not a part of the passenger's transit time. This is illustrated at Figure 5-3. In this example there are 4 samples of passenger departure delays (PDD) that are experienced by two passengers (P1 and P2). Passenger 1 (P1) experiences 3 departures delays. Passenger 2 (P2) has only one departure delay. The cabin has 3 cabin departure delays (CDD) that are experienced at least by one passenger each.



Total experienced passenger departure delays:
P1: 1 x arrival floor (floor 1) + 2 x intermediate stops (floor 5 and 7)
P2: 1 x arrival floor (floor 5)
→4 individual passenger departure delays are recorded

Figure 5-3: Experienced departure delays

5.3 Passenger departure delay (open doors)

The passenger departure delay with open doors (PDD) is the period of time after passenger transfer is complete until the doors begin to close where there is one measurement for each stop experienced by the passenger. PDD is illustrated in Figure 5-4.

During passenger loading and unloading times, passengers crossing the cabin door threshold interrupt the passenger detection beams.

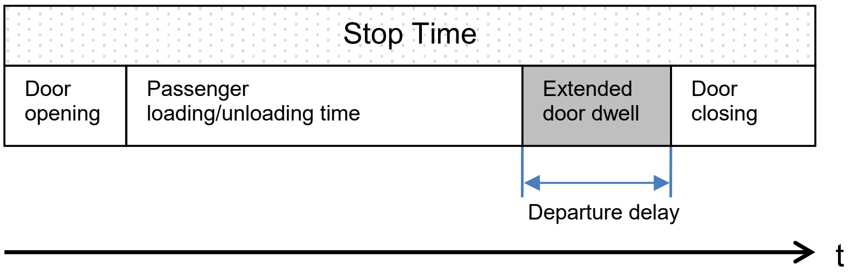


Figure 5-4: Passenger departure delay (normal stop)

In Figure 5-5 the PDD is extended because of traffic delays. For example, the door dwell time may have been lengthened because another car blocks the way of the car in a MCLS. Doors are held open for better passenger comfort compared to blind delays with closed doors.

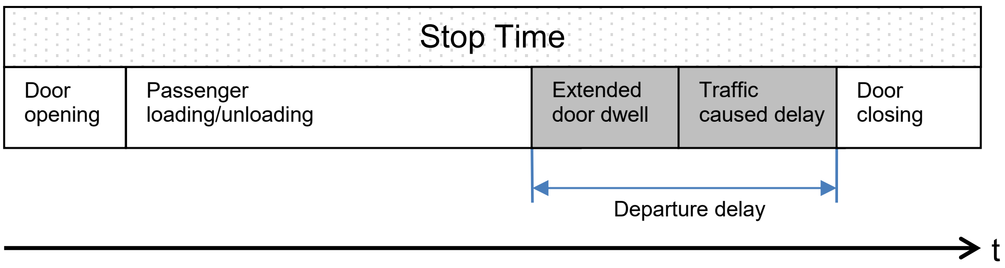


Figure 5-5: Passenger departure delay (normal stop + traffic caused delay)

Note 1: If there is a pause in passenger transfer, but the transfer re-starts before the doors start to close because it is less than the door dwell time/extended door dwell time and it is shorter than a “passenger transfer pause threshold” (PTPT), the departure delay does not start until the end of the final passenger transfer. This is illustrated in Figure 5-6. A reasonable value of PTPT is 1 second.

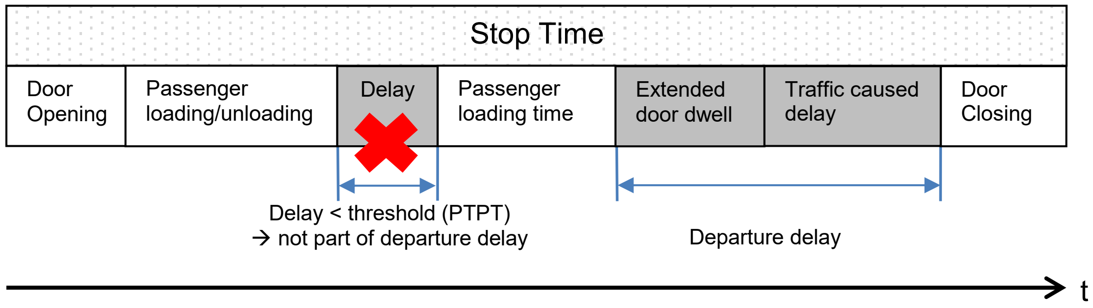


Figure 5-6: Short pause in passenger transfer

A short pause in passenger transfer can happen between normal unloading and loading of passengers especially where there are thick walls and deep door frames. When passengers are unloading and the walls are thick, door detection beams will be re-established for a short period of time until the loading passengers interrupt the detection beams. These short pauses are not seen as negative system delays.

Note 2: If there is a pause in passenger transfer without doors starting to close because of a traffic caused delay that is longer than or equal to a “passenger transfer pause threshold” (PTPT), for passengers already inside the cabin the departure delay includes the time during which there is no passenger transfer (passenger detection beams cleared). This is illustrated in Figure 5-7.

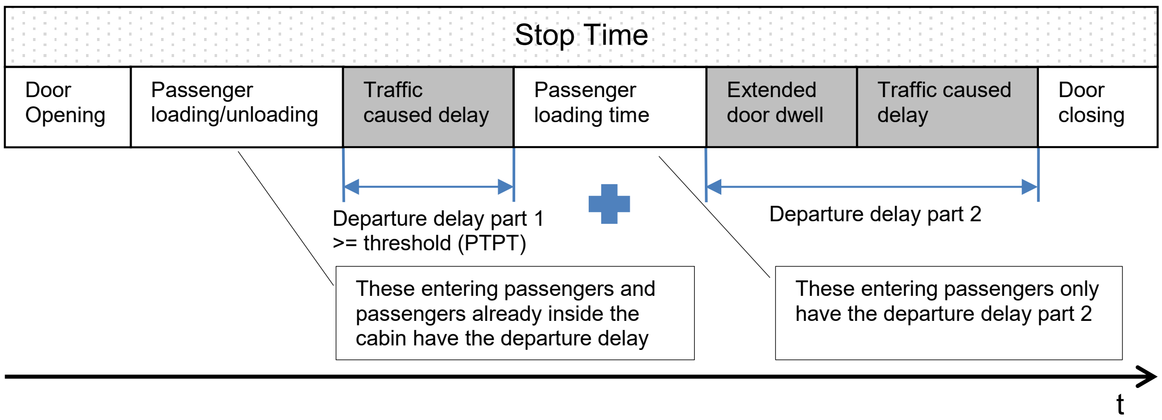


Figure 5-7: Pause in passenger transfer

Note 3: If the doors start to close, but are re-opened due to a new call being placed on the system, the departure delay re-starts when the next period of passenger transfer is complete. If the doors repeatedly re-open, there may be multiple periods of departure delay for a single stop, all of which are included in the departure delay for passengers already inside the cabin. This is illustrated in Figure 5-8.

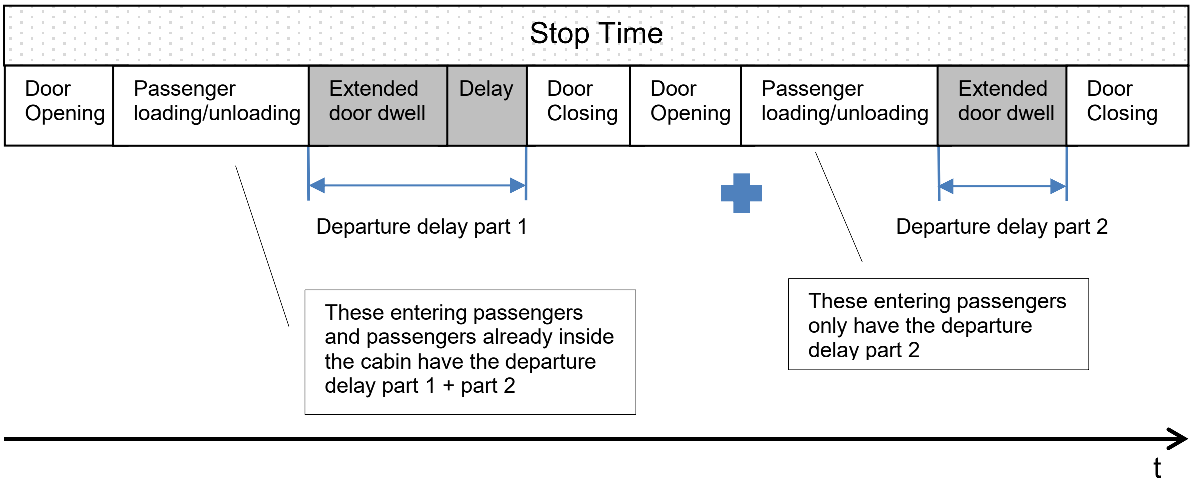


Figure 5-8: Door re-opening and departure delays

Note 4: If there is a false stop or passenger transfer finishes before the door is fully open, the time between when the doors are fully open and the time when the doors start closing is considered as departure delays for passengers inside the cabin. This may include door dwell time and traffic caused delays as shown in Figure 5-9 and Figure 5-10.

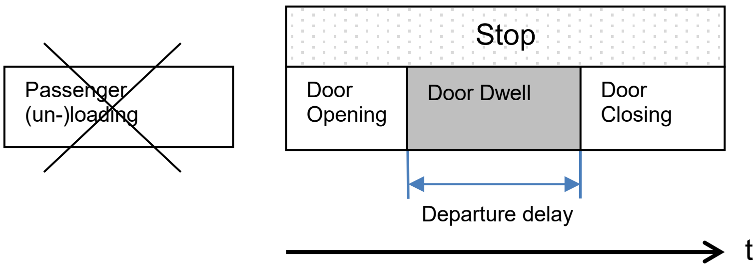


Figure 5-9: False stop

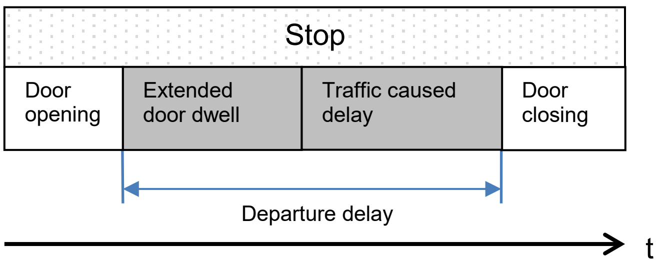


Figure 5-10: False stop + traffic caused delay

Note 5: If the passenger transfer is delayed e.g. because of walking times from the call input station to the already waiting cabin, the delay is included in the departure delay for passengers already in the cabin if it is longer than a “passenger transfer pause threshold” (PTPT). This is illustrated in Figure 5-11.

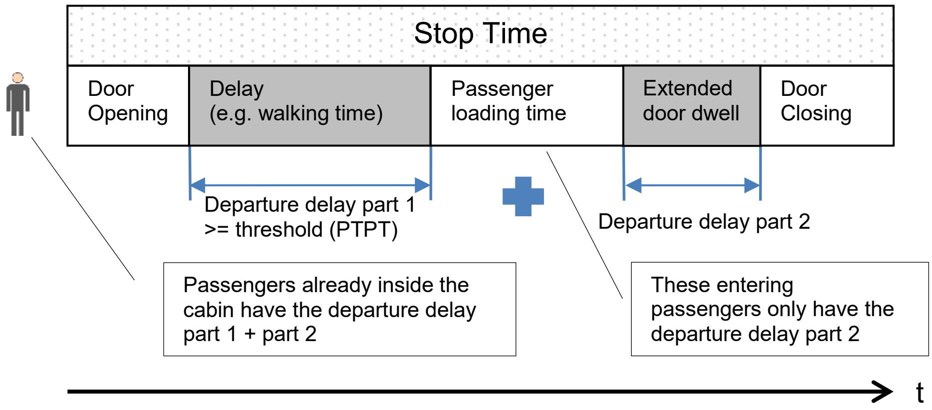


Figure 5-11: Delayed passenger transfer

5.4 Blind passenger departure delays (closed doors)

A blind passenger departure delay (BPDD) or passenger departure delay with closed doors is the time between the instant the doors are fully closed and time the car starts moving. In single cabin shafts with no traffic caused departure delay this equates to the motor start delay (Peters, 2012). This is shown in Figure 5-12. These start delays are caused by the locking shaft doors, the time required for relays to actuate, and the time required opening the machine brakes before the car starts moving.

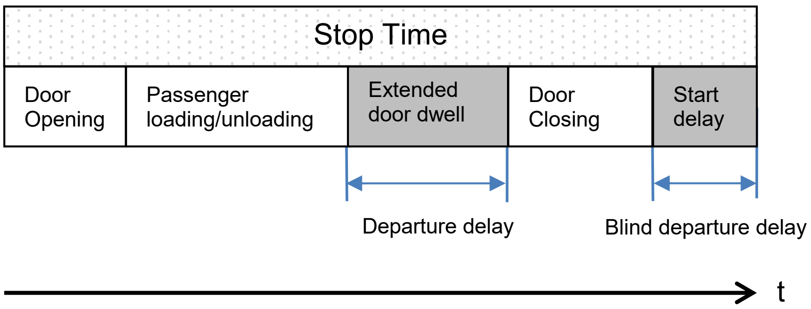


Figure 5-12: Blind departure delay

In a multi cabin lift system blind passenger departure delay can be extended because of traffic, see Figure 5-13.

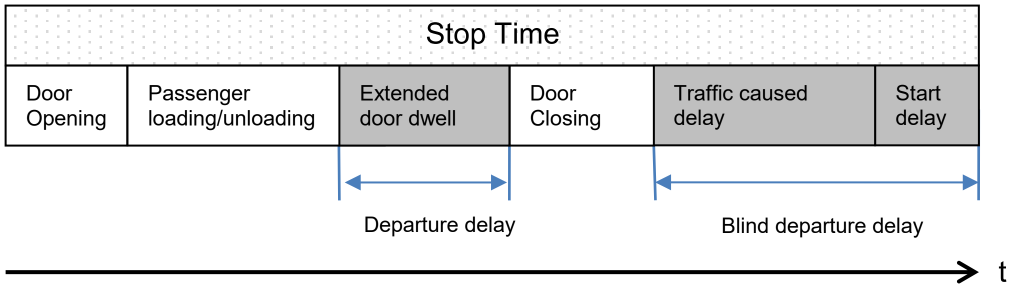


Figure 5-13: Blind departure delay + additional traffic caused delay

Note 6: In systems with multiple cabins in the same shaft, where one cabin is delayed by another and the doors do not cycle during that delay, the departure delay begins as soon as the cabin stops, and ends when the cabin starts to move again. This is illustrated in Figure 5-14.

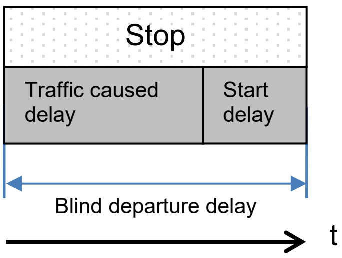


Figure 5-14: Blind stop

5.5 Cabin departure delay

PDD is a passenger-centric measure, useful in assessing the QOS from the prospective of the passenger. It is also helpful to have related system based measures for delay (Powell, 2015), cf. passenger WT and system response times where the system response time is equal to the WT of the first registered landing call of an arriving passenger at a floor (Barney, 2003).

The cabin departure delay (CDD) is the longest PDD at each stop. It is only measured if there are passengers inside the cabin (see also section 5.2).

The blind passenger departure delay (BPDD) is the same for all passengers in the cabin. This value is also the blind cabin departure delay (BCDD). It is only measured if there are passengers inside the cabin.

5.6 Measures and diagrams

Histograms can show the distribution of passenger and cabin departure delays. Cumulative values and average values help to assess the quality of a lift installation.

As there is a difference in passenger's departure delay experience and anxiety if doors are opened or closed, separate consideration of these departure delay measures is proposed. Departure delays with open doors include extended door dwell time after passenger detection beams are re-established. Departure delays with closed doors include motor start delays.

An example histogram showing the distribution of and average values of PDD are shown in Figure 5-15.

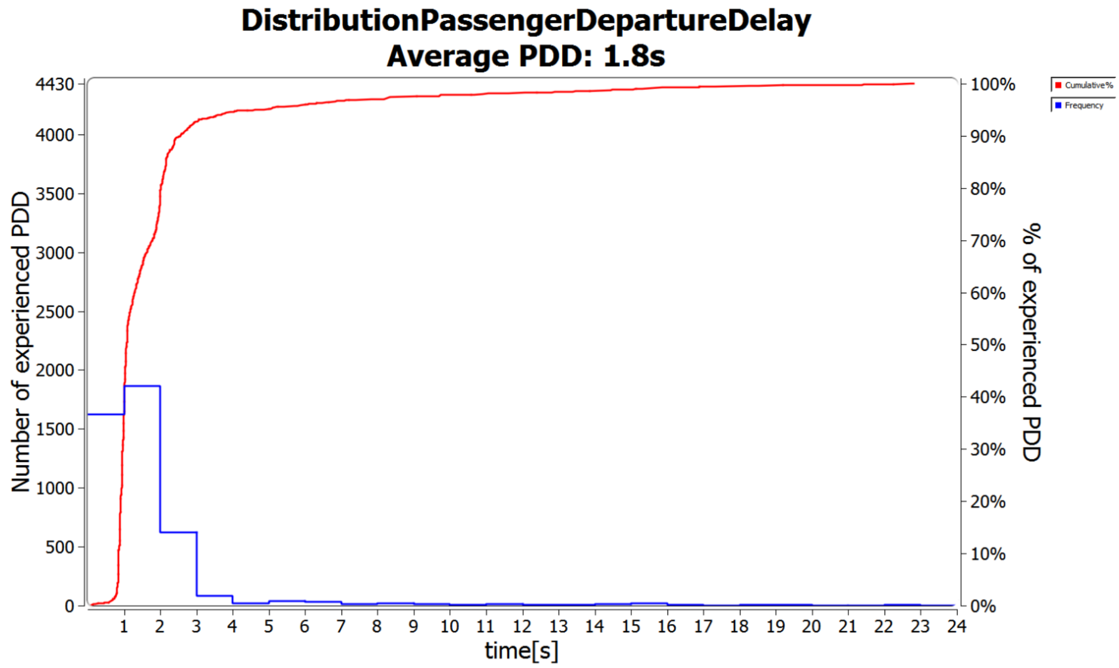


Figure 5-15: Histogram of the passenger departure delays (example)

5.7 Avoidance and reduction of departure delays

Departure delays are confusing and annoying for lift passengers. These delays should be reduced to a minimum or be avoided all together. In MCLSs, with multiple independent lift cars sharing the same shafts, flexible speed patterns can reduce departure delays (see chapter 8). In double deck lift systems co-incident stops of the lower and upper cabin can optimise departure delays. Door opening and closing times are in-process waits for passengers that are less painful than departure delays, but only if the door opening and closing times are appropriate (Maister, 1985). Slightly extended door opening and closing times may assist in a required delay to cabin departure in a way that is not detected by passengers.

Dispatching algorithms already consider passengers perception (R. Smith and Peters, 2004). To improve QOS, they should also consider departure delays to provide the required traffic handling without long departure delays (see chapter 6).

Intelligent dispatching and good lift planning help to reduce departure delays. For example, only allowing odd to odd and even to even floor traffic for double deck lifts (Sorsa and Siikonen, 2006). With two independent cars in one shaft (Müller, 2014), twin entrances with zoned low and high-rise operation helps to reduce scenarios causing departure delays. A planned stopping strategy for a circulating MCLS reduces car “traffic jams” that cause departure delay scenarios. This is demonstrated by the effective application of MCLSs as shuttle lifts (see chapter 10).

Intelligent door dwell times supported by additional sensors detecting passengers and passenger movement may reduce departure delays. By optimising start delays, blind departure delays can be reduced if they are not caused by traffic.

5.8 Summary

This chapter describes causes for departure delays, and defines them such that they can be measured in simulated and real systems. The measures can be used as quality criterion for all known lift systems: conventional one car per shaft, two independent cars in one shaft, double deck lifts, and circulating MCLSs. Because the measure is system independent, the QOS provided by different lift systems for the same traffic requirements can be compared.

Departure delay is part of transit time, but this part of transit time is more “painful” than when the car is moving. They should be considered and minimised by traffic control algorithms. Departure delays are considered in “QOS dispatching” as defined in chapter 6 of this thesis. Additionally, ideal lift kinematics reduces departure delays in MCLSs (see chapter 8). Therefore, the knowledge of required distances between cars is necessary (see chapter 7).

Acceptable levels of departure delay have not been assessed and will be a matter of judgement until further studies on the psychology of waiting can provide an objective view.

6 Quality of service dispatching

6.1 Introduction

Traffic control in general needs to consider psychology aspects helping to optimise the satisfaction level of passengers. Existing traffic control algorithms already look at some of these factors (see section 2.2.2). These are related to both, the “call control” and the “call dispatching” level. The “call control” level ensures a clear concept how calls are served and answered (“rules of call control”). The “call dispatching” level optimises on passengers’ preferences like waiting time (WT) or transit time (TT). The principle and effect of considering passengers’ perception in dispatch algorithms was published (R. Smith and Peters, 2004) and provides the basis for a quality of service (QOS) dispatching which is based on additional quality factors. These factors need to be defined and integrated into the optimisation function. This affects the “call dispatching” level of traffic control (see Figure 6-1).

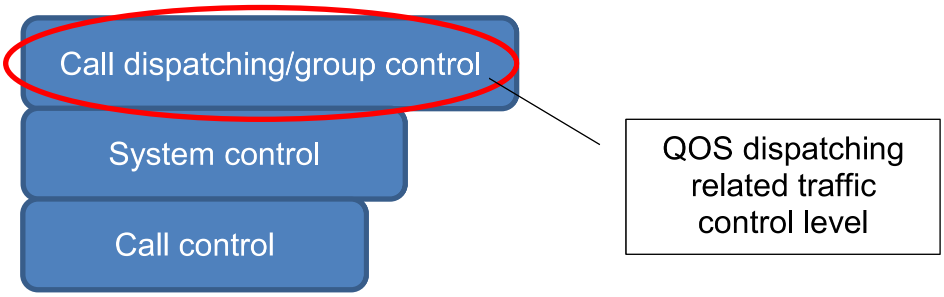


Figure 6-1: Traffic control levels – QOS dispatching

6.2 Online survey review

When thinking of different quality criteria in terms of traffic handling, it is valuable to know what the most important factors for passengers are when they think about their lift journey. An online questionnaire has been conducted by “Peters Research Ltd.” to identify expectations of lift passengers while using lifts (Bird *et al.*, 2016). The questionnaires focus was on WT, TT and intermediate stops experienced by passengers. People were invited via social networks and e-mail new-letters to participate in an online survey anonymously. 278 participants where answering up to five questions about their lift journey expectations and feelings.

The first question was asking about the feeling during four different aspects of their lift journey: waiting, travelling, a first intermediate stop and a second intermediate stop. Four different response options where provided by animated faces. Figure 6-2 shows the part of the first question asking about waiting for lifts.

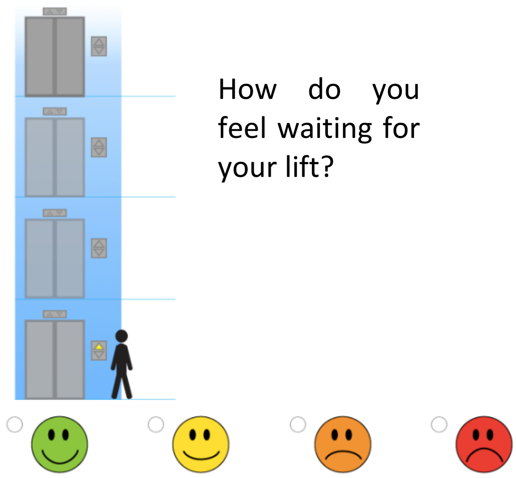


Figure 6-2: Question 1 part 1 with multiple choice response options (source: peters research (Bird *et al.*, 2016))

Question 2 was asking about the preferred choice out of three different theoretical journeys with the same journey time but with a different split of WT and TT. An example of the format of a theoretical journey is shown in Figure 6-3. Based on their answer of question 2 in question 3 an additional option was provided having a shorter journey time but for the price of a longer WT.

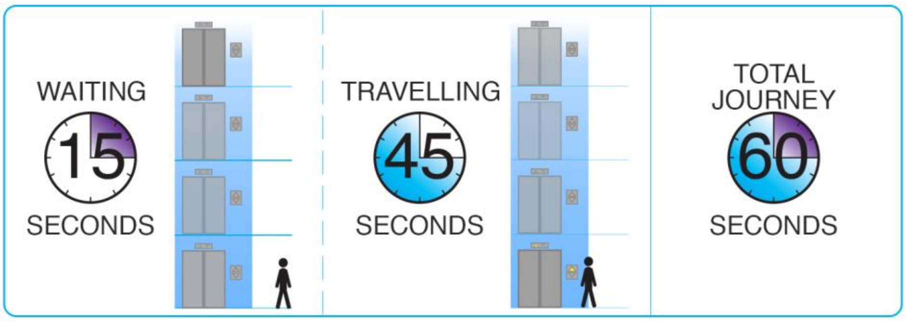


Figure 6-3: Format of a theoretical journey in Question 2 and 3 (source: peters research (Bird *et al.*, 2016))

Question 4 gave a choice of four different options similar to question 2, but focused on the associated stops for the different length of journey times. Question 5 was asking about the preferred ratio between WT and TT.

The overall results show that travelling time is the less painful part of the lift journey followed by WT (Bird *et al.*, 2016). Intermediate stops are the most painful part especially if they are repeated. This is consistent with existing QOS assumptions that WT is more painful than TT and passengers get impatient when experiencing multiple intermediate stops (see section 2.1.1). Based on the survey results, it is proposed that waiting is a third of the overall journey time. But intermediate stops as part of the TT are seen as much more painful than the time while travelling inside a lift car. This needs to be considered when thinking of the optimisation and weight factors. Additional waiting ought to be “appropriate”. The survey showed that different people have a different interpretation of “appropriate”.

All surveys, including this online questionnaire, have limitations (Bird *et al.*, 2016). A first limitation is that answering questions in a survey is not the same as experiencing an actual lift journey. This statement is supported by a study in the context of driving a car (Levinson *et al.*, 2004). A second limitation is that participants at this survey were given the information about the full journey and were asked about their preferred option. In reality, passengers are waiting for a lift to come without the knowledge and guarantee of their preferred transit with acceptable number of stops. Long WT may be frustrating if not explained.

6.3 Parameters considered by QOS dispatching

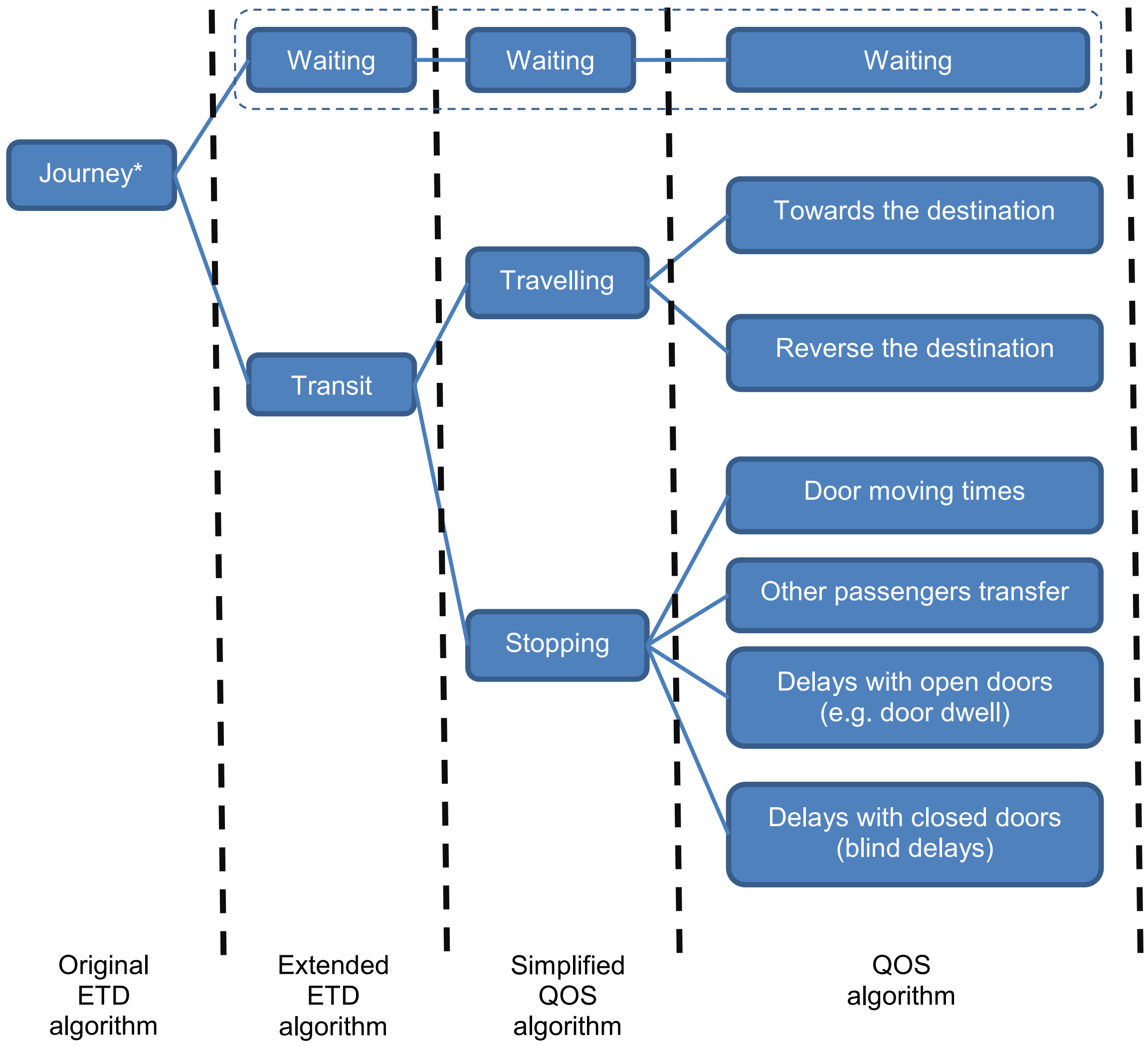
The online survey and the analysis of quality criteria based on psychology of waiting (see chapter 3) gives an indication on additional parameters that should be considered in dispatching algorithms. Especially the TT consists of different phases – travelling and stopping times.

Travelling times: Based on the reverse journey studies (see chapter 4) the travelling can be in two different “directions”: towards the direction of the passengers’ destination or the transit can start in the reverse direction. The “rules of call control” and psychology aspects clearly indicate a different pain level of both directions of travelling.

Stopping times: As described in the chapter 5 the stopping time can be split into different phases: door movement times (opening/closing), transfer times of (other) passengers, delays with open doors e.g. remaining door dwell and delays with closed doors (blind delays). These different periods during a stop may have different pain levels for passengers. As an outcome of the online survey the pain level will increase with each additional stop.

The different parameters considered by different dispatching algorithms are shown in Figure 6-4. All shown dispatching algorithms take into account the complete journey of passengers but with a different level of detail. The illustration shows how the estimated time to destination (ETD) dispatching algorithm is extended to QOS dispatching algorithms. The introduced QOS dispatching algorithms considers WT, different types of travelling times and the different parts of stopping times. A simplified version uses the different part of the stopping as a combined parameter and does not distinguish between the moving directions during travelling.

During the WT, different situations that can be experienced by passengers could be considered as additional parameters. Examples are described in section 3.4.1 (“Last come – first serve”; “Another lift car passing while waiting”). These different experiences during the waits are not considered in the definition of these QOS dispatching algorithms.



*: "journey" in terms of "time to destination"

Figure 6-4: Parameters of a journey to be considered by the different dispatchers

6.4 Dispatching algorithm

To weight all the different parameters of a journey considering different pain levels, the existing ETD dispatching algorithm was extended to become the QOS dispatching algorithm.

6.4.1 Extended ETD dispatching algorithm

The original core ETD algorithm (R. Smith and Peters, 2002) considers the cost in seconds of the time to destination (TTD) of the new passenger's call to be allocated to a specific lift. It also considers the degradation cost in seconds of the TTDs of all existing calls that are affected by a new call allocation. This is done to calculate the total cost for a new call to be allocated to a specific lift (see section 2.2.2).

The enhancement to the original ETD algorithm introduces a pain index (R. Smith and Peters, 2004) and splits the cost for the TTD into WT and TT as shown in equation (6-1).

$$ETD2C = WTC + TTC + \sum_{p=1}^{p_{exist}} \left(WTDC_p + TTDC_p\right) \tag{6-1}$$

where

$ETD2C$	Cost function of the extended ETD algorithm
WTC	Waiting time cost for the call in evaluation
TTC	Transit time cost for the call in evaluation
$WTDC_p$	Waiting time degradation cost for an existing call/passenger (p)
$TTDC_p$	Transit time degradation cost for an existing call/passenger (p)

To calculate each of the cost addends (e.g. WTC, TTC) the corresponding time/degradation time can be weighted with a factor (e.g. x_W as factor for the WT).
Example: $WTC = x_W \cdot WT$

The factor can be replaced by a function calculating the "cost" for an experienced time. It transfers the real time into a felt time – the "time cost".
Example: $WTC = C_W(WT)$

where

x_W	Weight factor for WT
$C_W(WT)$	"Time cost" function to calculate the "cost" for the WT based on the real time

If the factor is replaced by a function the degradation cost needs to be calculated with the degradation time like shown in the equation (6-2) as an example for the WT.

$$WTDC_p = C_W(WT_p + \Delta WT_p) - C_W(WT_p) \tag{6-2}$$

where

WT_p Waiting time for an existing call/passenger (p)

ΔWT_p Difference in waiting time for an existing call caused by a new call/passenger (p)

This is illustrated in Figure 6-5. The "time cost" function can be different for each type of "waiting" and could be individual for different passengers if they can be identified.

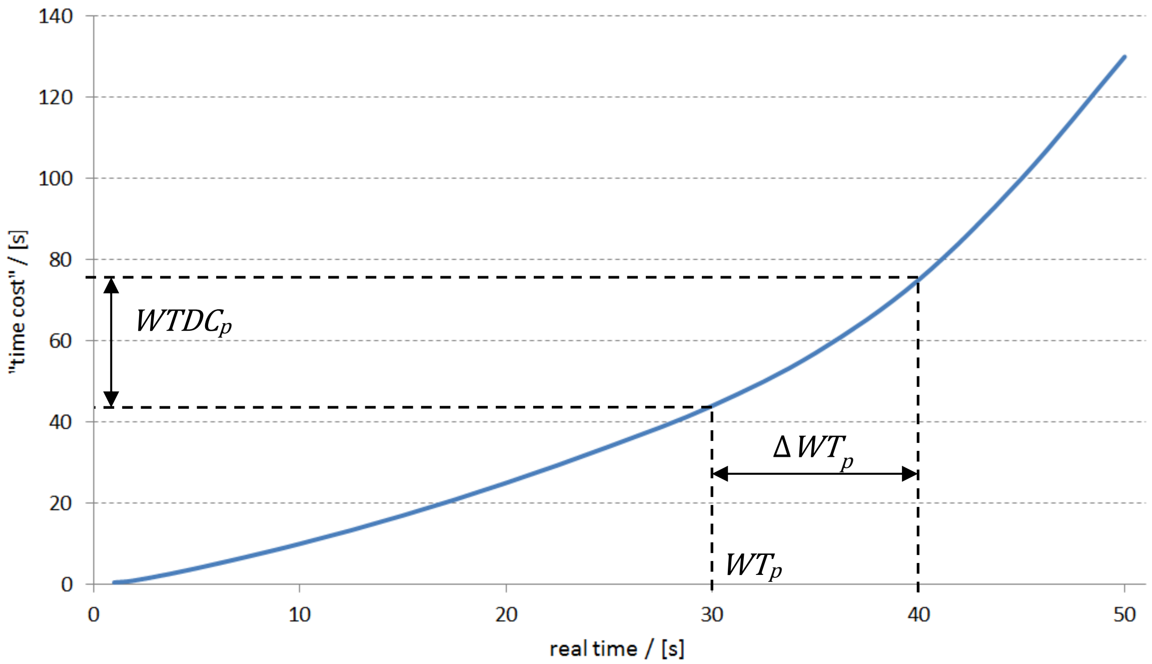


Figure 6-5: „time cost" function $C_W(WT)$

6.4.2 Simplified QOS dispatching algorithm

A simplified QOS dispatching algorithm splits the TT cost into moving time cost and stopping time costs. The stopping time cost can be different for each additional stop. According to the online survey results this enables the usage of different weight factors for moving times and intermediate stop times. The equation for the simplified QOS dispatching algorithm cost function is shown in equation (6-3). Another simplified version would not consider the stopping time; it could consider only the number of stops and its normalised cost. Similar to the description of extended ETD dispatching algorithm the weighting can be done by constant factors or individual “time cost” functions. For existing and affected passengers the degradation is considered.

$$QOSC = WTC + MTC + \sum_{st=1}^{st_{max}} STC_{st} + \sum_{p=1}^{p_{exist}} \left(WTDC_p + MTDC_p + \sum_{st=1}^{st_{max}} STDC_{p,st} \right) \quad \text{(6-3)}$$

where

$QOSC$	Cost function of the QOS algorithm
WTC	Waiting time cost for the call in evaluation
MTC	Moving time cost for the call in evaluation
STC_{st}	Stopping time cost of an individual stop (st) for the call in evaluation
$WTDC_p$	Waiting time degradation cost for an existing call/passenger (p)
$MTDC_p$	Moving time degradation cost for an existing call/passenger (p)
$STDC_{p,st}$	Stopping time degradation cost of an individual stop (st) for an existing call/passenger (p)

6.4.3 QOS dispatching algorithm

To extend the simplified QOS dispatching the moving time cost and the stopping time cost can be further split. This is shown with the equations (6-4) to (6-7). Practically the door opening, door closing and passenger transfer time may have the similar pain. Higher pain is expected for the departure delays with open and with closed doors. Similar to the description of the extended ETD dispatching algorithm the weighting can be done by constant factors or individual “time cost” functions. For existing and affected passengers the degradation is considered.

$$MTC = MFTC + MRTC \tag{6-4}$$

$$STC_{st} = STOC_{st} + STTC_{st} + STDC_{st} + STCC_{st} + STBC_{st} \tag{6-5}$$

$$MTDC_p = MFTDC_p + MRTDC_p \tag{6-6}$$

$$STDC_{p,st} = STODC_{p,st} + STTDC_{p,st} + STDDC_{p,st} + STCDC_{p,st} + STBDC_{p,st} \tag{6-7}$$

where

$MFTC$	Moving time cost for the call in evaluation towards the direction (forward)
$MRTC$	Moving time cost for the call in evaluation against the direction (reverse)
$STOC_{st}$	Stopping time cost of an individual stop (st) while opening the door
$STTC_{st}$	Stopping time cost of an individual stop (st) while passenger transfer
$STDC_{st}$	Stopping time cost of an individual stop (st) while remaining door dwell/departure delay before doors are closing (after passenger transfer)
$STCC_{st}$	Stopping time cost while closing the door
$STBC_{st}$	Stopping time cost with closed doors (e.g. start delay or blind stops)
$MFTDC_p$	Moving time degradation cost for the call/passenger (p) in evaluation towards the direction (forward)
$MRTDC_p$	Moving time degradation cost for the call/passenger (p) in evaluation against the direction (reverse)
$STODC_{p,st}$	Stopping time degradation cost of an individual stop (st) while opening the door for an existing call/passenger (p)

$STTDC_{p,st}$	Stopping time degradation cost of an individual stop (st) while passenger transfer
$STDDC_{p,st}$	Stopping time degradation cost of an individual stop (st) while remaining door dwell/departure delay before doors are closing (after passenger transfer) for an existing call/passenger (p)
$STCDC_{p,st}$	Stopping time degradation cost of an individual stop (st) while closing the door for an existing call/passenger (p)
$STBDC_{p,st}$	Stopping time degradation cost of an individual stop (st) with closed doors (e.g. start delay or blind stops) for an existing call/passenger (p)

6.5 Variations

Add on: For the described cost functions the individual factors and “time cost” functions may vary depending on specific situations and input parameters.

Situations and input parameters affecting the factors:

- Crowdedness of the lobby and cabin
- Available passenger information about the lift service
- Occupancy of the passengers’ time such as
  - walking time from the call input station to the allocated lift
  - available infotainment
- Time of the day
- Direction and intention of travel (incoming, outgoing)
- Current performance of the lifts
- Type of lift and lobby design

Additionally, personal preferences may be considered if passengers can be identified individually.

Dispatching objectives: The QOS cost (QOS_{Cost}) may be extended by energy cost ($Energy_{Cost}$) (may include wear out of elevator installation), handling capacity cost (HC_{Cost}) or additional rules (see equation (6-8)). The different components can be weighted by different factors (X_1, X_2, X_3) depending on static adjustments or dynamic adaption due to expected situations (learning).

$$Cost = X_1\ QOS_{Cost} + X_2\ Energy_{Cost} + X_3\ HC_{Cost} \quad (6\text{-}8)$$

Applications: This cost function can be applied to every kind of lift systems:

- Single car in shaft
- Double deck
- Two independent cars in one shaft
- Circulating multi car lift system (MCLS)

For MCLSs and double deck lift systems, the passenger degradation cost for passengers of other cars and cabins affected by an allocation needs to be considered with their degradation cost.

The cost function can be applied to lift groups with all kinds of control types:

- Conventional control (up/down buttons)
- Destination control
- Mixed control (up/down buttons with destination input stations at heavy floors)

6.6 Summary

The passengers' lift journey needs to be considered in more detailed phases as simplifications in WT and TT are too simplistic, especially for the TT in the cabin. This is supported by the results of an online questionnaire and psychological aspects.

Considering the different phases and situations of a passengers' journey the ETD dispatching cost function was extended to the QOS dispatching cost function. Dependent on weight factors the QOS dispatching will optimise call allocations in a way that parts of the journey with a high pain will be less likely to occur. QOS dispatching needs to be implemented and proven in traffic simulations. The relative pain of journey delays using lifts needs to be explored. A first hint was given by the online questionnaire in regard to WT, moving time and intermediate stops.

QOS dispatching will benefit from the best possible communication with passengers. An unexplained pause in lift operation or an unexpected reverse journey leads to confusion and mistrust.

But in MCLSs there are limits for a dispatching algorithm in reducing departure delays. If the control level “motion command” uses unsymmetrical travelling curves (see chapter 8) considering required distances between cars (see chapter 7) departure delays can be further reduced.

7 Safety distance control

List of symbols

Lift kinematics parameters:

v	Rated velocity [m/s] for normal operation (used as input for the equations) travelling up: $v > 0$, travelling down: $v < 0$
a	Rated acceleration [m/s²] for normal operation (used as input for the equations) travelling up: $a > 0$, travelling down: $a < 0$
j	Rated jerk [m/s³] for normal operation (used as input for the equations) travelling up: $j > 0$, travelling down: $j < 0$
d	Total distance [m] travelled for normal operation (used as input for the equations) travelling up: $d > 0$, travelling down: $d < 0$
$D(t)$	Distance [m] travelled at time t during normal operation
$V(t)$	Velocity [m/s] at time t during normal operation
$A(t)$	Acceleration [m/s²] at time t during normal operation
$J(t)$	Jerk [m/s³] at time t during normal operation
$D_i(t)$	Distance [m] travelled at time t during normal operation in period i
$V_i(t)$	Velocity [m/s] at time t during normal operation period i
$A_i(t)$	Acceleration [m/s²] at time t during normal operation period i
$J_i(t)$	Jerk [m/s³] at time t during normal operation period i
t_i	Time [s] after start of a normal operation journey the period i is finished

$D_{Car1}(t)$ Position [m] over time for car 1

$D_{Car2}(t)$ Position [m] over time for car 2

Safety system parameters:

v_{tr} Velocity [m/s] when an unexpected emergency deceleration is triggered

x_a First coefficient of common equation of real stopping distance uncontrolled deceleration

x_b Second coefficient of common equation of real stopping distance uncontrolled deceleration

x_c Third coefficient of common equation of real stopping distance uncontrolled deceleration

$d_{URS}(v_{tr})$ Uncontrolled real stopping distance [m], (common quadratic equation) (signed value depending on travel direction)

$d_{URSLD}(v_{tr})$ Uncontrolled real stopping distance [m] (lower) in down direction for an unbalanced system (signed)

d_{opU} Operational distance [m], levelling in up direction

d_{opD} Operational distance [m], levelling in down direction

d_{opD0} Operational distance [m] in down direction with $v = 0$ with open breaks

d_{opU0} Operational distance [m] in up direction with $v = 0$ with open breaks

d_{op} Operational distance [m]

$D_{URSLD}(t)$ Uncontrolled real stopping point [m] (lower) in down direction for an unbalanced system (signed)

$D_{URSi}(t)$	Uncontrolled real stopping point [m] in period i of the normal kinematic equations
t_{lmai}	Time [s] of the local maximum absolute value in period i for $D_{URSi}(t)$
d_{lmai}	Local maximum absolute value [m] in period i; $D_{URSi}(t_{lmai})$
d_{ch}	Car height [m]
d_{clS}	Minimum safety clearance [m]
d_{min}	Minimum distance between cars [m]
d_{minS}	Minimum safety distance [m]

Controlled deceleration parameters:

v_x	Velocity [m/s] when a deceleration process starts
a_x	Acceleration [m/s²] when a deceleration process starts travelling up: $a_x > 0$ (car is accelerating) travelling up: $a_x < 0$ (car is decelerating) travelling down: $a_x < 0$ (car is accelerating) travelling down: $a_x > 0$ (car is decelerating)
j_x	Jerk [m/s³] when a deceleration process starts (not applicable)
t_x	Time [s] a deceleration process starts
t_d	Time [s] for deceleration process that starts at time t_x ($t_d = 0$ at $t = t_x$)
$D_{Di}(t_d)$	Distance [m] travelled at time t_d during an emergency deceleration process for period i*
$V_{Di}(t_d)$	Velocity [m/s] at time t_d during an emergency deceleration process for period i*
$A_{Di}(t_d)$	Acceleration [m/s²] at time t_d during an emergency deceleration process for period i*

$J_{Di}(t_d)$	Jerk [m/s³] at time t_d during an emergency deceleration process for period i*

*: i is the period number during the emergency deceleration. That is numbered similar to the normal operation period numbers. For the emergency deceleration the period numbers 3, 5, 6, 7 exist.

t_{Di}	Time [s] after start of a deceleration process ($t = t_x$) when period i of emergency deceleration is finished
$d_{CISJ}(v_x)$	Controlled ideal stopping distance [m] depending on v_x with an infinite jerk
$d_{CIS}(v_x, a_x)$	Controlled ideal stopping distance [m] depending on v_x, a_x
$D_{CIS}(t)$	Controlled ideal stopping point [m] of a journey with higher values for deceleration and jerk like normal operation
$D_{CISr}(t)$	Controlled ideal stopping point [m] of a journey with deceleration and jerk values like normal operation
a_{dMax}	Maximum deceleration [m/s²] of the controlled deceleration process (used as input for the equations) travelling up: $a_{dMax} > 0$, travelling down: $a_{dMax} < 0$
a_d	Deceleration [m/s²] value that can be reached during the controlled deceleration process travelling up: $a_d > 0$, travelling down: $a_d < 0$
j_d	Jerk [m/s³] value of the controlled deceleration (used as input for the equations) travelling up: $j_d > 0$, travelling down: $j_d < 0$
v_d	Velocity [m/s] corresponding to the controlled deceleration at the beginning of period 5 which can be a virtual value if ($t_4 \leq t_x \leq t_7$). travelling up: $v_d > 0$, travelling down: $v_d < 0$

$D_S(t, t_x)$	Distance [m] travelled at time t, starting an emergency deceleration process at t_x
$V_S(t, t_x)$	Velocity [m/s] at time t starting an emergency deceleration process at t_x
$A_S(t, t_x)$	Acceleration [m/s²] at time t starting an emergency deceleration process at t_x
$A_{Sv}(t, t_x)$	Virtual acceleration [m/s²] at time t during an emergency deceleration process between $t_x + t_{D3}$ and t_x if $t_{D3} < 0$
$J_S(t, t_x)$	Jerk [m/s³] at time t starting an emergency deceleration process at t_x

Quantising safe position parameters:

d_m	Linear motor segment height [m]
d_x	Distance [m] added to the minimum distances due to linear motor segmentation
$D_{AMSU}(t)$	Based point [m] of the allowed motor segment for the car above
$D_{SaPo}(t)$	Save position [m] for a leading car ($D_{CIS}(t) + d_{min}$)
$D_{SaPoM}(t)$	Save position [m] for a leading car considering the linear motor segmentation
$D_{SaPoF}(t)$	Save position [m] for a leading car considering the following car stopping positions can only be at floors

7.1 Introduction

If multiple cars are moving together independently in one or multiple vertical and horizontal shafts and are stopping at the same floors, maintaining a safe distance between the cars is essential. For every multi car lift system (MCLS) it is important to have a control system that coordinates the operation of the cars. The control system needs to optimise handling capacity (HC) and quality of service (QOS) for passengers. Considering the interaction between cars sharing the same shafts includes the avoidance of “traffic jams” (a car is blocking the way for another car) and keeping departure delays of cars to a minimum. To ensure optimized operation the lift control system needs to consider the minimum distance possible between two cars while levelling and standing at floors as well as the possible distance between cars while travelling. This is illustrated in Figure 7-1 and Figure 7-2 showing positions of two cars over time.

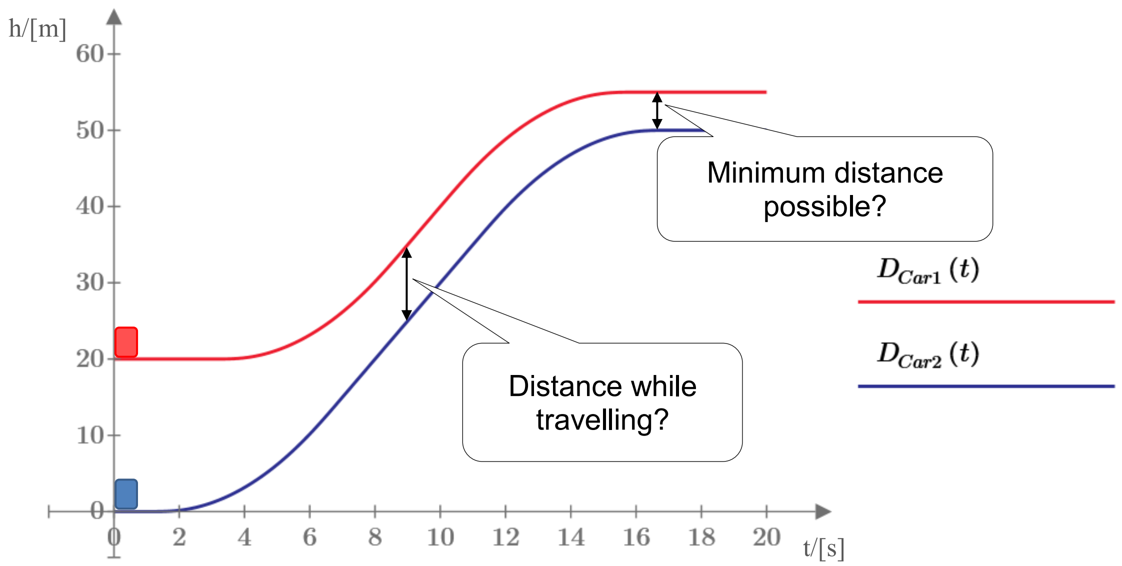


Figure 7-1: Unknown required distances between cars

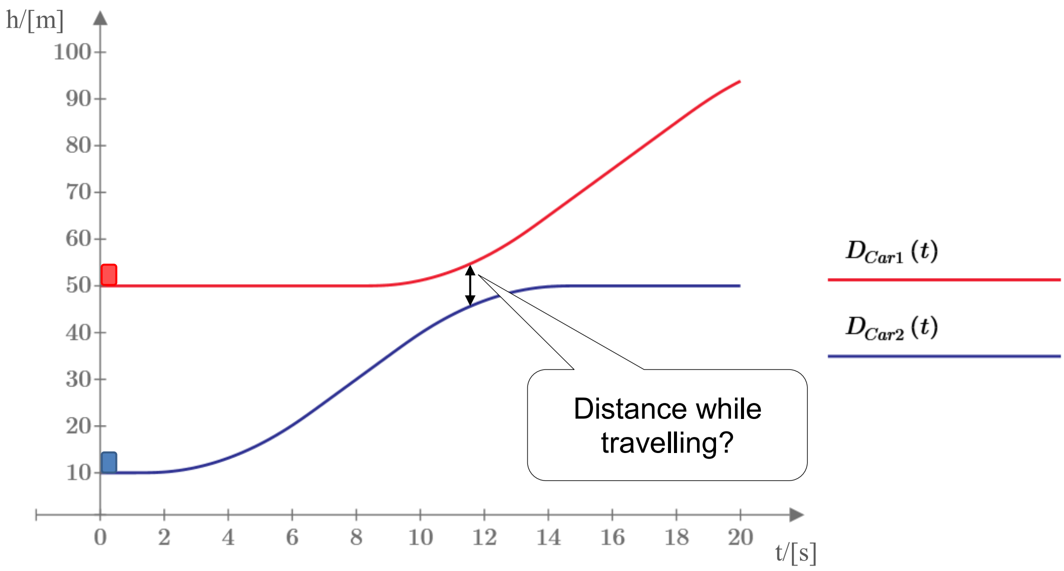


Figure 7-2: Unknown required distances between cars
(cars stopping at the same floor)

In case of lift control system failure, current systems with two independent cars are required to have a backup certified safety system to ensure that a minimum distance between cars is maintained at all times. A similar requirement will apply to circulating MCLSs.

To avoid activation other than in case of failure, the lift control system must be designed to ensure that the distance between cars during normal and unexpected operation will not violate the certified safety system rules. To achieve this, the rules that activate the certified safety system need to be fully understood. The current state of the safety distance theory of certified systems and how they are included in different control systems levels was explored and explained in the literature review (see section 2.3.5).

Even in unexpected situations, the lift control system should attempt to stop a car with a controlled deceleration before the certified safety systems stops the car in an uncontrolled manner. Controlled deceleration in unexpected situations can use a higher deceleration than is used in normal operation. The goal is to stop the car safely before the safety system activates. The stopping distance applying a controlled deceleration needs to be calculated at any time during a car journey. But during normal operation a lift car should not be stopped unexpectedly. For this reason, the knowledge of the stopping distance is important to develop optimized control strategies for MCLSs.

The minimum distance that is possible during normal operation considering existing certified safety systems is calculated in this chapter as well as the controlled stopping distance at any time of a lift journey. Necessary equations are derived in this chapter using mathematical software (PTC Inc., 2013).

7.2 Definitions

The following measures need to be defined:

Clearance	Distance between the lowest point of the upper car and the highest point at the lower car as shown in Figure 7-3.
Car height	The height of the car from the lowest to the highest point as shown in Figure 7-3.
Car distance	Distance between two cars measured from the same reference point of the cars (e.g. from cabin floor to cabin floor) as shown in Figure 7-3. This is the difference between the car vertical (or horizontal) positions. (Clearance + Car height)

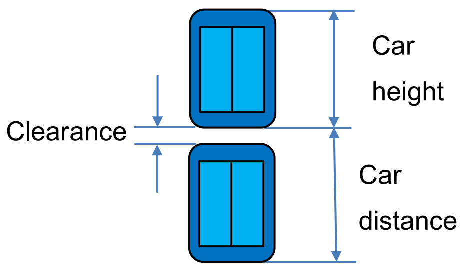


Figure 7-3: Dimensions of cars and distances

Minimum safety clearance	Minimum clearance between cars, including after failure of the system that causes a trigger of the safety system.

Minimum safety distance	Minimum distance between cars, including after failure of the system that causes a trigger of the safety system. (Car height + minimum safety clearance)
Operational distance	Additional distance that ensures that during controlled operation the safety system does not need to trigger an emergency stop to ensure the minimum safety distance.
Minimum distance	This distance between cars that must not be violated during controlled operation at any time. If it is about to be violated the certified safety system triggers an emergency deceleration/stop. (Minimum safety distance + Operational distance)
Ideal stopping distance	Distance travelled from the start of a decelerating process until the car has stopped ($v = 0$).
Reaction distance	Distance travelled during a system reaction time.
Real stopping distance	Distance travelled from the occurrence of a failure until the car has stopped ($v = 0$). This includes the stopping distance and the system reaction time. (Ideal stopping distance + reaction distance)
Ideal stopping point	Stopping position in the shaft after a deceleration process. (Current position + ideal stopping distance)
Real stopping point	Stopping position in the shaft after a deceleration process. (Current position + real stopping distance)

7.3 Minimum distance

7.3.1 Minimum distance during normal operation

The distance between cars is measured between floor levels of the cars, which is the difference in car positions. To define the minimum safety distance (d_{minS}) first the car height (d_{ch}) is added to the minimum safety clearance (d_{clS}) as shown in equation (7-1) (compare with Figure 7-3).

$$d_{minS} = d_{ch} + d_{clS} \tag{7-1}$$

But to calculate the minimum distance that is possible during normal operation it is essential to understand and consider the characteristics of the stopping point and stopping distances of uncontrolled deceleration triggered by certified safety systems described in section 2.3.5.2.

During the journey a stopping point after an emergency stop triggered by the certified safety system (level three – see section 2.3.5.1) can be calculated at any time. Figure 7-4 shows the travelling position of a car travelling to position=0 in down direction ($D(t) - d$). It also shows the lower stopping point of a ropeless lift system with linear motors in down direction ($D_{URSLD}(t) - d$) derived from equation (2-9) in section 2.3.5.2 (see also equation (7-2)). The lower stopping point in down direction has a local minimum before the lift arrives at the destination position, the "operational distance" in down direction (d_{opD}). This is equivalent to the additional offset between the emergency stop stopping point and the point the lift comes to stand still described by Nuebling (Nuebling, 2006) with the distance is shown in a diagram velocity over distance but is not calculated. This effect of the additional distance (operational distance) is relevant especially if lift cars shall stop at adjacent floors. This is known from real installations with balanced rope lift with two independent cars in one shaft and needs to be calculated for and by the lift control system.

$$D_{URSLD}(t) = D(t) + d_{URSLD}(V(t)) \tag{7-2}$$

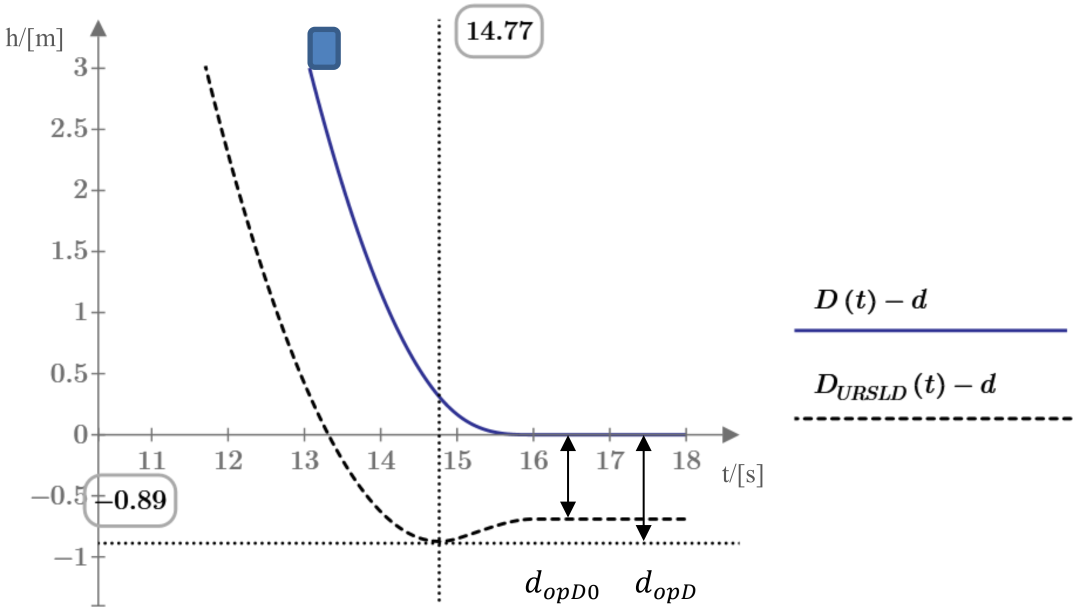


Figure 7-4: Travelling position and real stopping point in down direction

Like the operational distance in down direction, the same effect can be seen in up direction or for a balanced lift system. An operational distance for $v = 0$ with open breaks is shown with d_{opD0}. For simplicity this operational distance is used during travelling in up direction as operational distance in down direction for $v = 0$ and is used as part to calculate the operational distance and vice versa.

There are three cases of the operational distance:

1. One lift is standing or travelling in an up direction; the other lift follows or approached the first lift and is travelling in an up direction (see equation (7-3)).

$$d_{op} = |d_{opU}| + |d_{opD0}| \tag{7-3}$$

2. One lift is standing or travelling in a down direction; the other lift follows or approached the first lift and is travelling in a down direction (see equation (7-4)).

$$d_{op} = |d_{opD}| + |d_{opU0}| \tag{7-4}$$

3. Both lifts are travelling and approaching each other; one lift is travelling in an up direction the other lift is travelling in a down direction (see equation (7-5)).

$$d_{op} = |d_{opD}| + |d_{opU}| \quad (7\text{-}5)$$

The operational distance is an additional distance during controlled operation that needs to be considered to calculate the minimum distance to ensure that the safety system (level three, see section 2.3.5.1) does not trigger an uncontrolled emergency stop.

To calculate the minimum distance the operational distance is added to the minimum safety distance (see equation (7-6)).

$$d_{min} = d_{minS} + d_{op} \quad (7\text{-}6)$$

The operational distance depends on deceleration and jerk values of the travelling curve of a controlled deceleration. Since the controlled deceleration can be performed with different values the highest values of the operational distance should be used to calculate the minimum distance.

Depending on the travelling state of the cars the corresponding equation (7-3), (7-4) or (7-5) is used to calculate the operational distance. For simplicity equation (7-5) can be used and considered as operational distance because it covers all cases. If floor to floor distances are short it may be necessary to use equations (7-3) and (7-4) so that two cars can be moved to adjacent floors.

7.3.2 Operational distance calculation

To find and calculate the operational distance the maximum absolute value of the real stopping point levelling to position=0 needs to be evaluated. As the travelling curve is divided in different periods (see section 2.2.3) the different periods of the deceleration need to be considered to calculate the maximum absolute value of the stopping point. The two periods at the end of a journey (period p6 and p7 of the ideal lift kinematics) are considered in this chapter. The calculations are valid for balanced rope lifts and unbalanced ropeless lift systems with linear drives.

Uncontrolled real stopping distance (general): To calculate the operational distance (maximum absolute value of the stopping point while travelling to a destination position) the real stopping distance of the safety system can be shown as common quadratic equation (7-7) that is valid for balanced rope lifts and unbalanced ropeless lift systems with linear drives. The values of the parameters x_a, x_b and x_c characterise the uncontrolled deceleration of a specific lift system.

$$d_{URS}(v_{tr}) = x_a\, v_{tr}^2 + x_b\, v_{tr} + x_c \quad (7\text{-}7)$$

General equations of the absolute maximum stopping point: The following general equations are used for period p6 and p7 of the travelling curve ($i = [6;\ 7]$). The equations and results for period p6 and p7 are shown in the appendix. The stopping point after an uncontrolled deceleration triggered by the certified safety system ($D_{URSi}(t)$) can be calculated relative to the destination (d) by adding the stopping distance ($d_{URS}(v)$) depending on speed ($V_i(t)$) to the position of the lift ($D_i(t)$) shown in the equation (7-8).

$$D_{URSi}(t) = D_i(t) + d_{URS}\big(V_i(t)\big) - d \quad (7\text{-}8)$$

To find the local maximum absolute value differentiation is necessary (see equation (7-9))

$$\frac{d}{dt} D_{URSi}(t) \quad (7\text{-}9)$$

The time of the maximum absolute value can be calculated by setting the differential to 0 and solving for t (t_{lmai}).

Finding the maximum absolute value at time t_{lma6} is determined from equations (7-8), yielding equation (7-10).

$$d_{lmai} = D_{URSi}(t_{lmai}) \quad (7\text{-}10)$$

The result found for one period is valid only in the range $t_{i-1} \le t_{lmai} \le t_i$.

If the local maximum absolute value is not within period p6, the peak value of period p6 will be at the end of period p6 ($D_{URS6}(t_6)$). The condition of the local maximum in period 6 is shown in equation (7-11).

$$d_{ma6} = if(t_5 \leq t_{lma6} \leq t_6, d_{lma6}, D_{URS6}(t_6)) \tag{7-11}$$

As the equations of period p7 have 3 local maximum absolute values the maximum absolute value of period p7 is the maximum of these values that applies in the range of period p7 and the value at the beginning of period p7 (t_6). This is shown in equation (7-12).

$$d_{ma7} = \max(|d_{lma7}|, |\, D_{URS7}(t_6)|) \tag{7-12}$$

Overall operational distance: The overall maximum absolute operational distance is the maximum absolute value of all valid local maximum absolute values of period p6 and p7 shown in equation (7-13).

$$d_{opU/D} = \max(|d_{ma6}|, |d_{ma7}|) \tag{7-13}$$

7.4 Controlled deceleration/controlled stopping distance

The lift control needs to ensure that the safety system does not trigger an emergency stop (level three, see section 2.3.5.1). In case of an unexpected operation of a lift car, the lift control may need to perform a controlled deceleration for any other car using the propulsion system (level two, see section 2.3.5.1). This could be performed by a pure deceleration (with infinite jerk values) or with a controlled deceleration with jerk. In each case a system reaction time needs to be considered.

The controlled deceleration needs to have a higher value for the ideal stopping distance than the stopping distance of the triggered emergency stop by the safety system (level three, see section 2.3.5.1). Equations in this chapter are valid in general for balanced rope lifts and unbalanced ropeless lift systems.

7.4.1 System reaction time

In case of an unexpected lift operation, the lift control system performs a controlled deceleration. That deceleration of the car starts after a system reaction time. During the system reaction time it is assumed that the lift car needing to be decelerated continues its journey in the same way as its expected journey. The system reaction time is not considered in the following calculations for controlled deceleration. The velocity, acceleration and jerk values after the reaction time are the input values/start parameters of the ideal deceleration.

7.4.2 Deceleration with infinite jerk

To stop a car with a controlled deceleration with an infinite jerk the equations are the same as for uncontrolled deceleration of the safety system.

The ideal stopping distance can be calculated with equation (7-14).

$$d_{CISJ}(v_x) = \frac{v_x^2}{2\,a_d} \tag{7-14}$$

Deceleration can be theoretical values since the propulsion system needs to be able to build up/apply the deceleration instantly. To calculate the realistic stopping distance a controlled deceleration considering a finite jerk needs to be calculated.

7.4.3 Deceleration with jerk

During a journey of a lift car, deceleration with same or higher acceleration and jerk values will be performed to stop the car in an unexpected situation. The usage of jerk values during a controlled deceleration does support a more comfortable stop for passengers and considers limitations of the propulsion system.

To calculate the ideal stopping distance, different periods exist until the lift car is stopped. The end times and periods of the deceleration are named equivalent to the periods of case A of the ideal lift kinematics.

The deceleration process starts at time t_x which is the zero/start point for the controlled deceleration. The time points for the controlled deceleration (t_{D3}...t_{D7}) are relative to t_x.

Period D3 ends at time t_{D3}: reduction of the acceleration with a constant jerk (this period only exists if the lift is in the acceleration phase)

Period D4:	In case A of the ideal kinematics period p4 is the constant velocity period. This period does not exist for the deceleration process.
Period D5 ends at time t_{D5}:	increasing the deceleration with a constant jerk
Period D6 ends at time t_{D6}:	constant deceleration (This period only exists if the maximum deceleration (a_{dMax}) of the controlled deceleration can be reached. Otherwise the next period D7 is directly following period D5.)
Period D7 ends at time t_{D7}:	reduction of the deceleration. This period ends with the standstill of the car

Figure 7-5 shows an ideal controlled deceleration starting at $t_x = 3s$. Jerk and deceleration values of the deceleration are higher that the values of the normal journey.

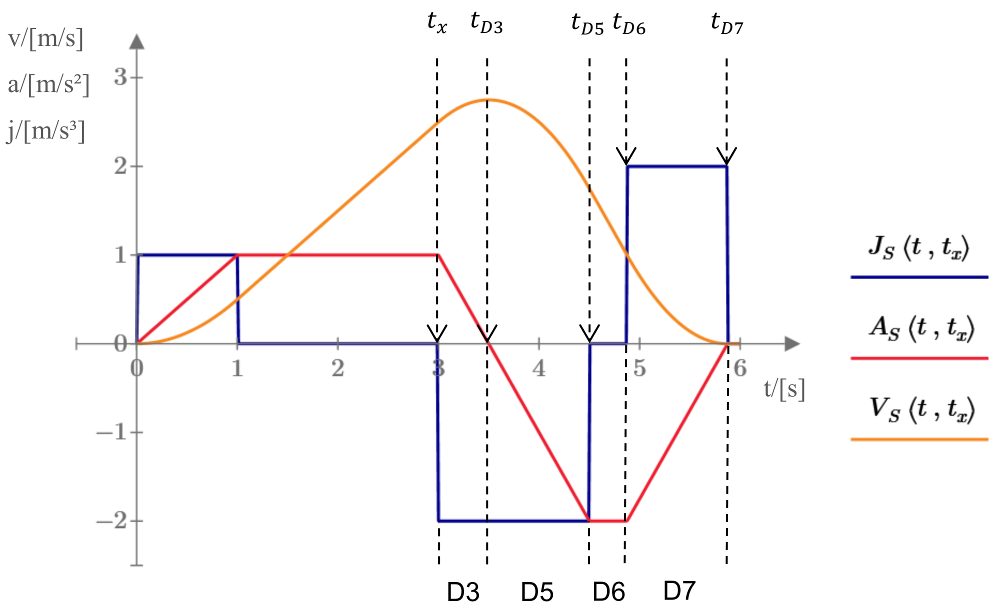


Figure 7-5: Jerk, acceleration and velocity of an ideal controlled deceleration starting at t_x

7.4.3.1 Time points

The time points that mark the end of each period of the deceleration process (D3…D7) of the controlled deceleration relative to t_x (zero/start point for the deceleration) are shown in equations (7-15) to (7-18).

Period D3 does not exist if the controlled deceleration starts when the lift is already decelerating (lift is in period p5, p6 or p7 during normal movement of the traveling curve when controlled deceleration starts). In this case the controlled deceleration starts directly with period D5. The current acceleration of the lift at the beginning of the deceleration (a_x) at time t_x has a negative value. A virtual t_{D3} and a virtual period D3 can be calculated and used for the calculation of the controlled deceleration.

$$t_{D3} = \frac{a_x}{j_d} \tag{7-15}$$

$t_{D3} > 0$ Lift is in acceleration phase at the beginning of the controlled deceleration ($t_x < t_3$).

$t_{D3} = 0$ Lift is in constant speed at the beginning of the controlled deceleration ($t_3 \leq t_x \leq t_4$).

$t_{D3} < 0$ Lift is (already) in deceleration phase at the beginning of the controlled deceleration ($t_4 \leq t_x \leq t_7$). t_{D3} gives a virtual value what time the deceleration would have been started with a_d and j_d. This is illustrated with the following Figure 7-6. $A_{Sv}(t,\ t_x)$ shows the virtual graph between t_{D3} and t_x.

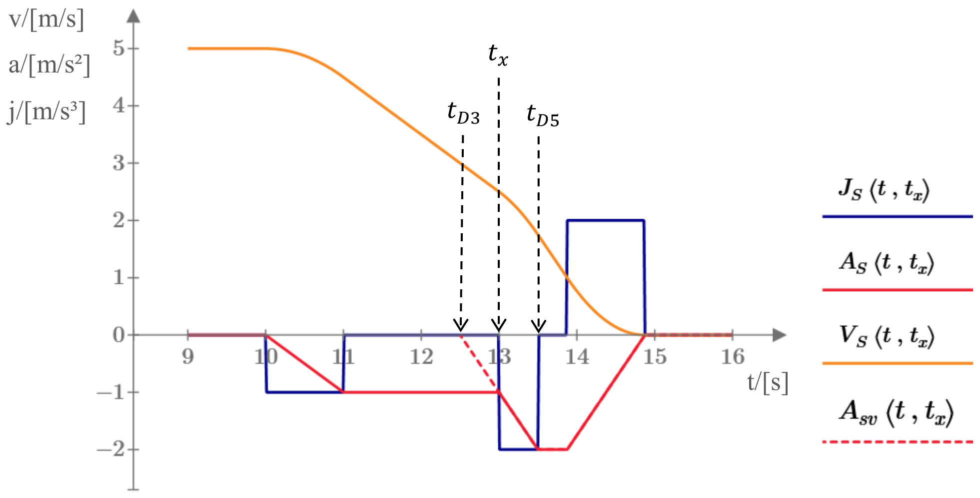


Figure 7-6: Virtual t_{D3} of an ideal controlled deceleration

At time t_{D5} the phase building up the deceleration ends (see equation (7-16)). Period D5 is only necessary if the deceleration value of the controlled deceleration $(-a_d)$ is higher than the current deceleration of the lift at the beginning of the controlled deceleration (a_x) at time t_x. If the lift is already decelerating with the deceleration value of the controlled deceleration (a_d) the controlled deceleration starts directly with period D6.

$$t_{D5} = \frac{a_d}{j_d} + t_{D3} \text{ yields } t_{D5} = \frac{a_d + a_x}{j_d} \tag{7-16}$$

$t_{D5} = 0$ Current deceleration of lift is $a_x = -a_d$ at the beginning of the controlled deceleration

$t_{D5} > 0$ Current deceleration of lift is $if(v_x > 0)\ a_x > -a_d,\ if(v_x < 0)\ a_x < -a_d$ at the beginning of the controlled deceleration

At time t_{D6} the constant deceleration ends (see equation (7-17)). There is no constant deceleration if the maximum deceleration of the controlled deceleration (a_{dMax}) is not reached. In that case t_{D6} equals t_{D5}.

$$t_{D6} = \frac{v_d}{a_d} + t_{D3} \text{ yields } t_{D6} = \frac{v_d}{a_d} + \frac{a_x}{j_d} \tag{7-17}$$

Time t_{D7} is the endpoint of the controlled deceleration (see equation (7-18)). The lift car comes to stand still.

$t_{D7} = \frac{a_d}{j_d} + \frac{v_d}{a_d} + t_{D3}$ yields $t_{D7} = \frac{a_d}{j_d} + \frac{v_d}{a_d} + \frac{a_x}{j_d}$ (7-18)

7.4.3.2 General equations of the controlled deceleration

This chapter shows how to calculate acceleration, velocity and distance travelled during the controlled deceleration starting at time t_x shown in Figure 7-5. The detailed results can be found in the appendix.

Controlled deceleration starts with the constant negative jerk value. This can result in a step of the current jerk rates of the car. If the lift is currently in an acceleration phase the period D3 is necessary to reduce the current acceleration rate. The reduction of the current acceleration rate is followed by increasing the deceleration rate, period D5. Period D5 continues period D3.

If the lift is currently in constant velocity or is already decelerating the controlled deceleration starts with period D5 and period D3 is not necessary. Period D5 is not necessary if the lift is already in period p7 of the normal travelling with the ideal lift kinematics and the current jerk rate (j_x) equals the jerk rate of the controlled deceleration (j_d).

Period D4 with constant velocity during the controlled deceleration does not exist. Therefore, $t_{D4} = t_{D3}$. For consistency the following conditions are used:
$A_{D4}(t_{D4}) = A_{D3}(t_{D3})$, $V_{D4}(t_{D4}) = V_{D3}(t_{D3})$, $D_{D4}(t_{D4}) = D_{D3}(t_{D3})$.

Each of the periods during controlled deceleration (period D3, D5, D6, D7) has a specific jerk value.

$J_{D3}(t) = -j_d$; $J_{D5}(t) = -j_d$; $J_{D6}(t) = 0$; $J_{D7}(t) = j_d$;

The acceleration of period D3 is the acceleration at the start of the controlled deceleration process (a_x) added to the integration of the jerk of period D3 (see equation (7-19)).

$$A_{D3}(t_d) = a_x + \int_0^{t_d} J_{D3}(\tau_d)d\tau_d \quad (7\text{-}19)$$

The acceleration of the following periods is the acceleration at the end of the previous period added to the integration of the jerk of this period ($i = [5;\ 6;\ 7]$) (see equation (7-20)).

$$A_{Di}(t_d) = A_{Di-1}(t_{Di-1}) + \int_{t_{Di-1}}^{t_d} J_{Di}(\tau_d) d\tau_d \tag{7-20}$$

The velocity of period D3 is the velocity at the start of the controlled deceleration process (v_x) added to the integration of the acceleration of period D3 (see equation (7-21)).

$$V_{D3}(t_d) = v_x + \int_0^{t_d} A_{D3}(\tau_d) d\tau_d \tag{7-21}$$

The velocity of the following periods is the velocity at the end of the previous period added to the integration of the acceleration of this period ($i = [5;\ 6;\ 7]$) (see equation (7-22)).

$$V_{Di}(t_d) = V_{Di-1}(t_{Di-1}) + \int_{t_{Di-1}}^{t_d} A_{Di}(\tau_d) d\tau_d \tag{7-22}$$

The distance travelled in period D3 starting from the controlled deceleration process is the velocity integrated (see equation (7-23)).

$$D_{D3}(t_d) = \int_0^{t_d} V_{D3}(\tau_d) d\tau_d \tag{7-23}$$

The distance travelled during the controlled deceleration of the following periods is the distance travelled at the end of the previous period added to the integration of the velocity of this period ($i = [5;\ 6;\ 7]$) (see equation (7-24)).

$$D_{Di}(t_d) = D_{Di-1}(t_{Di-1}) + \int_{t_{Di-1}}^{t_d} V_{Di}(\tau_d) d\tau_d \qquad (7\text{-}24)$$

7.4.3.3 Velocity (v_d) and deceleration (a_d)

To use the equations for the controlled deceleration, it is necessary to know the maximum deceleration that can be reached during the controlled deceleration. This means it is necessary to know the velocity at t_{D3}. This can be a virtual value if the controlled deceleration starts while the lift is already in deceleration $t_{D3} < 0$ or $(t_4 \leq t_x \leq t_7)$. These can be calculated with equations (7-25) and (7-26).

Velocity at t_{D3}:

$$v_d = V_{D3}(t_{D3}) \text{ yields } v_d = v_x + \frac{a_x^2}{2\, j_d} \qquad (7\text{-}25)$$

A negative value of t_{D3} indicates that the time point t_{D3} is a virtual value in the past, before t_x (time controlled deceleration starts).

The deceleration that can be reached during the controlled deceleration may be calculated with

$$a_d = if(|v_d| \geq \left|\frac{a_{dMax}^2}{j_d}\right|, a_{dMax}, \sqrt[2]{v_d\, j_d}\ \frac{a_{dMax}}{|a_{dMax}|}) \qquad (7\text{-}26)$$

The deceleration is limited by thy maximum deceleration (a_{dMax}) that is required for the controlled deceleration. If the maximum deceleration cannot be reached, period D6 (constant deceleration) does not exist.

7.4.3.4 Ideal stopping distance

The ideal stopping distance with controlled deceleration can be calculated at time t_{D7} (equation (7-18)) used with the equation (7-24) for the distance travelled during deceleration for period $i = 7$ (see equation (7-27)):

$$d_{CIS}(v_x, a_x) = D_{D7}(t_{D7})$$

yields

$$d_{CIS}(v_x, a_x) = \frac{2\,a_x\,(a_x^2 + 3\,v_x\,j_d)}{6\,j_d^2} + \frac{3\,a_d\,(a_x^2 + 2\,v_x\,j_d - j_d\,v_d)}{6\,j_d^2} + \frac{3\,j_d\,v_d\,(a_x^2 + 2\,v_x\,j_d - j_d\,v_d)}{6\,a_d\,j_d^2} \tag{7-27}$$

With equation (7-25) for v_d the ideal stopping distance is shown in equation (7-28).

$$d_{CIS}(v_x, a_x) = \frac{8\,a_x^3 + 24\,v_x\,j_d\,a_x}{24\,j_d^2} + \frac{a_d\,(6\,a_x^2 + 12\,v_x\,j_d)}{24\,j_d^2} + \frac{3\,a_x^4 + 12\,v_x\,j_d\,a_x^2 + 12\,v_x^2\,j_d^2}{24\,a_d\,j_d^2} \tag{7-28}$$

If the jerk (j_d) approaches infinity the equation (7-28) equals equation (7-14), the ideal stopping distance with an infinite jerk. This is shown with equation (7-29). To use mathematical software (PTC Inc., 2013) for that a_d and j_d are added as input parameters for the equation (7-28) $d_{CIS}(\dots)$.

$$\lim_{j_d \to \infty} d_{CIS}(v_x, a_x, a_d, j_d) = \frac{v_x^2}{2\,a_d} \tag{7-29}$$

7.4.3.5 Diagrams controlled deceleration

The following Figure 7-7 to Figure 7-13 show the controlled deceleration process starting in every period (p1…p7) of a normal journey of ideal lift kinematics. The time t_x, starting a controlled deceleration, is indicated with a dotted line in each of the diagrams including the time value of t_x. Each diagram shows the jerk ($J_S(t, t_x)$, m/s³, blue line), acceleration ($A_S(t, t_x)$, m/s², red line) and velocity ($V_S(t, t_x)$, m/s, yellow line) over time (x-axis) before and after t_x. The rated values of the controlled deceleration are $j_d = 2m/s^3$ and $a_{dMax} = 2m/s^2$. The rated values of the normal journey are $j = 1m/s^3$, $a = 1m/s^2$ and $v = 5m/s$.

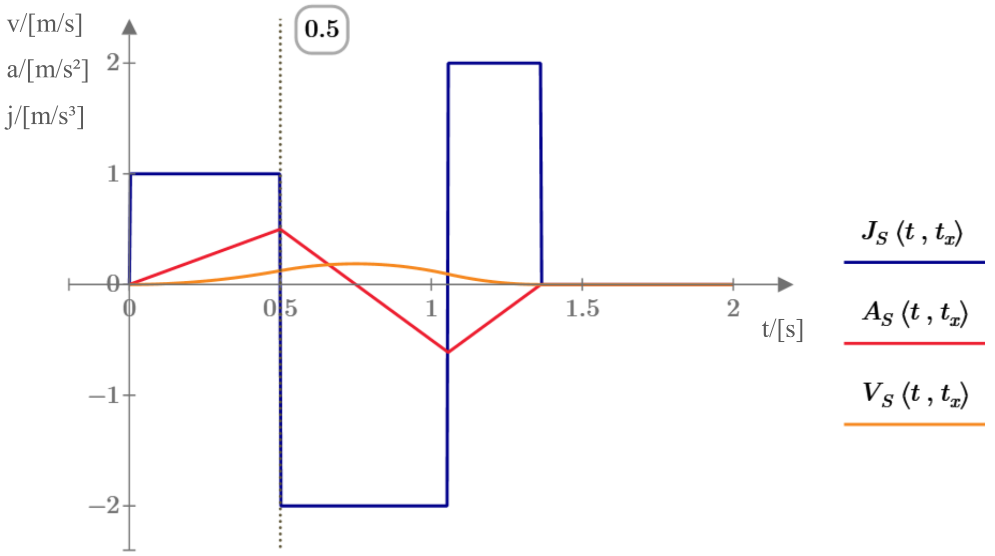


Figure 7-7: Ideal controlled deceleration starting in period 1of the journey

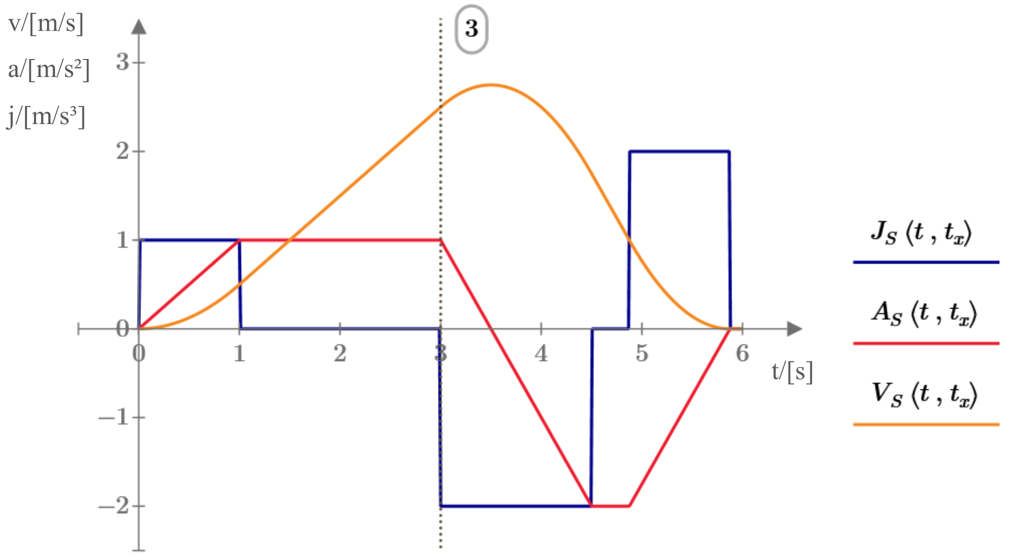


Figure 7-8: Ideal controlled deceleration starting in period 2 of the journey

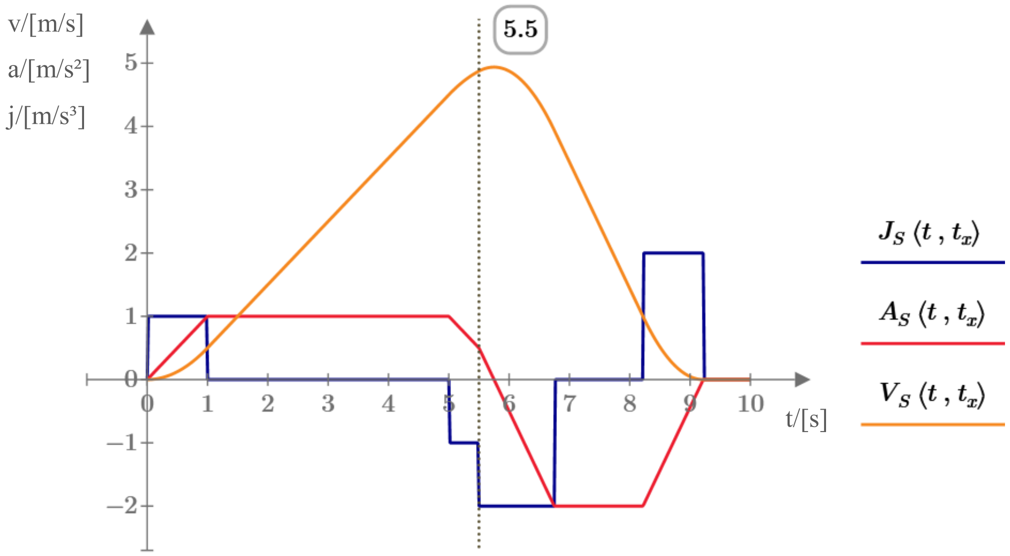


Figure 7-9: Ideal controlled deceleration starting in period 3 of the journey

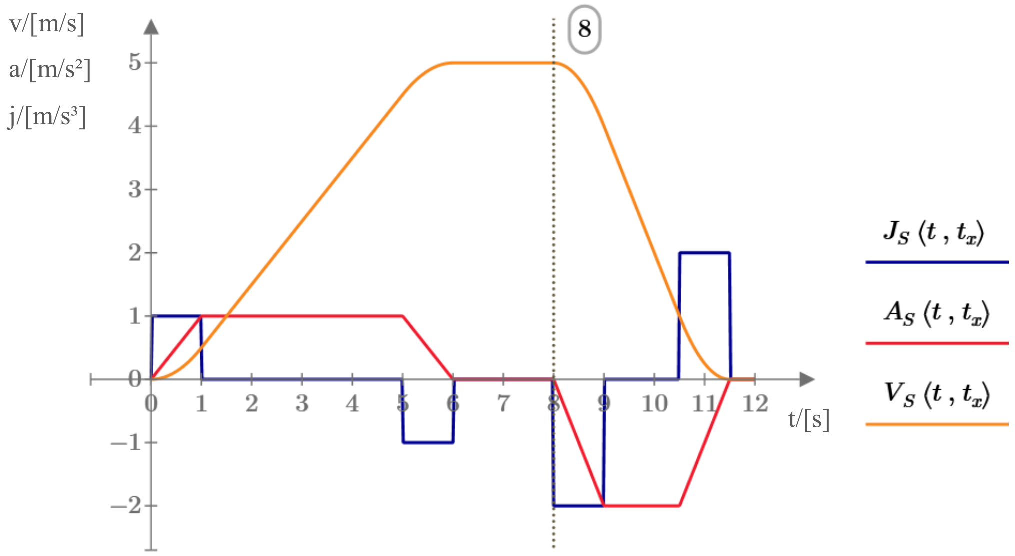


Figure 7-10: Ideal controlled deceleration starting in period 4 of the journey

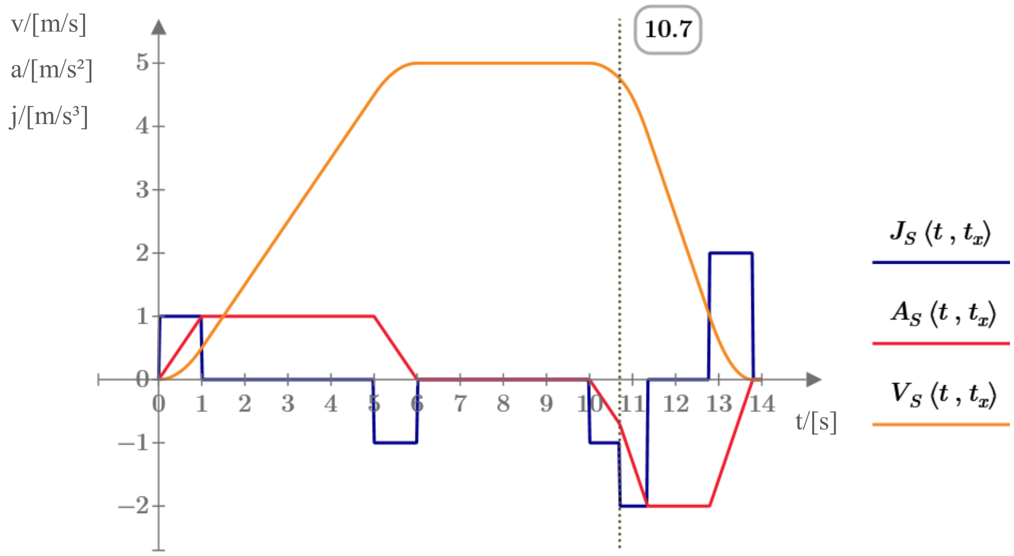


Figure 7-11: Ideal controlled deceleration starting in period 5 of the journey

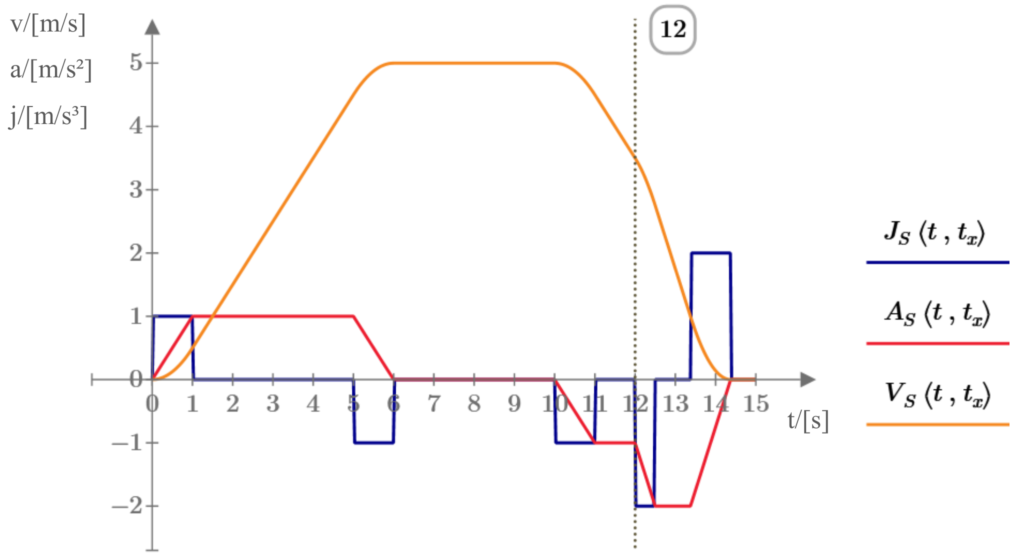


Figure 7-12: Ideal controlled deceleration starting in period 6 of the journey

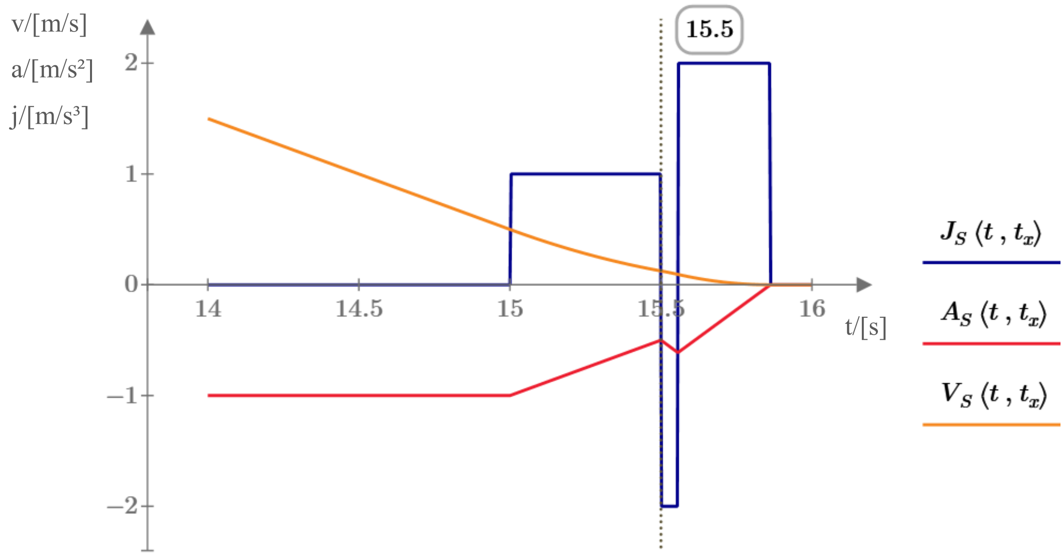


Figure 7-13: Ideal controlled deceleration starting in period 7 of the journey

7.5 Stopping point or distance during a journey

Figure 7-14 shows the travelling position $D(t)$ of a car during a journey from position 0m to 50m with $v = 5m/s$, $a = 1m/s^2$ and $j = 1m/s^3$ starting at $t = 3s$. It also shows the ideal stopping point ($D_{CISr}(t)$) after a spontaneous controlled deceleration with rated deceleration values. The stopping point ($D_{CISr}(t)$) shows the position where the car comes to a standstill if the controlled deceleration with rated values is triggered at time t while the lift is moving on its normal run ($D(t)$) from 0m to 50m. If the lift is in the deceleration process (period p5 to p7) to the 50m level (13s-19s) the spontaneous controlled deceleration cannot stop the car earlier if the rated values for deceleration and jerk are used. This is represented by the constant stopping point ($D_{CISr}(t)$) at the destination position (50m) between 13s and 19s. The stopping point is also constant if a spontaneous deceleration is started during the end of the acceleration process during period p3 (8s-9s) while the acceleration is reduced by a negative jerk. The controlled deceleration can also be operated with higher values for deceleration and jerk. The ideal stopping point $D_{CIS}(t)$ looks different with higher values for deceleration and jerk ($a_{dMax} = 1.4m/s^2$ and $j_d = 1.4m/s^3$). This diagram does not consider the system reaction time.

The idea stopping point during a journey is calculated with equation (7-30).

$$D_{CIS}(t) = D(t) + d_{CIS}(V(t), A(t)) \quad (7\text{-}30)$$

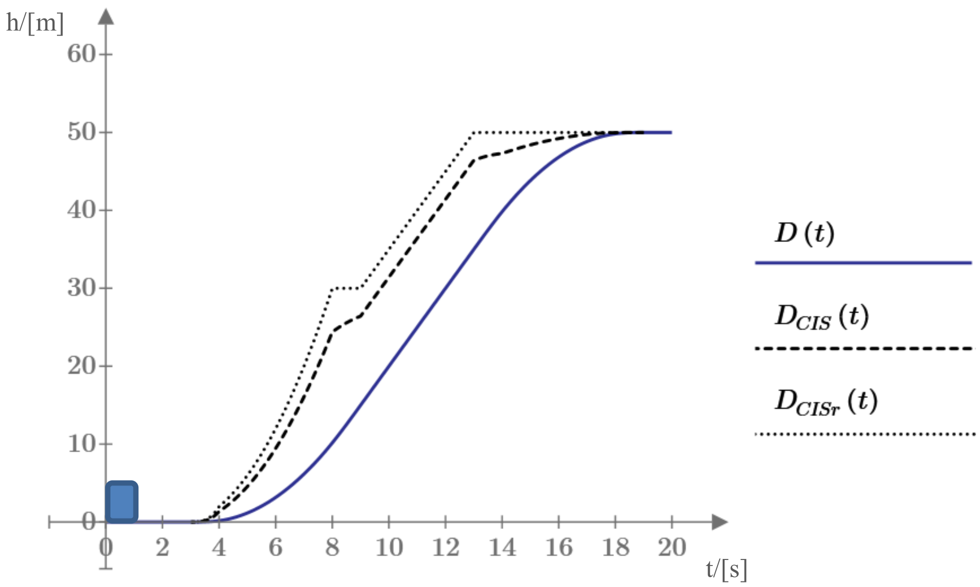


Figure 7-14: Travelling position and ideal stopping point for a controlled deceleration with rated and higher values for deceleration and jerk

If the minimum distance d_{min} is added to the stopping point, a critical position of another car can be calculated. If another car is at that critical position or closer the controlled deceleration needs to be started. Figure 7-15 and Figure 7-16 shows the usage of the stopping point added to the minimum distance during a lift journey in a multi car lift system. The travelling position of two cars are shown ($D_{Car1}(t)$ and $D_{Car2}(t)$). Both cars are running with $v = 5m/s$, $a = 1m/s^2$ and $j = 1m/s^3$. The controlled deceleration to calculate the stopping point added to the minimum distance ($D_{CIS}(t) + d_{min}$) is calculated with $a_{dMax} = 1.4m/s^2$ and $j_d = 1.4m/s^3$.

The control system needs to consider the stopping point and the position of the front car to control the start of the journey of the following lower car. It also needs to consider the minimum possible distance at the destination of the journey.

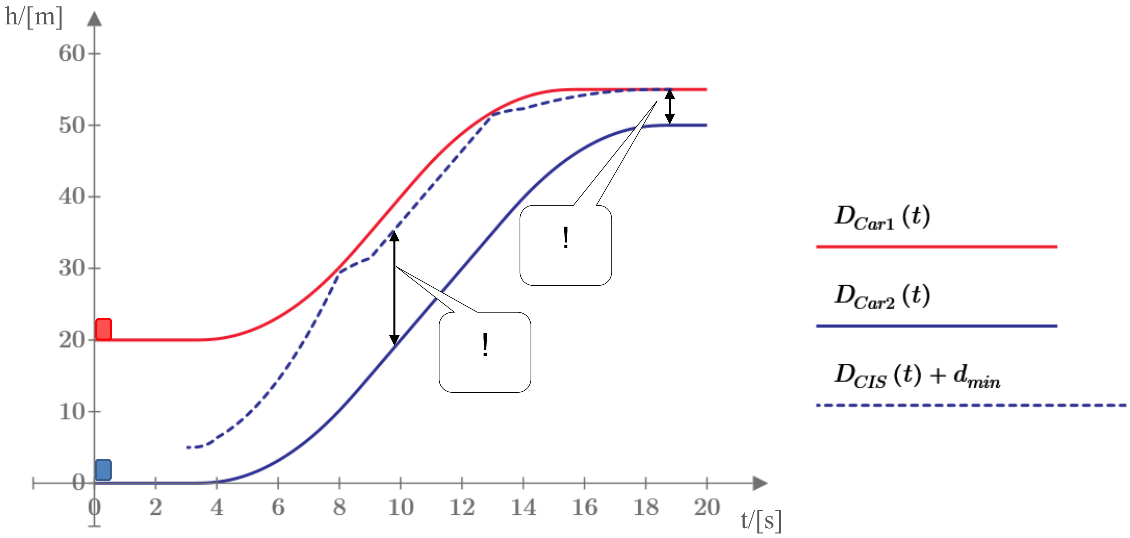


Figure 7-15: Known required distances between cars

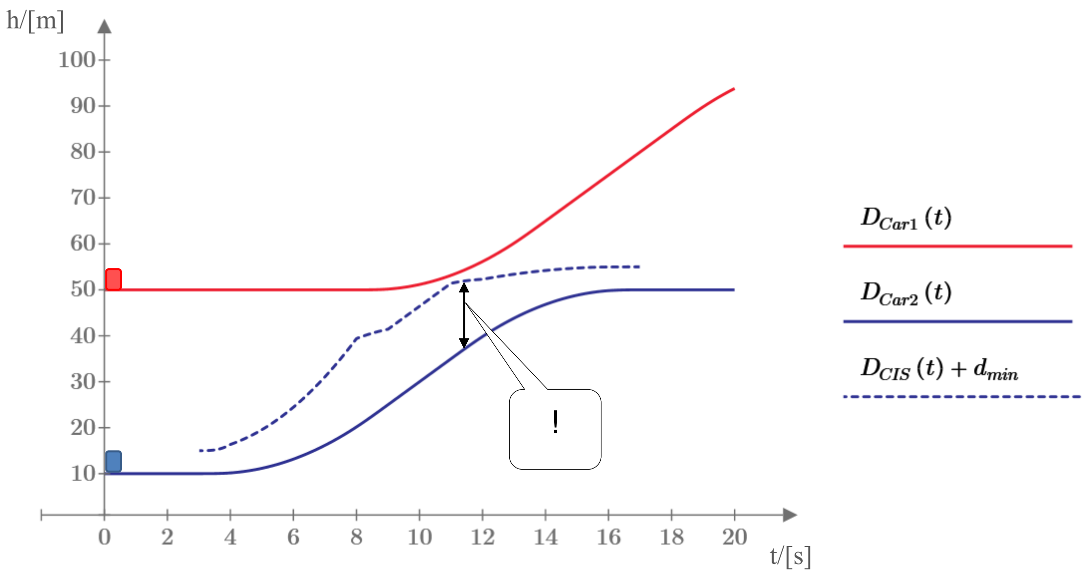


Figure 7-16: Known required distances between cars
(cars stopping at the same floor)

7.6 Constraints (Quantising safe positions)

Because of additional system constraints the safe positions of other cars may not be at any position in a shaft. This will affect interaction between cars and needs to be considered by the control systems.

Linear motor segmentation: Lifts without ropes can be propelled with linear motors (see section 2.3.4.1). Coil units installed in the shafts are split into segments. Only segments of coil units covered by the magnet yokes mounted on the cars are involved in the movement of a specific car. Only the magnet yoke of one car is allowed to cover one motor segment. If safety distances and controlled stopping points are calculated, the segmentation of the linear motors also needs to be considered. Figure 7-17 shows that the minimum distance (d_{min}) is possible in case A, but not for case B, as two cars cover the same linear motor segment. This can be solved by an additional distance (d_x) as shown in case C.

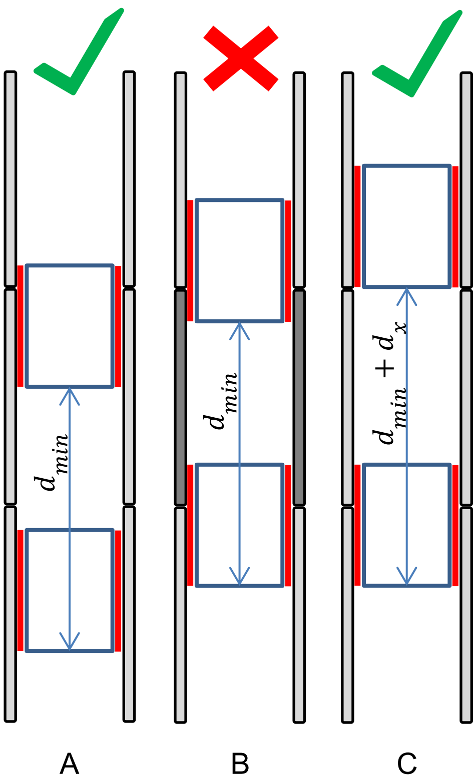


Figure 7-17: Linear motor segmentation

The additional distance is only necessary at special positions in the shaft. This needs to be considered for the safe position for another car ahead. The effect of the motor segmentation can be calculated.

The following calculations and equations are valid for up direction assuming that the cars position reference point is at the bottom/lowest point of the car and the magnet joke is mounted from the bottom to the top of the car.

In up direction, first the highest motor segment “touched” by the following car needs to be calculated. This is done by calculating the stopping point after a controlled deceleration ($D_{CIS}(t)$) added the car height (d_{ch}). The function “$MotorSegment(\dots)$” returns the base point of the highest “touched” motor segment. This base point is added to the motor segment height (d_m). This results in the base point of the allowed motor segment for the car above ($D_{AMSU}(t)$) as shown in equation (7-31). To ensure that the minimum distance (d_{min}) is not violated and only an allowed motor segment is used with equation (7-32) the (allowed) safe position considering the motor segmentation ($D_{SaPoM}(t)$) is calculated.

$$D_{AMSU}(t) = MotorSegment(D_{CIS}(t) + d_{ch}) + d_m \quad (7\text{-}31)$$

$$D_{SaPoM}(t) = \max\left(D_{CIS}(t) + d_{min}, D_{AMSU}(t)\right) \quad (7\text{-}32)$$

The effect of this additional distance to the safe position of a front car is shown in Figure 7-18. It shows the position over time of two cars ($D_{Car1}(t)$ and $D_{Car2}(t)$), the safe position of the leading car 1 ($D_{SaPo}(t)$) and the safe position affected by the motor segmentation $D_{SaPoM}(t)$. This needs to be considered especially if the minimum distance is needed between stops or floors.

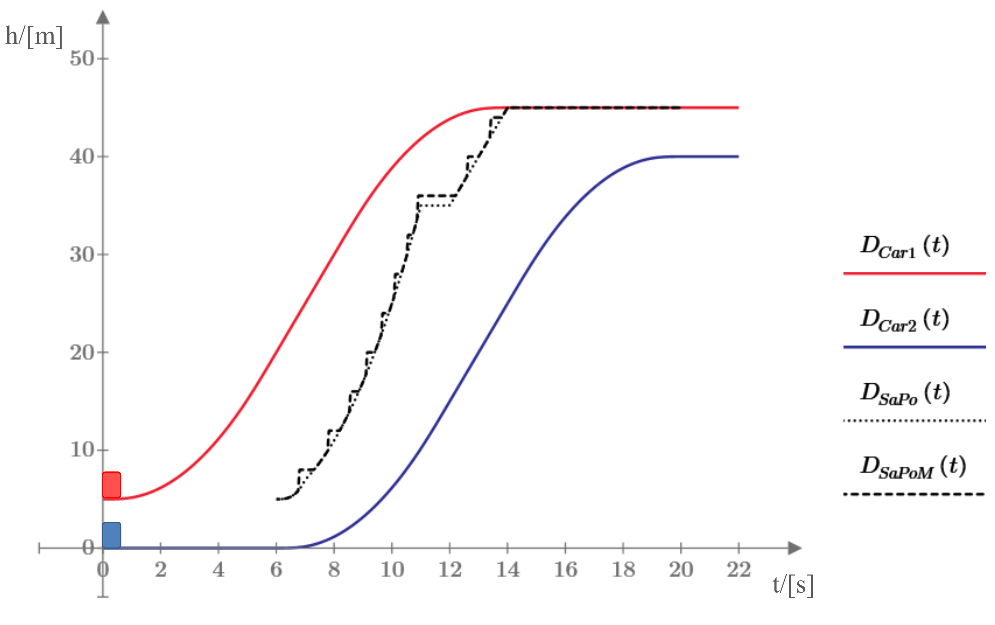


Figure 7-18: Modified safety distance due to motor segmentation

Stopping at landings/floors: In lift systems where a car only can or shall be stopped at landings, the stopping distance can be longer. For example, in up direction, the function "$NextFloor(..)$" of equation (7-33) calculates the stopping position at the next landing based on the ideal stopping position. This results in a modified safe position for the leading car $D_{SaPoF}(t)$ as shown in Figure 7-19 ($floor\ to\ floor\ distance\ = 5m$, $d_{min} = 5m$). This affects especially the required arrival time of the leading car and should be solved by an additional delay for the following car.

$$D_{SaPoF}(t) = \text{NextFloor}\big(D_{CIS}(t)\big) + d_{min} \tag{7-33}$$

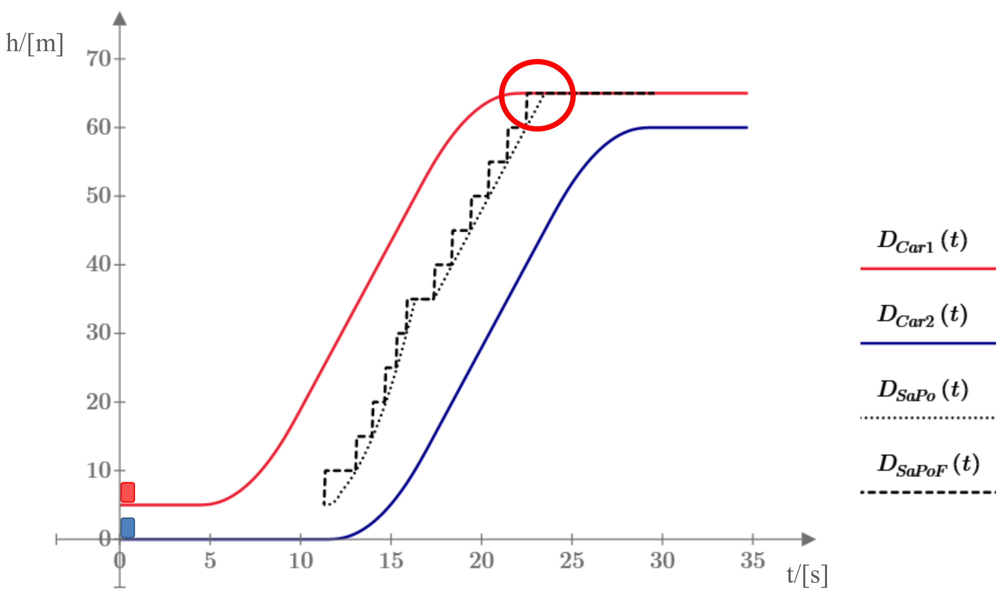


Figure 7-19: Modified safety distance due to floor segmentation

7.7 Summary

The minimum distance between two cars in a multi lift car environment includes an operational distance. The operational distance depends on the real stopping distance after an uncontrolled deceleration or stop triggered by a certified safety system. Equations to calculate the operational distance were derived based on the equations of the ideal lift kinematics and general quadratic equations of uncontrolled deceleration (valid for balanced rope lifts and unbalanced ropeless lift systems). The minimum distance is an important input parameter for control systems and relevant for minimum floor to floor distances.

Additionally, equations for an ideal controlled deceleration starting at any time of a lift journey were derived. This includes the equations of the ideal stopping distance of a controlled deceleration with equal or higher values than the normal journey.

The maximum possible values of a controlled deceleration depend on the configuration of the lift system propulsion system and human constraints of a comfortable deceleration. This can be different for up and down direction and for horizontal movement.

The equations of the controlled deceleration are used as input for optimising departure delays for the following cars moving with an unsymmetrical travelling curve (see chapter 8). The equations can also be used for horizontal passenger transportation systems when jerk values apply for passenger comfort or system constraints.

8 Ideal lift kinematics for multi car lift systems

List of symbols

v	Rated velocity [m/s] for normal operation (used as input for the equations) travelling up: $v > 0$, travelling down: $v < 0$
a_1	Rated acceleration [m/s²] for normal operation (used as input for the equations) travelling up: $a_1 > 0$, travelling down: $a_1 < 0$
a_2	Rated deceleration [m/s²] for normal operation (used as input for the equations) travelling up: $a_2 > 0$, travelling down: $a_2 < 0$
j_k	Rated jerk [m/s³] for normal operation (used as input for the equations) travelling up: $j_k > 0$, travelling down: $j_k < 0$ $k = [1..4]$ corresponds to the 4 different jerks of the travelling curve
d	Total distance [m] travelled for normal operation travelling up: $d > 0$, travelling down: $d < 0$
d_{accel}	Distance [m] travelled during acceleration (equation in the appendix)
d_{decel}	Distance [m] travelled during deceleration (equation in the appendix)
d_{min}	Minimum distance between cars [m]
v_{Max}	Maximum velocity [m/s] that can be reached during a trip (used to calculate velocity for case B)

$V_{Gtv}(t, spvg)$	Velocity at time t during normal operation $spvg$: travelling curve parameters for a trip
$A_{Gtv}(t, spvg)$	Acceleration at time t during normal operation $spvg$: travelling curve parameters for a trip
$J_{Gtv}(t, spvg)$	Jerk at time t during normal operation $spvg$: travelling curve parameters for a trip
$D_{Gtv}(t, spvg)$	Distance [m] travelled at time t during normal operation $spvg$: travelling curve parameters for a trip
$D_{SPparam}(t, spvg, a_{req}, j_{req}, 0)$	Stopping point [m] of a journey with travelling curve parameters ($spvg$) at time t. Controlled deceleration with a_{req} and j_{req}.
$D_{CIS}(t)$	Stopping point of a controlled deceleration [m]
$spvg_{Test}$	Travelling curve parameters for a trip
$spvg_{Front}$	Travelling curve parameters for a trip
$spvg_{AB}$	Travelling curve parameters for a trip
$V_{Gi}(t)$	Velocity at time t during normal operation period i
$A_{Gi}(t)$	Acceleration at time t during normal operation period i
$J_{Gi}(t)$	Jerk at time t during normal operation period i
$D_{Gi}(t)$	Distance [m] travelled at time t during normal operation in period i

t_{Gi}	Time [s] after start of a normal operation journey the period i is finished

Case study parameters:

$HC5_{Pair}$	Handling capacity [persons] per 5 minutes of a pair of cars in one shaft
P_t	Number of passengers transported during a roundtrip in one car
RTT_{Pair}	Round trip time [s] of a pair of cars (two independent cars in on shaft)
t_c	Door closing time [s]
t_{dwell}	Door dwell [s]. Time after door beam is released until door starts closing
$t_{FollowingCarDelay}$	The delay [s] a following car starts its journey after the front car has started its journey
t_o	Door opening time [s]
t_P	Transfer time of a passenger to enter or exit the cabin [s]
$t_{StandMin}$	Minimums standing time [s] including all passenger transfers (enter and exit the cabin) and all door times (opening, closing, dwell)
$t_{TravelFollow}$	Travel time [s] of the following car between the entrance floor and the sky lobby
$t_{TravelLead}$	Travel time [s] of the front car between the entrance floor and the sky lobby
$t_{\Delta PassengerDepartureDelay}$	Difference in passenger departure delay [s] experienced by passengers in a following car compared to a front car or compared to a start without traffic caused delay.

8.1 Introduction

8.1.1 General

The motion of lift cars and required safety distances in a multi car lift system (MCLS) defines the freedom with which lift cars can to travel within the same shaft. Mutual interaction between cars affects handling capacity (HC) and quality of service (QOS) for lift users. This chapter shows the effect on HC and QOS aspects if symmetrical travelling curves are used in a multi car lift application. Unsymmetrical travelling curves are derived for lifts without considering forces, masses, system delays and reaction times. Separate values for velocity, acceleration, deceleration and all four jerk values are used. The positive effects in HC and QOS of an unsymmetrical travelling curve in a MCLS are shown with a case study where a MCLS is used in a shuttle lift application. Required safety distances between cars as explored and calculated in chapter 7 are considered. Travelling curves are used and considered in dispatchers, traffic control algorithms, traffic simulation and traffic calculations.

8.1.2 Current situation

Symmetrical travelling curves as described in section 2.2.3 are also most likely to be used for lifts in MCLSs. Symmetrical travelling curves have the same absolute values for acceleration, deceleration and the same absolute values for all jerk rates. Group control algorithms (“call dispatcher” “system control” and “call control”) as described in section 2.2.2 consider the movement of lift cars. The motion command of the lift control uses the rated values for symmetrical travelling curve.

The logic of controlling a MCLS with two cars in one shaft considering a distance between cars was published as an extension of the estimated time to destination (ETD) lift dispatching algorithm (R. Smith and Peters, 2004). Cars are held back from departure if the following car may catch up the leading car. Cars are only allowed to start a trip with the rated symmetrical travelling curve if start permission is given by the system control based on safety distances. Other control and dispatching strategies for MCLS exist to avoid any collision of cars (Tanaka and Watanabe, 2009). These strategies only consider fixed configured speed profiles without any adaption of the parameters and the usage of unsymmetrical travelling curves.

Holding cars back from departure causes a delayed car departure that is experienced by passengers inside the cabin. This general delay is linked to departure delays and is confusing for lift passengers and reduces the QOS (see also section 3.4.3 and 5.1.6). It may also reduce HC. A delayed departure of a following car also delays the arrivals of travelling passengers. An example of two lift cars starting from adjacent floors going to adjacent floors is shown in Figure 8-1. It shows the position over time of two lift cars and a dotted line indicating the safe position for the leading car (see chapter 7) derived from the stopping point of a controlled deceleration of the following car added to a minimum distance between cars. The safe position of the leading car must never be crossed by the leading car position. A deceleration distance of the leading car is ignored to allow the following car to stop safely if the leading car stops instantaneously. The controlled deceleration of the following car uses a deceleration changed with a jerk. Rated values of the symmetric travelling curves are $v = 5m/s$, $a = 1m/s^2$, $j = 1m/s^3$. A delayed departure time for the following car of 6 s is necessary so that the dotted line of its safe position does not cross the leading car position. The distance between the leading car and its safe position ($D_{LS}(t)$) is shown in Figure 8-2. The critical time point with no distance between leading car position and its safe position is marked with a red circle. The following car arrives at its destination floor 6 seconds after the leading car arrives at its destination floor.

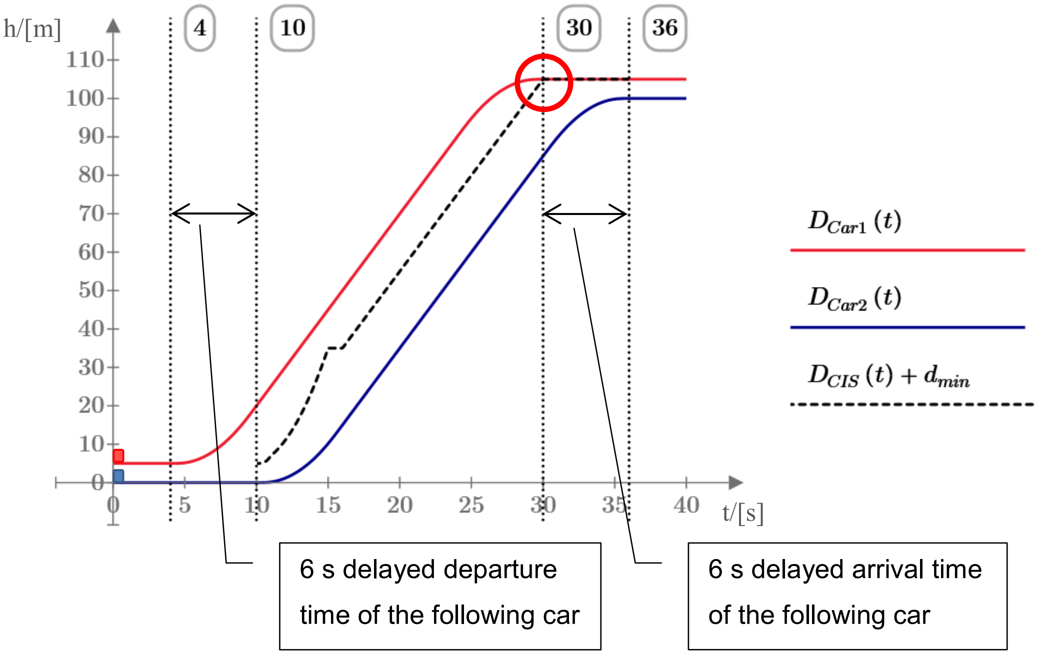


Figure 8-1: Position of two following cars over time (symmetrical travelling curve)

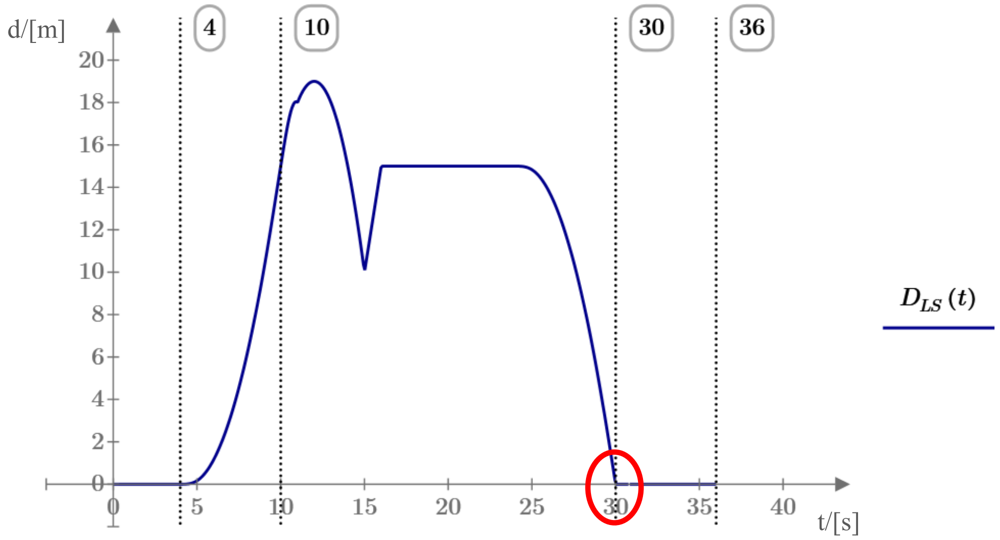


Figure 8-2: Distance between leading car and its safe position (symmetrical travelling curve)

8.1.3 Approach

An unsymmetrical travelling curve with individual jerk rates, acceleration and deceleration can shorten departure delays of following cars and optimise the arrival of a following car. This improves QOS in terms of reduced departure delays experienced by passengers and increased HC. Stopping distances and safety distances need to be considered. To use and consider travelling curves and travelling times in dispatchers, traffic control algorithms, traffic simulation and traffic calculations, calculation of unsymmetrical travelling curves is necessary.

The derivation of unsymmetrical travelling curves, their usage in lift dispatching, and effect on the QOS in the case of a shuttle application with two independent cars in one shaft is explored in this chapter. Mathematical software (PTC Inc., 2013) is used to derive equations and draw diagrams. System delays and reaction times are not considered.

8.2 Calculations unsymmetrical travelling curve

As with the symmetrical travelling curve (see section 2.2.3), the unsymmetrical travelling curve can be divided into the same 7 periods. Three different cases need to be considered:

- Case A: full velocity and full acceleration and deceleration is reached
- Case B: full acceleration and full deceleration is reached, but not full velocity reached
- Case C: full velocity not reached and full acceleration or full deceleration is not reached

If full velocity is reached but not full acceleration or full deceleration than the configuration does not makes sense (similar to the symmetrical travelling curve (Peters, 1996)) and an adaption of parameter is necessary (see section 8.2.3.1). An example of the unsymmetrical travelling curve is shown in Figure 8-3. Velocity ($V(t)$) [m/s], acceleration ($A(t)$) [m/s²] and jerk ($J(t)$) [m/s³] is shown over time.

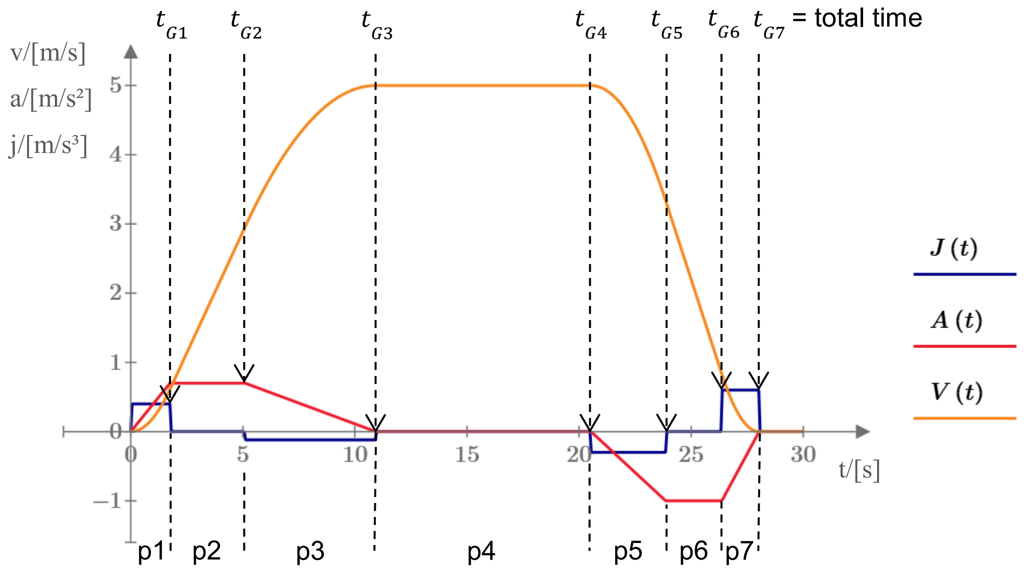


Figure 8-3: Seven periods (p1..p7) of the ideal unsymmetrical lift kinematics

8.2.1 Times

To calculate and derive equations for distance travelled, velocity, acceleration and jerk of the different periods the time points a period ends and a next period starts needs to be calculated (details can be found in the appendix).

Period 1 ends after the rated acceleration reached (see equation (8-1)).

$$t_{G1} = \frac{a_1}{j_1} \tag{8-1}$$

Period 2 ends when the acceleration needs to be reduced by jerk 2 (see equation (8-2)).

$$t_{G2} = \frac{v}{a_1} - \frac{a_1\,(j_1 - j_2)}{2\,j_1\,j_2} \tag{8-2}$$

Period 3 ends after the acceleration is reduced to 0 and the velocity of the trip is reached (see equation (8-3)).

$$t_{G3} = \frac{v}{a_1} + \frac{a_1\,(j_1 + j_2)}{2\,j_1\,j_2} \tag{8-3}$$

Period 4 ends when the increasing of the deceleration is started with the jerk 3 (see equation (8-4)).

$$t_{G4} = \frac{d}{v} + \frac{v}{2\,a_1} - \frac{v}{2\,a_2} + \frac{a_1}{2\,j_1} - \frac{a_2}{2\,j_3} - \frac{{a_1}^3}{24\,v\,{j_1}^2} + \frac{{a_1}^3}{24\,v\,{j_2}^2} + \frac{{a_2}^3}{24\,v\,{j_3}^2} - \frac{{a_2}^3}{24\,v\,{j_4}^2} \qquad (8\text{-}4)$$

Period 5 ends when the deceleration is fully reached (see equation (8-5)).

$$t_{G5} = t_{G4} + \frac{a_2}{j_3} \qquad (8\text{-}5)$$

Period 6 ends when the deceleration needs to be reduced by jerk 4 (see equation (8-6)).

$$t_{G6} = t_{G4} + \frac{v}{a_2} - \frac{a_2\,(j_3 - j_4)}{2\,j_3\,j_4} \qquad (8\text{-}6)$$

Period 7 ends when the lift car comes to a standstill after reducing the deceleration to 0. This equals the total traveling time of a trip (see equation (8-7)).

$$t_{G7} = t_{G4} + \frac{v}{a_2} + \frac{a_2\,(j_3 + j_4)}{2\,j_3\,j_4} \qquad (8\text{-}7)$$

8.2.2 General equations (Case A)

The equations for jerk, acceleration, velocity and distance travelled for the different periods (i) depending on time can be calculated with integration (definite integral). For simplicity, the results are not shown as they are very long and can be derived with mathematical software. How the equations can be generated are shown as general equations for periods $i = 1$ to $i = 7$.

The assumption for the equations is that rated values of acceleration, deceleration and velocity are reached during the trip.

Before the trip begins (period 0) jerk, acceleration, velocity and distance travelled are 0.

$J_{G0}(t) = 0; A_{G0}(t) \coloneqq 0;\ V_{G0}(t) \coloneqq 0;\ D_{G0}(t) \coloneqq 0$

Each of the periods has a specific jerk value.

$J_{G1}(t) = j_1;\ J_{G2}(t) = 0;\ J_{G3}(t) = -j_2;\ J_{G4}(t) = 0; J_{G5}(t) = -j_3;\ J_{G6}(t) = 0;\ J_{G7}(t) = j_4$

The acceleration of a period is the acceleration at the end of the previous period added to the integration of the jerk of this period (see equation (8-8)).

$$A_{Gi}(t) = A_{Gi-1}(t_{Gi-1}) + \int_{t_{Gi-1}}^{t} J_{Gi}(\tau)d\tau \qquad (8\text{-}8)$$

The velocity of a period is the velocity at the end of the previous period added to the integration of the acceleration of this period (see equation (8-9)).

$$V_{Gi}(t) = V_{Gi-1}(t_{Gi-1}) + \int_{t_{Gi-1}}^{t} A_{Gi}(\tau)d\tau \qquad (8\text{-}9)$$

The distance travelled of a period is the distance travelled at the end of the previous period added to the integration of the velocity of this period (see equation (8-10)).

$$D_{Gi}(t) = D_{Gi-1}(t_{Gi-1}) + \int_{t_{Gi-1}}^{t} V_{Gi}(\tau)d\tau \qquad (8\text{-}10)$$

8.2.3 Adapt rated values

The general equations are similar to case A of the symmetric travelling curve. The rated values of acceleration, deceleration and velocity are reached during a trip. If the rated values of acceleration, deceleration and velocity cannot be reached because the trip is too short, the input values to the equations are reduced.

8.2.3.1 Adaption of rated acceleration/deceleration

An illogical configuration would be for the rated velocity to be reached before the rated acceleration or deceleration is achieved. In this instance the acceleration and deceleration input values to the equations need to be adapted (reduced). In this case, period 2 (p2) of the travelling curve (Figure 8-3) is of zero duration ($t_{G1} = t_{G2}$).

If the following condition in equation (8-11) is true, the acceleration needs to be adapted.

$$v < \frac{{a_1}^2 (j_1 + j_2)}{2\, j_1\, j_2} \tag{8-11}$$

Equation (8-12) can be used to adapt the rated value of the acceleration.

$$a_1 = \sqrt{\frac{2\, v\, j_1\, j_2}{j_1 + j_2}} \tag{8-12}$$

The same equations can be used for deceleration with the following substitutions: $a_1 = a_2;\ j_1 = j_4;\ j_2 = j_3$

8.2.3.2 Condition of case A

The condition of case A is that the rated velocity can be reached. The minimum distance is the distance travelled during full acceleration and full deceleration. The following equation (8-13) needs to be true for case A.

$$d \geq d_{accel} + d_{accel}$$

yields in

$$d \geq \frac{v^2}{2\, a_1} + \frac{v^2}{2\, a_2} + \frac{{a_1}^3}{24\, {j_1}^2} - \frac{{a_1}^3}{24\, {j_2}^2} - \frac{{a_2}^3}{24\, {j_3}^2} + \frac{{a_2}^3}{24\, {j_4}^2} + \frac{v\, a_1}{2\, j_2} + \frac{v\, a_2}{2\, j_3} \tag{8-13}$$

8.2.3.3 Case B

For shorter travel distances the rated value of the velocity may not be reached (see condition of case A), while the rated value of acceleration and deceleration is reached. In this case t_{G3} and t_{G4} are at the same time. To use the general equations the rated value of the velocity needs to be adapted with the following equation (8-14).

$$v_{Max} = a_1\, a_2 \left(\sqrt{\frac{(j_2\, a_2 + j_3\, a_1)^2}{4\, {j_2}^2\, {j_3}^2 \cdot (a_1 + a_2)} + \frac{{a_1}^3\, {j_1}^2\, {j_3}^2\, {j_4}^2 - {a_1}^3\, {j_2}^2\, {j_3}^2\, {j_4}^2 - {a_2}^3\, {j_1}^2\, {j_2}^2\, {j_3}^2 + {a_2}^3\, {j_1}^2\, {j_2}^2\, {j_4}^2 + 24\, d\, {j_1}^2\, {j_2}^2\, {j_3}^2\, {j_4}^2}{12\, a_1\, a_2\, {j_1}^2\, {j_2}^2\, {j_3}^2\, {j_4}^2\, (a_1 + a_2)}} - \frac{a_2}{2\, j_3\, (a_1 + a_2)} - \frac{a_1}{2\, j_2\, (a_1 + a_2)} \right) \quad (8\text{-}14)$$

A diagram for the travelling curve for case B is shown in Figure 8-4:

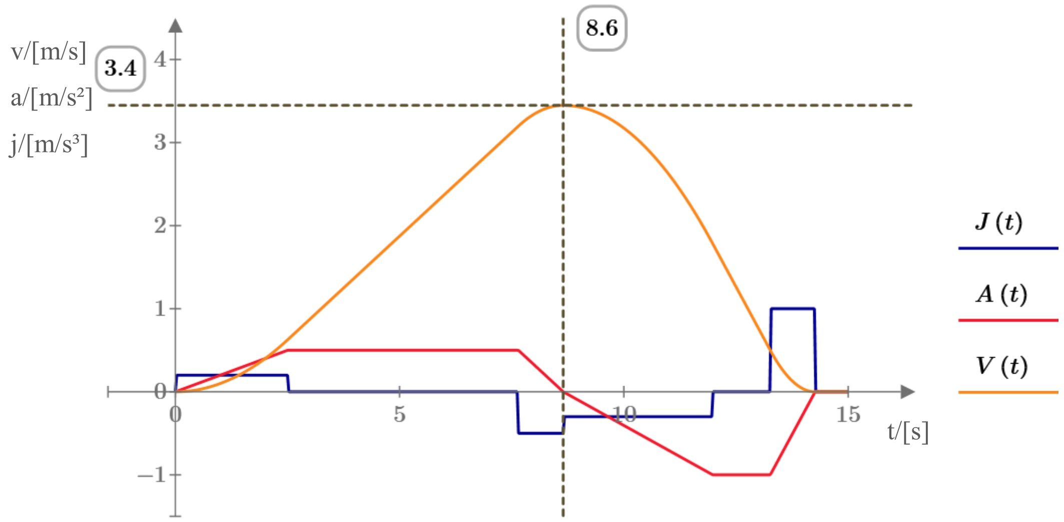


Figure 8-4: Unsymmetrical travelling curve case B

The condition for case B is that rated acceleration and deceleration can be reached. The minimum possible velocity for case B (equation (8-17)) is the higher velocity that is necessary to reach the rated acceleration (see equation (8-15)) or deceleration (see equation (8-16)).

$$v_{minAccel} = \frac{{a_1}^2\, (j_1 + j_2)}{2\, j_1\, j_2} \quad (8\text{-}15)$$

$$v_{minDecel} = \frac{{a_2}^2\, (j_3 + j_4)}{2\, j_3\, j_4} \quad (8\text{-}16)$$

$$v_{minCaseB} = if(v_{minAccel} > v_{minDecel}, v_{minAccel}, v_{minDecel}) \quad (8\text{-}17)$$

With the minimum possible velocity, the minimum distance can be calculated with equation (8-18) (see also equation (8-13) for case A).

$$Calc\_d_{minCaseB} = d_{accel} + d_{decel}$$

$$Calc\_d_{minCaseB} = \frac{{v_{minB}}^2}{2\,a_1} + \frac{{v_{minB}}^2}{2\,a_2} + \frac{{a_1}^3}{24\,{j_1}^2} - \frac{{a_1}^3}{24\,{j_2}^2} - \frac{{a_2}^3}{24\,{j_3}^2} + \frac{{a_2}^3}{24\,{j_4}^2} + \frac{v_{minB}\,a_1}{2\,j_2} + \frac{v_{minB}\,a_2}{2\,j_3} \quad (8\text{-}18)$$

8.2.3.4 Case C

For an unsymmetrical general travelling curve for case C, three subcases exist. For all subcases $t_{G3} = t_{G4}$, and rated value of the velocity is not reached.

- Rated acceleration not reached but rated deceleration is ($t_{G1} = t_{G2}$ → a_1 needs to be adapted)
- Rated deceleration not reached but rated acceleration is ($t_{G5} = t_{G6}$ → a_2 needs to be adapted)
- Rated acceleration and deceleration are both not reached ($t_{G1} = t_{G2}$ and $t_{G5} = t_{G6}$ → a_1 and a_2 needs to be adapted)

These cases are not considered in this chapter as the complexity of the solution does not justify the savings achieved through its implementation. In this case, a pragmatic approach would be to apply a symmetrical travelling curve.

8.3 Usage of the unsymmetrical travelling curve

For example, the usage of an unsymmetrical travelling curve with adapted values is shown in Figure 8-5. It shows the position of two cars over time each starting at adjacent floors and travelling to adjacent floors. The leading car is using rated values applying a symmetrical travelling curve.

Parameters for leading car are:

$$v = 5\,\frac{m}{s};\;\; a_1 = 1\,\frac{m}{s^2};\;\; a_2 = 1\,\frac{m}{s^2};\;\; j_1 = 1\,\frac{m}{s^3};\;\; j_2 = 1\,\frac{m}{s^3};\;\; j_3 = 1\,\frac{m}{s^3};\;\; j_4 = 1\,\frac{m}{s^3}$$

The following car uses adapted parameters with a lower acceleration and adapted jerk rates for j_1, j_2 and j_3. Velocity $V(t)$ [m/s], acceleration $A(t)$ [m/s²] and jerk $J(t)$ [m/s³] of the following car travelling curve over time are shown in Figure 8-6.

Parameters for following car are:

$$v = 5\frac{m}{s};\ a_1 = 0.66\frac{m}{s^2};\ a_2 = 1\frac{m}{s^2};\ j_1 = 0.22\frac{m}{s^3};\ j_2 = 0.055\frac{m}{s^3};\ j_3 = 0.17\frac{m}{s^3};\ j_4 = 1\frac{m}{s^3}$$

The dashed line in Figure 8-5 indicates the safe position of the leading car. It is derived from the controlled deceleration stopping point ($D_{CIS}(t)$) of the following car added to a minimum safety distance (d_{min}). The controlled deceleration is calculated with rated values higher than the speed profile parameters of the current trip of the following car.

The controlled deceleration parameters are:

$$a = 1\frac{m}{s^2};\ j = 1\frac{m}{s^3};$$

In Figure 8-5 it can be seen that the following car can start at the same time as the leading car as it is using the lower values for acceleration and jerk rates for j_1, j_2 and j_3 (see Figure 8-6). The distance between the leading car position and its safe position ($D_{LS}(t)$) is shown in Figure 8-7. The position of the leading car never violates its safe position.

If the distance between the starting floors or the destination floors of the two cars are increased or the start time of the following car is delayed the speed profile parameters can be adapted and higher values closer to the rated/maximum values can be used. In configurations where cars have different nominal velocities, the velocity of the following car may be reduced to the rated speed of the front car.

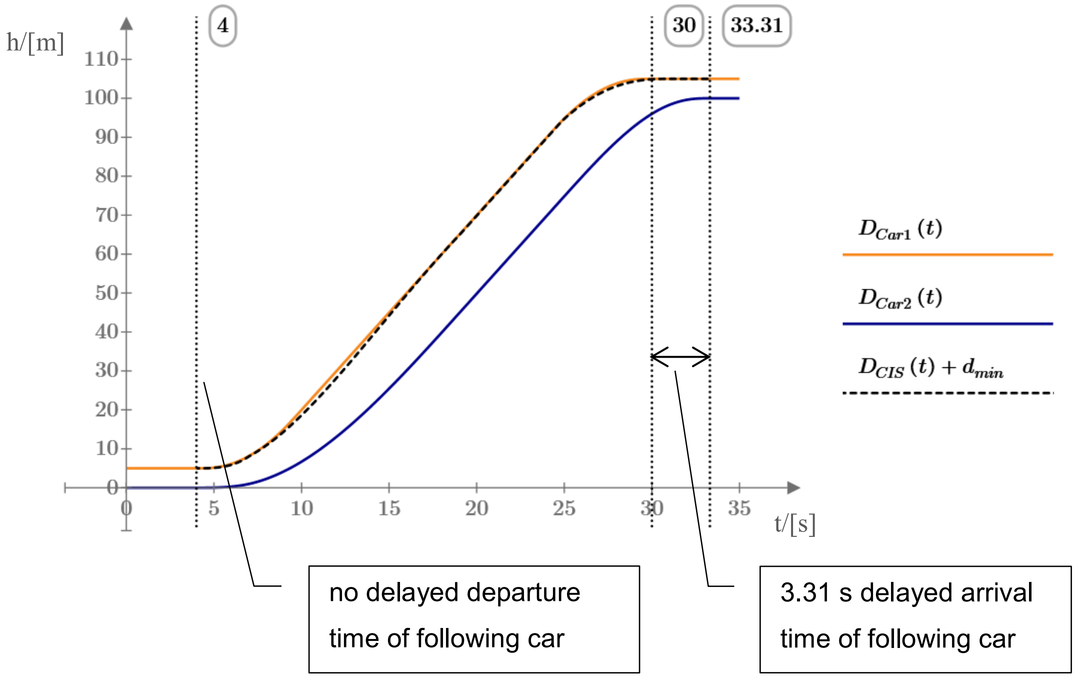


Figure 8-5: Position of two following cars over time (unsymmetrical travelling curve)

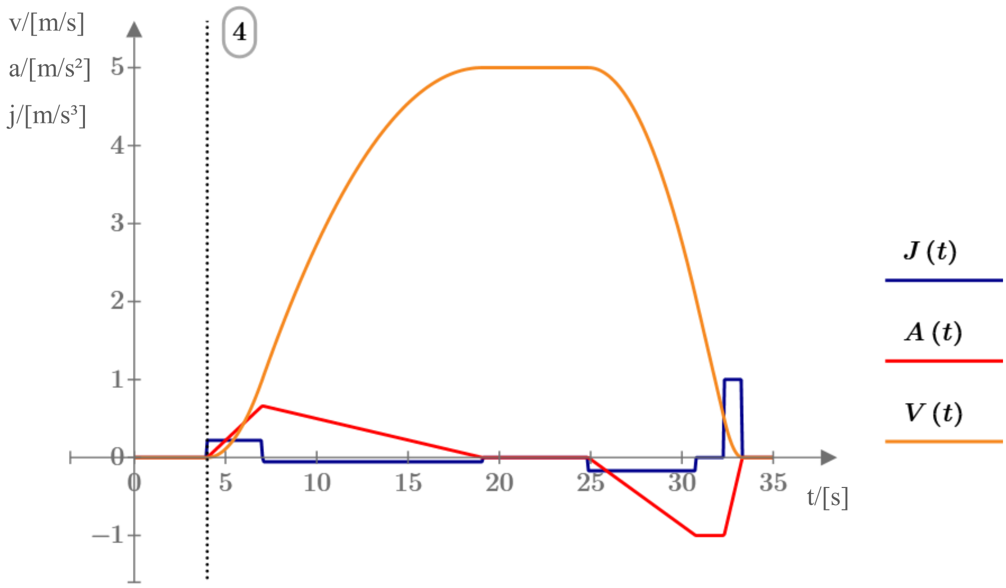


Figure 8-6: Velocity, acceleration and jerk profile of the following car (unsymmetrical)

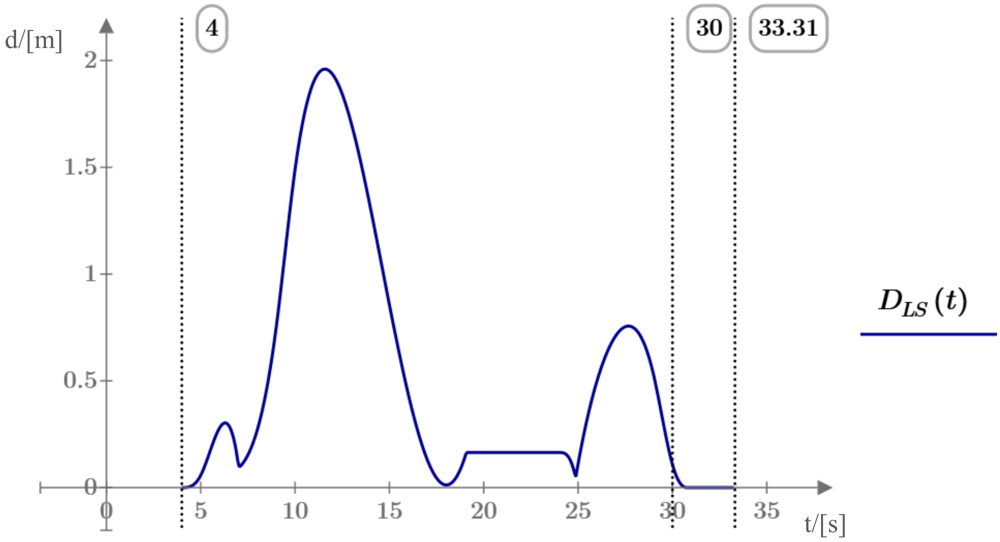


Figure 8-7: Distance between leading car and its safe position (unsymmetrical travelling curve)

The unsymmetrical travelling curve with adapted parameters needs to be considered as a part of the traffic control algorithms (see Figure 8-8). Speed profile parameters are selected in the motion command section. This is used by the system control. A start permission of a trip is combined with a specific selected speed profile to start earlier and to reduce times cars are held back from departure, minimising experienced departure delays for passengers. The dispatching algorithms need to consider adapted speed profiles and system control algorithms. Adapted speed profiles are a means of improving QOS and HC in MCLSs.

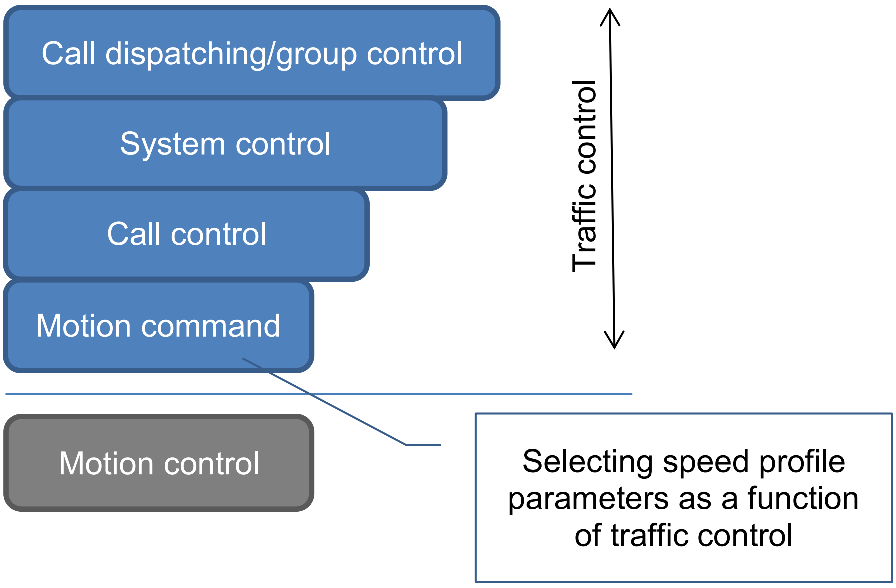


Figure 8-8: Traffic control including motion command

8.4 Case study

The effect of the unsymmetrical travelling curve on HC and QOS in a MCLS is shown in a case study using round trip time (RTT) calculations (CIBSE, 2015). Two independent cars in one shaft are used in a shuttle application serving two adjacent entrance floors and two adjacent sky lobbies. The traffic mix is 80% incoming and 20% outgoing, passengers equally distributed in both lobbies. This results in fully loaded cars in up direction and partially loaded cars in down direction. Results are compared with and without the application of an unsymmetrical travelling curve for the following car.

8.4.1 Configuration

The general configuration of the lift shaft is shown in Figure 8-9. The travelling height is 100 m.

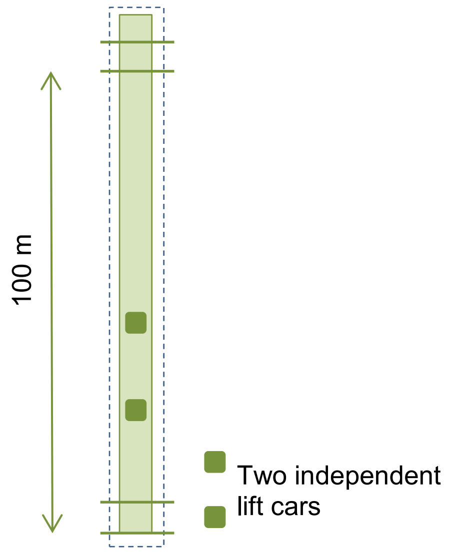


Figure 8-9: Shaft with two independent lift cars in one shaft

Rated values of the travelling curve are:

$v = 5\,m/s \qquad a_1 = a_2 = 1\,m/s^2 \qquad j_1 = j_2 = j_3 = j_4 = 1\,m/s^3$

This equals a symmetrical travelling curve.

A maximum of 16 passengers can load a car. With the given traffic mix there are 16 passengers in the car in up direction and 4 passengers are travelling in down direction. Per stop, 20 passengers are transferring in/out a car ($P_t = 20\,passengers$). Passengers transfer time is 1 second per passenger ($t_P = 1\,s$).

Door times are:

$t_o = 1.8\,s \qquad t_c = 2.1\,s \qquad t_{dwell} = 2\,s$

8.4.2 General calculations

Assuming both cars are transporting the same number of passengers and the passenger transfer time to enter and exit the car is the same for both cabins.

8.4.2.1 Handling capacity

The minimum standing time without any addition delays includes the door times (opening, closing, dwell) and passenger transfer times. The minimum standing time is equal for the main entrance floor and the sky lobby as the total number of passengers entering and exiting the car is that same. The minimum standing time can be calculated with equation (8-19).

$$t_{StandMin} = t_o + P_t\, t_p + t_{dwell} + t_c \qquad (8\text{-}19)$$

The RTT of a pair of cars (RTT_{Pair}) travelling independently in the same shaft includes the additional delay due to the following car starting its journey after the front car has started its journey ($t_{FollowingCarDelay}$), the minimum standing time of a car ($t_{StandMin}$) and the travel time of the cars represented by the travel time of the following car ($t_{TravelFollow}$). The following car is assumed to have a longer travel time than the leading car. It can be calculated for the example shuttle scenario with equation (8-20).

$$RTT_{Pair} = 2\,(t_{TravelFollow} + t_{FollowingCarDelay} + t_{StandMin}) \qquad (8\text{-}20)$$

Based on the known RTT calculation (CIBSE, 2015) the HC of the two cars in one shaft can be calculated with equation (8-21). P_t is the number of passengers transported per roundtrip in one car.

$$HC5_{Pair} = 2\,\frac{300s\, P_t}{RTT_{Pair}} \qquad (8\text{-}21)$$

8.4.2.2 Quality of service – additional departure delays

To assess QOS in MCLSs, departure delays needs to be considered. These additional traffic caused delays occur if the following car is not able to start its journey due to the other car (see “traffic caused delays” in section 5.3). This can confuse passengers. In the example shuttle scenario, the difference in passenger departure delays ($t_{\Delta PassengerDepartureDelay}$) can be calculated with equation (8-22). This is illustrated in Figure 8-11 and Figure 8-13 for both cases with the symmetrical and unsymmetrical travelling curve. The assumption is that $t_{StandMin}$ (see equation (8-19)) is equal for both cars.

$$t_{\Delta PassengerDepartureDelay} = t_{FollowingCarDelay} + t_{TravelFollow} - t_{TravelLead} \qquad (8\text{-}22)$$

8.4.3 Spatial plots comparison

The minimum standing time, including door times and passenger transfer, is $t_{StandMin} = 25.9\ s$. The journey time of a car with the rated values (symmetrical travelling curve) using equation (8-7) is $26\ s$.

8.4.3.1 Symmetrical travelling curve

In this case, both cars are using the symmetrical travelling curve with the rated values. Travelling times are $t_{TravelFront} = t_{TravelFollow} = 26\ s$. With consideration of the safety distance constraints the RTT of both cars is $RTT_{Pair} = 115.8\ s$. This is shown in Figure 8-10. Figure 8-11 shows the situation with standing times and any delays at each stop in detail. The following car has a delayed arrival. During that delay the leading car can start opening the doors and begin passenger transfer. The former following car (lower car) can starts its journey in the down direction after its minimum standing time. The former leading car (upper car) must wait for permission to start. Therefore, passengers who loaded the upper car early experience an additional delay before their car’s departure.

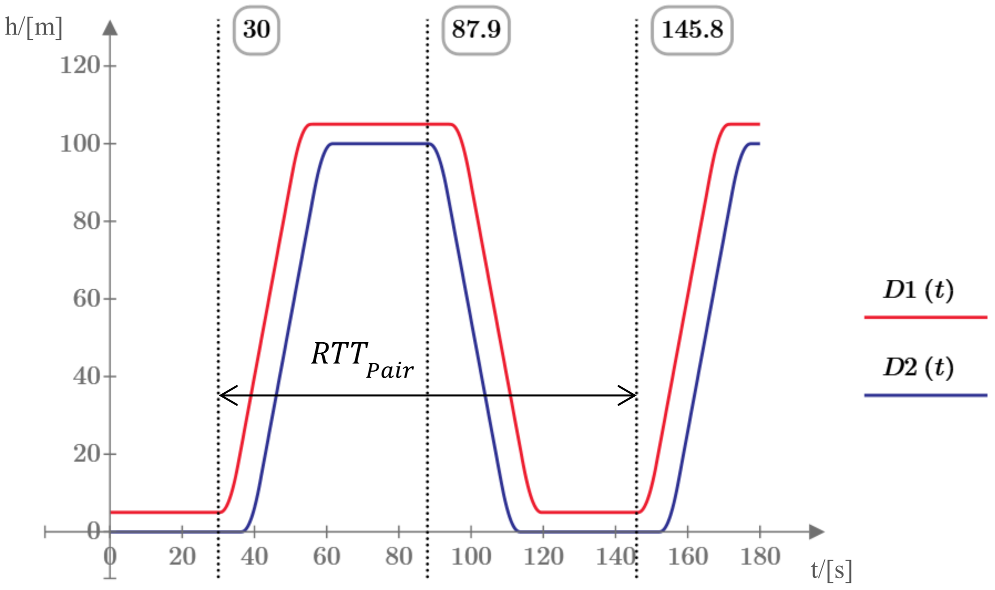


Figure 8-10: Round trip of two cars in the same shaft (symmetrical travelling curve)

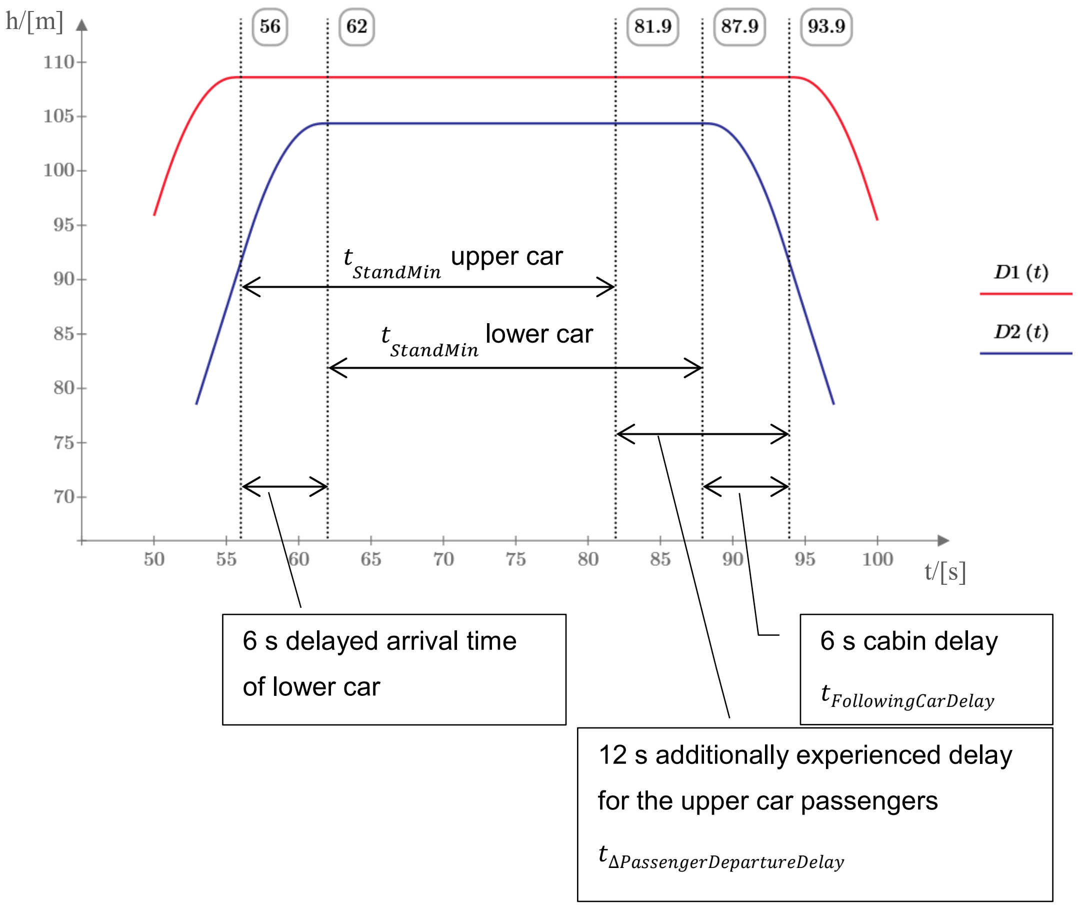


Figure 8-11: Standing time and departure times of two cars (symmetrical travelling curve)

8.4.3.2 Unsymmetrical travelling curve

In this case the leading car is using the symmetrical travelling curve with the rated values. Travelling time is $t_{TravelLead} = 26\ s$. The following car uses the unsymmetrical travelling curve with the adapted parameters:

$$v = 5\frac{m}{s};\ a_1 = 0.5\frac{m}{s^2};\ a_2 = 1\frac{m}{s^2};\ j_1 = 0.2\frac{m}{s^3};\ j_2 = 0.2\frac{m}{s^3};\ j_3 = 0.2\frac{m}{s^3};\ j_4 = 1\frac{m}{s^3}$$

The travelling time of the following car using equation (8-7) is $t_{TravelFollow} = 29.45\ s$. With consideration of the safety distance constraints the $RTT_{Pair} = 110.7\ s$. This is shown in Figure 8-12. Figure 8-13 shows the situation with standing times and any delays at each stop in detail. The following car has a shorter, but still delayed arrival. During that delay the leading car can start opening the doors and begin passenger transfer. The former following car (lower car) can starts its journey in the down direction after its minimum standing time. The former leading car (upper car) can start its journey at the same time. This means that passengers only experience the delay coming from the delayed arrival of the lower car.

The unsymmetrical travelling curve provides an improved RTT_{Pair} over the symmetrical travelling curve.

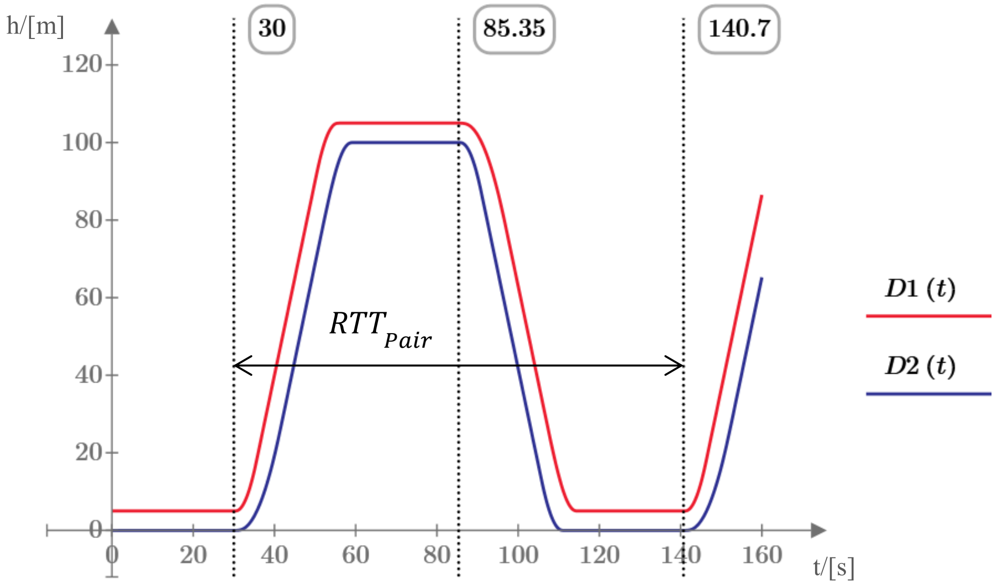


Figure 8-12: Roundtrip of two cars in the same shaft (unsymmetrical travelling curve)

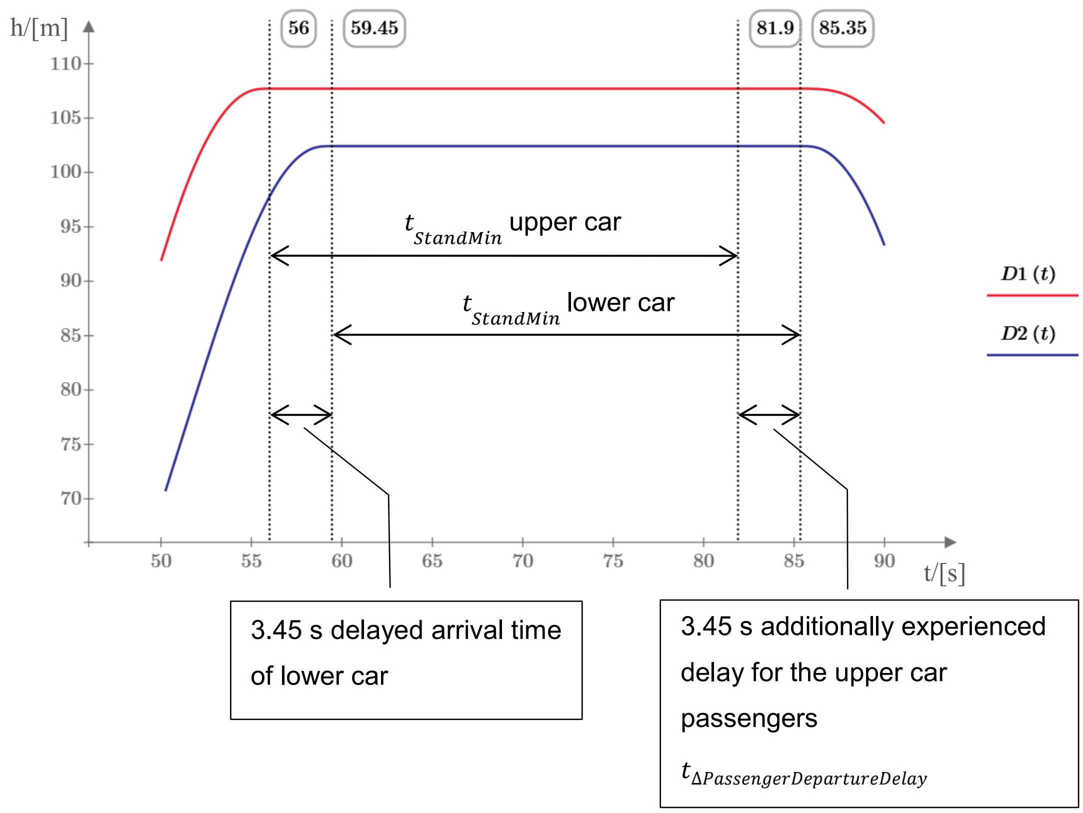


Figure 8-13: Standing time and departure times of two cars (unsymmetrical travelling curve)

8.4.3.3 Effect on handling capacity and quality of service

A comparison of both scenarios in Table 8-1 shows that there is a small benefit to HC with the unsymmetrical travelling curve. A more noticeable benefit is seen in QOS in a reduced additional passenger departure delay (traffic caused delay) experienced in the following car.

Table 8-1: Comparison of performance parameter

	Symmetrical travelling curve	**Unsymmetrical travelling curve**
Δ Passenger departure delay (following car)	12 s	3.45 s
Handling capacity in 5 minutes (HC5)	103.6 passengers	108.4 passengers

8.5 Summary

The unsymmetrical travelling curve has applications including where there are two independent cars in the same shaft, and for circulating ropeless MCLSs.

The application of unsymmetrical travelling curves considering controlled stopping distance constraints (see chapter 7) helps to reduce the additional traffic caused departure delays (see chapter 5) in a MCLS where cars are sharing the same shafts. Reduced departure delays of following cars also reduce the arrival time of the following car.

The selection of speed profile parameters needs to be a part of the MCLS traffic control (see chapter 12), modified and combined with start permissions of lift car trips and considered in assignments of dispatching algorithms.

The case study of a shuttle application shows that the unsymmetrical travelling curve has a significant effect on QOS though reduced departure delays, and increases HC.

Equations to derive the unsymmetrical travelling curve are provided. Cases where the rated parameters cannot be reached due to shorter travel distances were considered. In real applications system delays and reaction times also need to be considered.

9 Circulating multi car lift systems - characteristics

9.1 Introduction

The new generation of lifts currently under development applies magnetic linear propulsion and does not need ropes. Shafts are shared, and lifts move in two or more dimensions (see section 2.3). Lift cars can change shafts horizontally and therefore cars can circulate while shafts are used as one way tracks.

Engineers planning lift installations have new options and need new ways to assess the handling capacity (HC) and quality of service (QOS) provided by ropeless lifts. QOS aspects need to be considered in planning lift arrangements. Besides the technical challenges (linear propulsion system, light weight design, certified safety systems) system characteristics (opportunities and constraints) need to be understood and considered if traffic analysis and traffic control algorithms shall be developed. They are related to QOS and HC.

In this chapter options and constraint regarding QOS and HC are discussed.

9.2 Handling capacity

In the specified circulating multi car lift systems (MCLS) lift cars are sharing the same shafts, guiderails and are stopping at the same landings. Cars cannot bypass each other without changing shafts. Changing shafts to bypass another car would require additional stops and is time consuming. In a ropeless lift system with the possibility to change shafts horizontally it is obvious to operate these systems in a circulating manner like a paternoster (see section 2.3.2), at least during peak times. Shafts are used as one way tracks. This is illustrated in Figure 9-1.

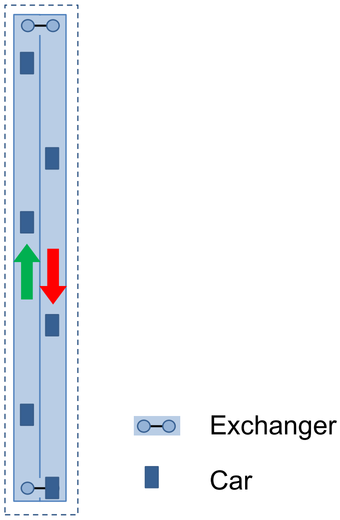


Figure 9-1: Circulating MCLS with one way tracks

In conventional lift groups the HC for incoming traffic depends on the average interval (see section 2.1.2), which is the average time between car departures from the main entrance floor. In a circulating MCLS with two shafts the circulating cars are using the same shaft in one direction and are using the same main entrance shaft door to serve the incoming traffic. For one circulating MCLS the HC for incoming traffic depends on the average time between two subsequent cars (cycle time) picking up passengers at the main entrance lobby from the same shaft door (see “cycle time” in section 10.2).

To achieve a minimum possible cycle time the critical factors are stops made by the cars and safety distance constraints (see chapter 7). For an express shuttle system all cars have the same stops. This is different if a MCLS is used as a local lift group. Due to different call allocations and individual car calls (passenger destination floors) cars using the same shaft will have different stops. To avoid departure delays and “traffic jams”, the time between two subsequent cars (cycle time) measured at the main entrance floor needs to be increased if cars have individual and unequal stops. This is illustrated in Figure 9-2. Car 1 ($D1(t)$) and car two ($D2(t)$) have the same stops. The cycle time (t_{Cy}) can be kept to a minimum. A following car needs to have a delayed departure (t_{CyD}) if a leading car has stops closer than its safe position defined by the following car next stop. Without an additional delay (t_{CyD}) safety distance rules would be violated. In Figure 9-2 car two

($D2(t)$) has two stops $S_2 1$ and $S_2 2$ that are closer to the safe position ($S3SP(t) + d_{min}$) defined by the next stop $S_3 1$ of car 3 ($D3(t)$). Each additional stop of the leading car requires a delay of the following car. An increased cycle time, used to avoid "traffic jams", results in lower HC compared to a shuttle application where all cars have the same stops.

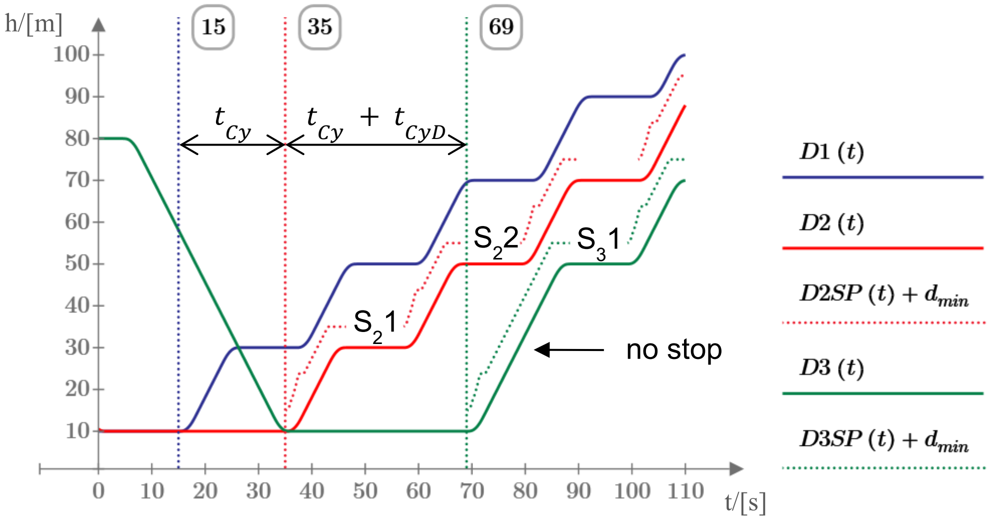


Figure 9-2: Delayed cycle time of subsequent cars

To avoid collisions and "traffic jams", this kind of graphical method in combination with Monte Carlo simulation was described by Al-Sharif et al. (Al-Sharif *et al.*, 2016). The Monte Carlos simulation is used to simulate the different stops of the cars.

9.3 Quality of service

In general, the QOS is associated with psychology aspects and the user experience of passengers when using lifts (see section 2.1.1). Traffic control algorithms need to consider QOS aspects. The "rules of call control" (see section 2.2.2) are a guideline for designing traffic control algorithms. Also traffic analysis is based on these rules. To emphasise the relevance of these accepted rules they are listed again:

1. Do not bypass a car call/destination of a passenger.
2. Do not transport passengers away from their destination.
3. Only stop at a floor because of a car call or landing call.

These rules apply to the car behaviour also in a circulating MCLS as they alleviate the negative psychological effects of reverse journeys and apparently unnecessary stops. For a circulating MCLS the rule 2 “Do not transport passengers away from their destination”, associated with reverse journeys, becomes less important if the cars in the system that are able to change shafts horizontally are circulating, and shafts are used only in one direction at a time.

For MCLSs these rules need to be extended to cover situations that occur if multiple cars are operated in the same shafts as mutual influence between cars occurs. These additional “rules of MCLS control” consider passengers’ perception and expectation of how lifts currently operate, taking into consideration the additional control system options.

4. Stops at a floor without a car call or landing call are allowed if the doors stay closed and no passenger is inside the car (an exception to rule 3).
5. Departure delays of cars with passengers inside the car shall be reduced to a minimum.
6. A cabin arriving at a landing and opening its doors for passenger transfer shall serve, in addition to its cabin car call, all landing (or destination) calls allocated to this landing door in the direction it is travelling.

Rule 4 gives controllers more flexibility, especially if a car ahead blocks the way for a following car. With the circulating MCLS described in this thesis it is necessary to stop at floors where exchangers are located in order to change direction of movement from vertical to horizontal.

The departure delays referred to in rule 5 can occur if loading times of cars are not equal, the number of stops is not equal, or if one car blocks the way of another (see also chapter 5). The control system can avoid such situations, although in special instances a departure delay could be the best choice. Departure delays are a concept that can be built into the controller. Communicating to passengers the reason for a departure delay can reduce passenger’s anxiety about their service. But even explained departure delays can be annoying for passengers.

Rule 6 is related to the allocating of calls to cabins/cars rather than to lift or cabin/car behaviour. This rule addresses the fact that in a MCLS a call allocation to a shaft door can be served by different cabins/cars. The next arriving car serves the calls allocated to the shaft door. This topic is highly related to user interface (see section 9.4), control types and algorithms (see section 9.5).

9.4 User interfaces

The user interface of lift groups depends on the control type. Conventional control (collective control, two button control) (Barney, 2003) and destination control (R. Smith and Peters, 2002) are widely applied. Their user interfaces have different components and setups.

Lift users differ from those of other transportation systems. At train/metro platforms serving multiple lines, it is common that not everyone will take the train to next depart. Some passengers wait for a following train as instructed by a departure board. Is the same scenario, breaking rule 6 of section 9.2, possible with lifts? If adopted, alternative means of indication would give the control system more options to improve HC and QOS. Instant allocations after destination call registration and late allocations (on arrival of the allocated car) may be considered. Lift lobby arrangements including their size needs to fit as well.

Figure 9-3 shows an example of two passengers allocated to the same shaft door (left illustration) but not to both passengers are allocated to the next arriving car (right illustration).

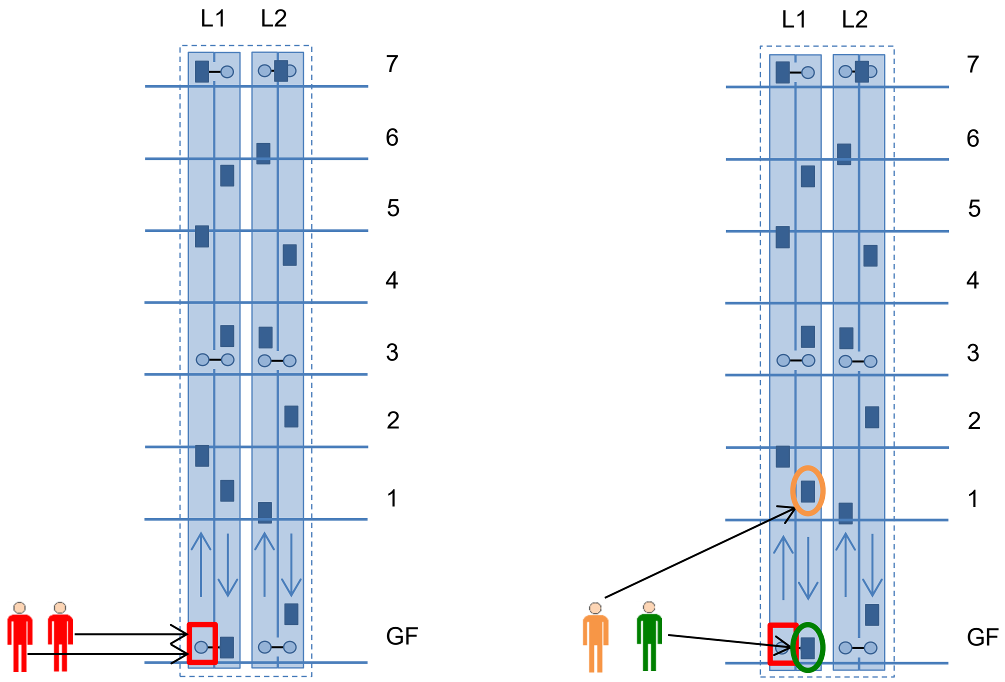


Figure 9-3: Allocation to the same shaft door but to different cars

Lift user interfaces need to be as simple as possible and support passenger expectation. Therefore, an allocation to the car after the next arriving car is not considered in this thesis. However, user interfaces are likely to evolve in the future as new technologies enable new passenger guidance systems for the wider transportation industry.

9.5 Lift control types

The control types (conventional control, destination control and mixed control) are linked to their user interfaces. The control systems and their user interfaces are widely applied. Both conventional and destination control can be an option for a circulating MCLS.

Conventional control: In conventional control systems a lift car can be called with an up or a down direction push button on each floor. The dispatchers allocate lifts from a lift group to answer the landing calls. The destination of the passenger is registered inside the car with car call buttons. The advantages of using conventional control with circulating MCLSs are that most people are familiar with the user interface, especially in public places. Passengers will fill the next arriving car in their travelling direction to a maximum that is culturally acceptable, and register car calls inside the car. Individual stops of the cars, particularly due to car calls, are not under control of the control system. So, to avoid “traffic jams”, times between subsequent cars need to be high. Longer cycle times reduce HC. However, if the number of passengers per car is low and the number of floors served is small, the probable number of different destinations and stops of cars is limited. Conventional control could be the preferred control system as it is easy to use for passengers with the disadvantage of higher cycle times and its effect on HC. If cycle times are too low, “traffic jams” are probable.

Destination control: Destination control systems allow passengers to register their destination on the floor. Passengers are allocated to lifts. The registration of a car call inside the car is not necessary as the system already knows where the passenger wants to go. The benefit of using destination control for circulating MCLSs is that the control system knows the destination stops before passengers enter the cars. The control of movement and synchronisation of cars using the same shafts can be optimised to reduce cycle time and increase HC. One of the main advantages of destination control is that passengers with the same destination are grouped and allocated to the same lift car. Passengers have less intermediate stops during travelling inside the car. If a lift group has two 2-shaft MCLS loops, the MCLS dispatcher has only the choice between two shafts. The “grouping” effect will be minimal. If in the future appropriate user interfaces (see section 9.4) meant that the MCLS dispatcher was not limited to allocating the next car in a shaft (breaking rule 6 of section 9.2), its options would increase.

Dynamic destination control: The benefit of current destination control systems is that they group passengers together to reduce the number of stops. Dynamic destination control would require passengers to register their destination, but then direct them to take the next lift travelling in their direction. Car call registration would not be required. The advantage to the MCLS dispatcher would be that it would not need to commit early to an allocation, and would have passenger destination information in advance to help it optimise the synchronisation of cars using the same shafts.

9.6 Horizontal passenger transportation

The described lift car guidance and propulsion system supports horizontal passenger transportation as well. Passenger safety issues also in case of emergency stops need to be considered. For horizontal passenger transportation, passenger comfort needs to be considered when defining jerk rates and acceleration/deceleration rates. In order that passengers are not falling over, supporting means like those used in trains and metros can help. This can be beside others slings hanging down from the ceiling, grab poles or standing aids. Horizontal transportation gives new opportunities in passenger transportation in buildings (So *et al.*, 2014) and metro stations. However, horizontal passenger transportation within the circulating MCLS is not considered in this thesis.

9.7 Lift arrangements and traffic concept

Current vertical transportation concepts divide building into zones. Multiple entrance floors and shuttle lifts with sky lobbies are used for passenger transfer to local lift groups to provide efficient lift arrangements for buildings (see section 2.1.5). Current roped lift systems are used as local lift groups to bring passengers to their desired destination floors, and these lift systems are used as shuttle lift groups to connect entrance floors with sky lobbies. Both applications (local and shuttle lift groups) in general are possible for a circulating MCLS and are considered in chapters 10 and 11. The system characteristics need to be considered. The ropeless lift system also enables other new lift arrangements, especially if horizontal passenger transportation is considered. These arrangements are out of scope for this thesis.

9.8 Summary

This chapter introduces characteristics of circulating MCLSs that result in opportunities and constraints for traffic control algorithms and traffic analysis. Individual stops of cars will affect the times between two subsequent cars (cycle time) and HC if “traffic jams” are to be avoided. It is important to consider passengers expectations and QOS criteria. Therefore, the “rules of call control” were expanded by the “rules of MCLS control”. This will also affect user interfaces and control types. The usage of a circulating MCLS should be as simple as possible. For the analysis in this research the usage of the MCLS was chosen to be as close as possible to the usage of existing lift systems. This applies to the analysis for a MCLS used as a shuttle lift system (see chapter 10) and for a MCLS used as a local group (see chapter 11). Horizontal passenger transportation, although possible, is not considered and existing user interfaces should be applied. This includes that passengers will not skip cars showing up at shaft doors to wait for the next car at the same shaft door. Departure delays as explained and defined in chapter 5 should be kept to a minimum. The focus in the following chapters is on known traffic concepts with shuttle (express) lift groups (see chapter 10) and local lifts groups (see chapter 11).

10 MCLS as shuttle lift system

List of symbols

INT	Interval between two cars departure from the main floor [s]
N_C	Number of cars in a MCLS
N_S	Number of MCLSs
P	Number of passengers in a car
t_{Arr}	Arrival time of a car at a landing after a previous car departure [s]
t_c	Door closing time (before a car depart a landing) [s]
t_{Cy}	Minimum possible cycle time in a MCLS loop [s]
t_{CyEx}	Minimum cycle time at an exchanger landing [s]
t_{CyF2}	Minimum cycle time at an intermediate stop where two subsequent cars are stopping [s]
t_{CyR}	Real cycle time of a MCLS loop [s]
t_{Dep}	Departure time of a car from a landing before a following car can arrive [s]
t_{dwell}	Door dwell after passenger detection clearance and before doors start closing [s]
t_{Ex}	Exchanger preparation time for 90° rotated movement [s]
t_o	Door opening time (after car has arrived at a landing) [s]
t_p	Transfer time of a passenger to enter of exit the cabin [s]
t_{s2s}	Time between a first car depart for a floor until the subsequent car can stop at the floor [s]

t_{Stand} Standing time of a car at a landing [s]

$UPPHC$ Up peak handling capacity [passengers per 5 minutes]

10.1 Introduction

A circulating ropeless multi car lift systems (MCLS) eliminates limits and disadvantages of traditional roped shuttle lifts and enables more flexible arrangements. In this chapter, possible express shuttle lift arrangements for MCLSs are considered as well as traffic design principles being established by applying cycle time calculations. For example, shuttle lift applications are considered and compared with current roped shuttle solutions.

10.1.1 Single entrance

Similar to roped shuttle lifts, there are different options for simplified traffic concepts, including a circulating MCLS such as a shuttle with a single entrance floor (see Figure 10-1). Different MCLS loops can be assigned to different zones in the building (S1). A MCLS loop can serve one or multiple sky lobbies, thus it can be assigned to multiple building zones (S2). Multiple MCLS loops can be combined to a group serving the same zone(s)/sky lobbies in the building (S2).

Local lift groups can be stacked as single car groups (L2) or groups of two independent cars in a single shaft having distributed lobbies for the lower and the upper cars (L1). This enables direct inter-zone traffic.

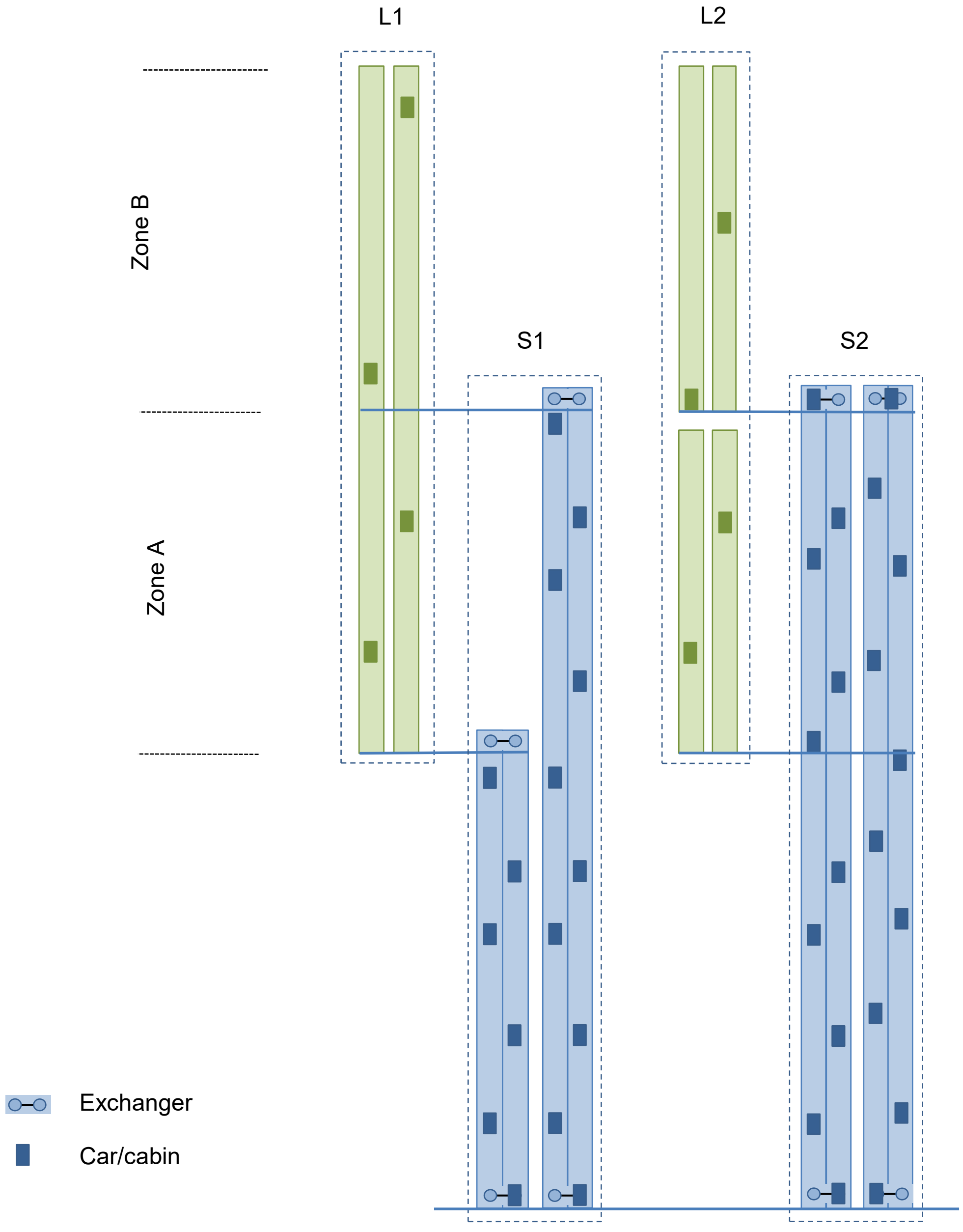


Figure 10-1: Options of simplified lift arrangements, including a circulating MCLS as a shuttle with a single entrance floor

10.1.2 Double entrance

There are different options of lift arrangements, including a circulating MLCS such as a shuttle with a double entrance floor (see Figure 10-2). There are two options for the sky lobby arrangement. A double sky lobby (S3), equivalent to concepts applied with double deck lifts, and a pair of distributed sky lobbies (S4). The latter has an advantage as cars are independent from each other.

In case of a double entrance floor arrangement, each entrance floor and the two highest sky lobbies will be equipped with an exchanger unit. This requires an exchanger unit somewhere in the middle of the shafts. Similar to a single entrance floor configuration, different MCLS loops can be assigned to different and multiple zones in the building. This means a MCLS loop can serve multiple double sky lobbies (S5) or multiple pairs of distributed sky lobbies, similar to solution (S2).

Local lift group options for pairs of distributed sky lobbies are similar to the single entrance floor arrangement. Additional options for local groups are possible with a double sky lobby. Similar to local groups in double decker shuttle concepts, a double deck or two independent cars in one shaft can be used as a local group (L3).

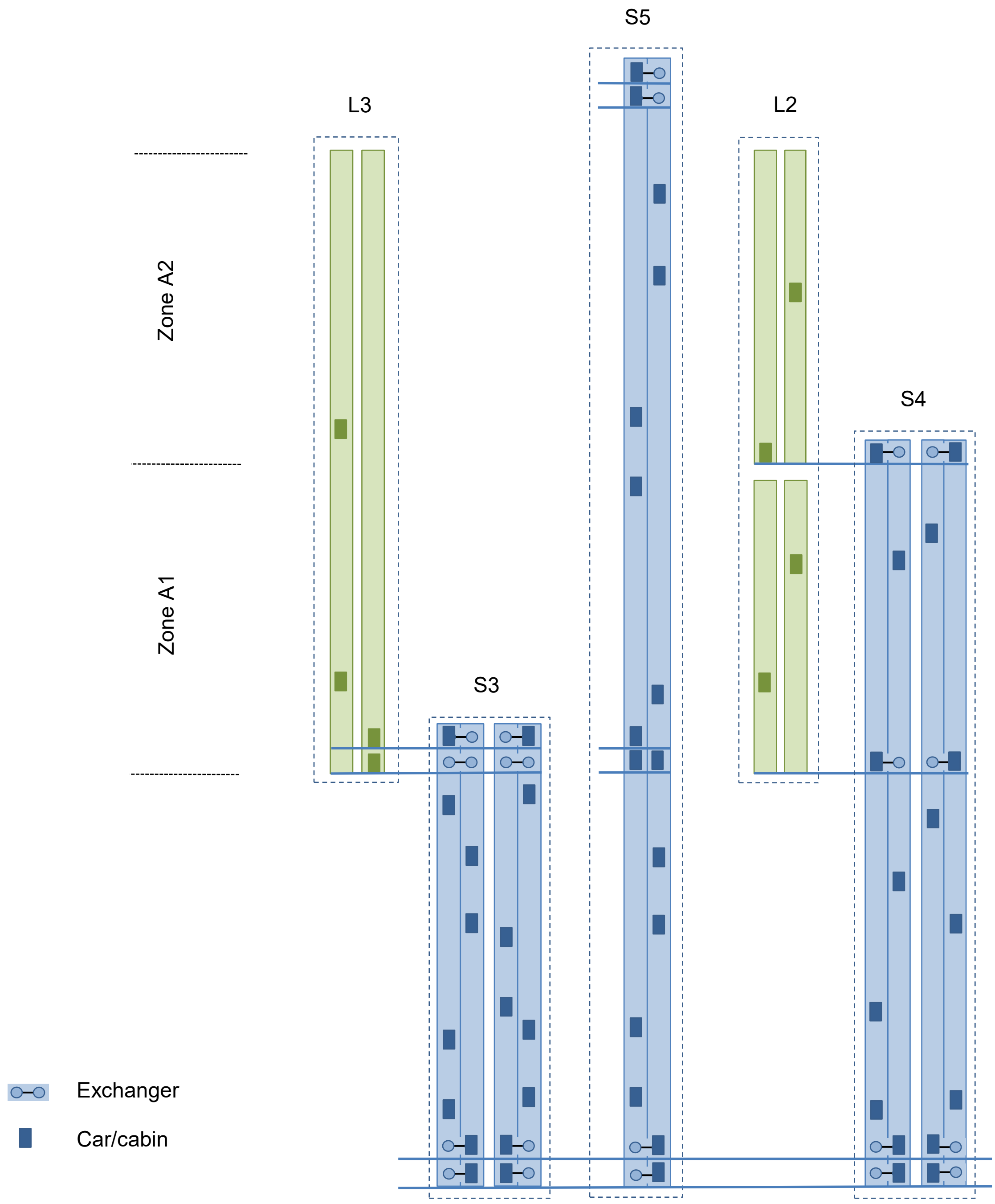


Figure 10-2: Options of simplified lift arrangements including a circulating MCLS as a shuttle with a double entrance floor

Spatial plots of one pair of cars show how a pair of cars move within the shafts. Travel in the up direction is in a different shaft than the down direction. Figure 10-3 show the spatial plot of a pair of cars, $D1a(t)$ and $D1b(t)$, in a circulating MCLS with a pair of distributed sky lobbies like the arrangement in (S4).

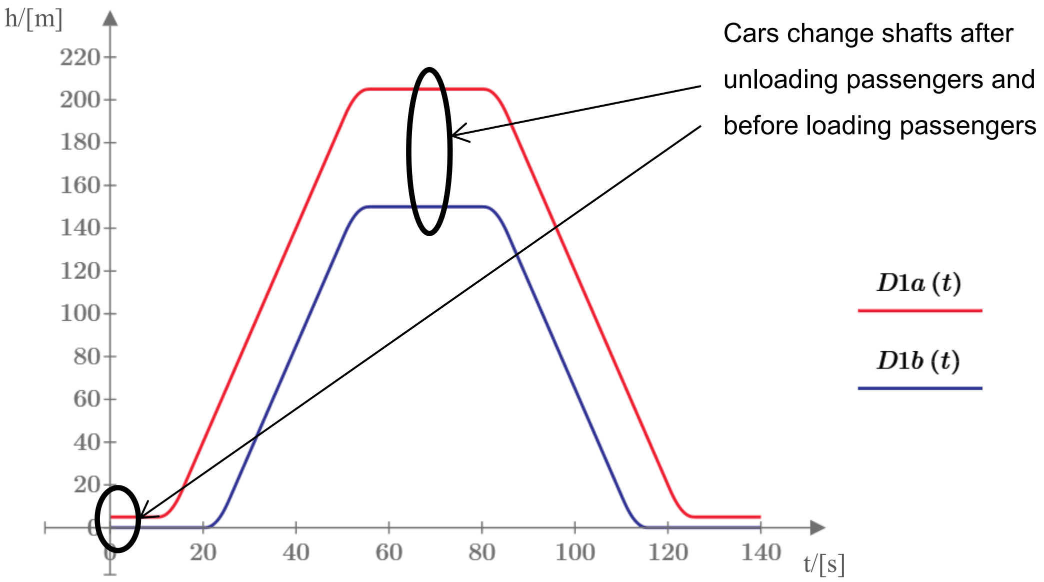


Figure 10-3: Spatial plot of two cars with a pair of distributed sky lobbies

Figure 10-4 shows the spatial plot of a pair of cars, $D1a(t)$ and $D1b(t)$, in a circulating MCLS. It has two pairs of distributed sky lobbies, similar to the arrangement in (S5), which has two double sky lobbies. A multi car loop can be assigned different zones with different pairs of distributed sky lobbies.

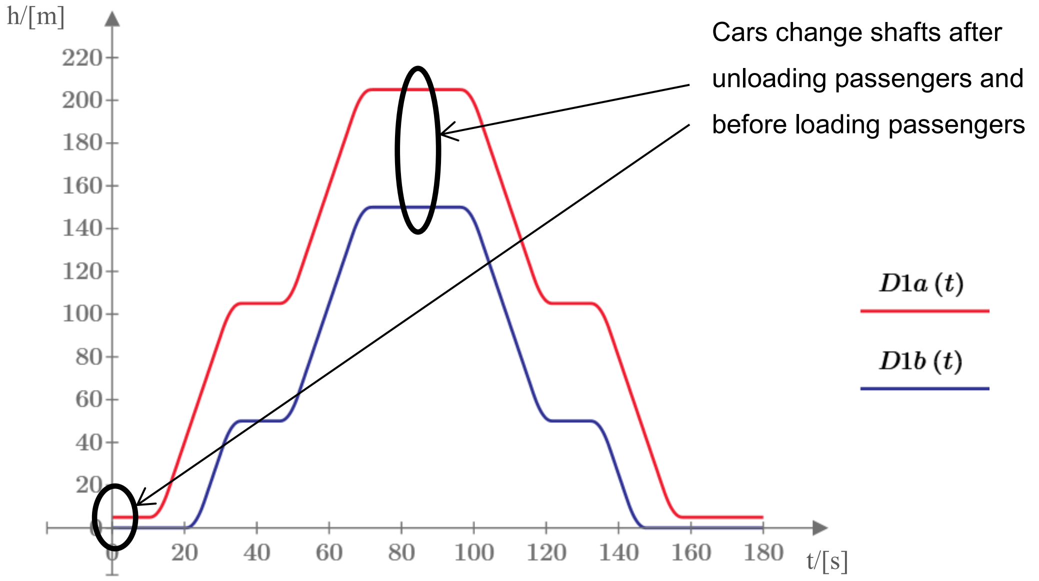


Figure 10-4: Spatial plot of two cars with two pairs of distributed sky lobbies

The arrangement of vertical transportation for vertical cities can be compared with horizontal transportation. The shuttle lifts are like little intercity trains connecting the main stations – the sky lobbies. The local lift groups are like the local transportation with a bus or underground metro. The circulating inter-lobby lift system enables flexible arrangements in vertical transportation concepts. It is not limited to the examples and options shown, and is not limited in height.

10.2 Minimum possible cycle time

The number of passengers arriving at a specific lobby that can be transported by the MCLS within a specific time can be calculated by the number of departing full cars. The shortest time between two subsequent cars is the minimum possible cycle time.

10.2.1 Cycle time

The cycle time in a MCLS is the time between the departures or arrivals of two subsequent cars. It can also be defined as the time between two subsequent cars passing a specific position in the shaft travelling at the same speed and in the same direction.

Figure 10-5 shows the vertical positions over time of two subsequent cars $D_{VCar1}(t)$ and $D_{VCar2}(t)$. Both cars are travelling in the up direction in the first shaft, both change shafts at the top floor at 100m and travel in the down direction in a second shaft. While car 1 has already changed to the down direction shaft, car 2 is arriving at 100m in the up direction shaft. At the bottom floor the cars are changing shafts again. Both cars are stopping in each direction at an intermediate floor at the 50m level. The time between car 1 and car 2 is the cycle time. For a better overview the position of additional cars travelling in the MCLS is not shown. As the minimum possible cycle time is limited by the minimum distance during a complete round trip of the cars, critical situations need to be considered in detail. It is obvious that only one car can be at a specific position at the same time. If cars are travelling they are changing position continuously and make the position available for the next car. If cars are standing, only one car can be at that position for the time the car is located at that position. To find the minimum possible cycle time over a complete round trip the stops of the cars need to be analysed in detail. To define the minimum possible cycle time between cars in a MCLS, safety distance constraints need to be considered. There must be minimum distance between cars at any time during normal operation (see chapter 7).

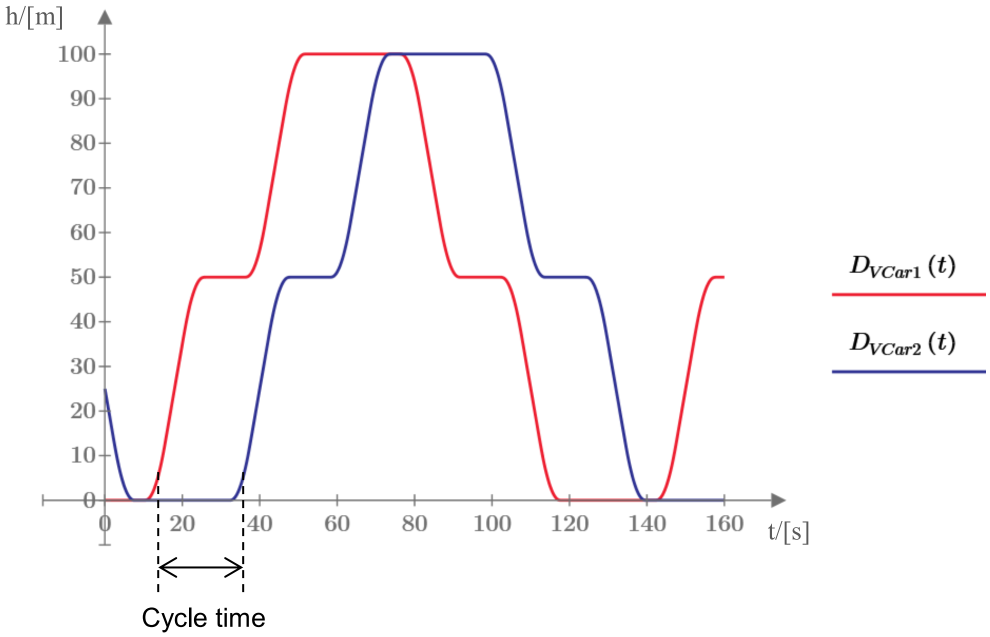


Figure 10-5: Vertical position of two subsequent cars

10.2.2 Calculation of the minimum possible cycle time

As the minimum possible cycle time (t_{Cy}) is when cars are stopping, these are the situations analysed. This includes stops at the exchanger units and intermediate stops where both cars stop successively.

Cycle time at an exchanger landing: The minimum cycle time at an exchanger landing (t_{CyEx}) with passengers loading and unloading can be calculated with equation (10-1). The passenger transfer during the standing time (t_{Stand}) of the car can be done in parallel to the exchanger preparation time t_{Ex} (rotation of the shaft element) for the following horizontal or vertical movement.

$$t_{CyEx} = t_{Arr} + \max(t_{Stand}, t_{Ex}) + t_{Dep} + t_{Ex} \tag{10-1}$$

After the leading car has departed from the exchanger unit (t_{Dep}) the following car arrival time (t_{Arr}) is the time that it takes a car to arrive after the time the exchanger unit has been prepared for the next car (t_{Ex}). A long car arrival time (t_{Arr}) for the following car may enable the parallel preparation of the exchanger after the leading car has departed the exchanger landing.

The standing time (t_{Stand}) is calculated with equation (10-2) and includes passenger transfer times (t_p), average number of passengers in the car (P) and door times (door open time: t_o, door dwell: t_{dwell}, door closing time: t_c).

$$t_{Stand} = t_o + P\ t_p + t_{dwell} + t_c \qquad (10\text{-}2)$$

Cycle time at an intermediate floor (both stopping): The minimum cycle time at an intermediate floor with two subsequent cars stopping at the same floor (t_{CyF2}) can be calculated with equation (10-3). The time between departure of the leading car 1 and the arrival of the following car 2 (start to stop time t_{s2s}) depends on stopping distances and minimum distances between cars, shown in Figure 10-6. The safe position for car 1 in relation to car 2 is shown with $D_{2SfP}(t)$ and depends on the position, the stopping point of a controlled deceleration with rated values of car 2, and an additional minimum distance between car 2 and car 1. The safe position must not touch the position of car 1.

$$t_{CyF2} = t_{Stand} + t_{s2s} \qquad (10\text{-}3)$$

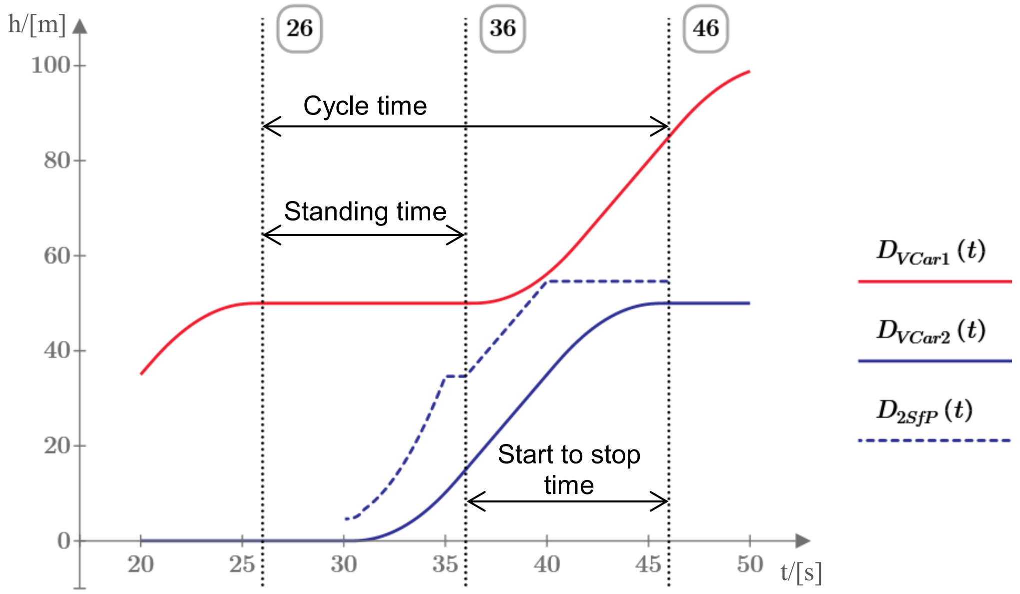


Figure 10-6: Cycle time at an intermediate floor

The situation with the longest minimum cycle time is the minimum possible cycle time of the MCLS and is defined with equation (10-4).

$$t_{Cy} = \max(t_{CyEx}, t_{CyF2}) \tag{10-4}$$

10.3 Number of cars

The number of cars (N_C) in a circulating MCLS depends on the round trip time (RTT) and the cycle time (t_{Cy}). It can be calculated with equation (10-5).

$$N_C = \frac{RTT}{t_{Cy}} \tag{10-5}$$

This is illustrated with Figure 10-7. It shows a complete round trip of a car ($D1(t)$). The RTT is divided by the cycle time and shows every position of the car after a period of the cycle time. These positions equal the current position of the other cars in the MCLS at time $t = 0$ which is shown with the two shafts of a MCLS in Figure 10-7. With double entrance configurations and pairs of cars the number of cars is doubled.

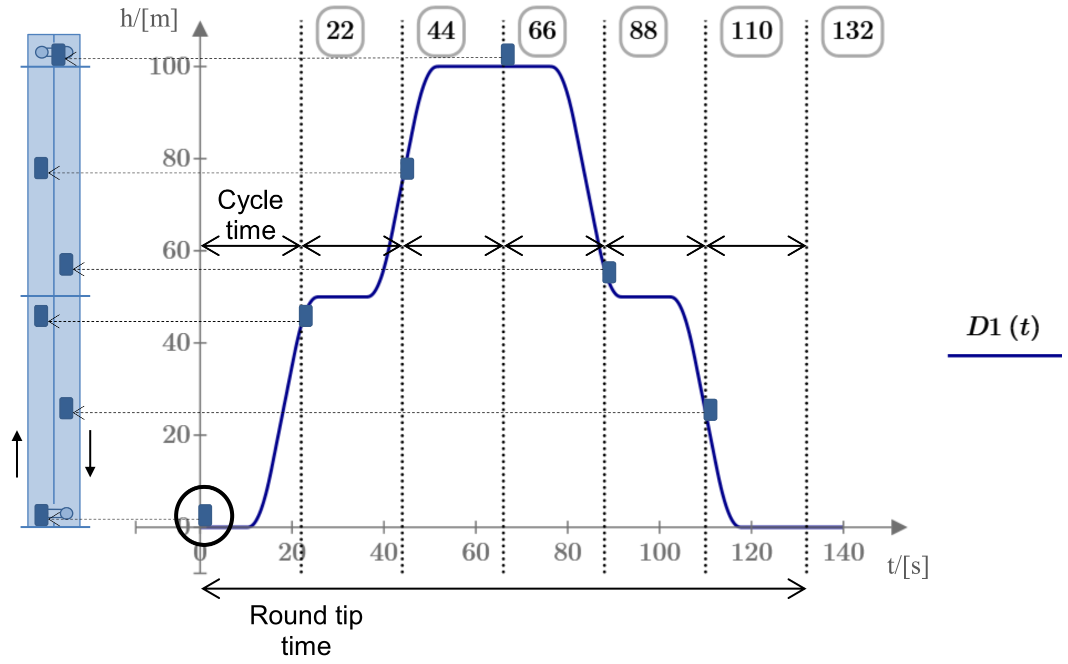


Figure 10-7: Cycle time, RTT and number of cars

It is only possible to put an integer number of cars into the system. In case of an unchanged RTT and rounding down the number of cars/the result of equation (10-5) the real average cycle time (t_{CyR}) will be higher than the minimum possible cycle time (see equation (10-6)). To achieve the same handling capacity (HC) the RTT needs to be reduced e.g. by increasing the speed of the cars.

$$t_{CyR} = \frac{RTT}{N_C} \tag{10-6}$$

In case of rounding up the number of cars/the result of equation (10-5) the average minimum possible cycle time cannot be reduced because it is limited to a minimum. The RTT needs to be increased according to equation (10-7) to avoid “traffic jams” e.g. by reducing the speed of the cars.

$$RTT = N_C\, t_{Cy} \tag{10-7}$$

10.4 Handling capacity for shuttle arrangements

To use a circulating MCLS in a vertical traffic concept, it is necessary to know the HC in 5 minutes (HC5). As the lift system is different in comparison to traditional lift systems, the known equations need to be adapted to the new system.

10.4.1 General

The HC for incoming passengers ($UPPHC$) can be calculated with the simple equation for conventional lifts using the interval (INT) and number of passengers per car (P) (see equation (10-8)) (CIBSE, 2010). This is also true for a circulating MCLS.

$$UPPHC = \frac{300s}{INT} P \tag{10-8}$$

The interval of a group of circulating MCLSs is defined by the average cycle time (t_{Cy}) and the number of MCLSs (N_S) (see equation (10-9)).

$$INT = \frac{t_{Cy}}{N_S} \tag{10-9}$$

The HC for incoming passengers served in an up direction shaft is independent from any down traffic or traffic between upper floors (e.g. sky lobbies). Additional down traffic will affect the RTT of a car because of passenger transfer times and door times of existing or additional stops. If the RTT of the cars changes then the number of cars or the speed of the cars need to be adapted accordingly in order to keep the average cycle time between subsequent cars to a constant value.

10.4.2 Cabin size

Increasing the cabin size of a car will increase the HC especially in shuttle applications. However, in shuttle applications the HC5 is not a linear function of the cabin size. Doubling the cabin size does not double the HC as passenger transfer times and cycle times increase.

10.4.3 Double entrance

As HC is limited by the passenger loading and unloading time, double entrance lobbies (two lobbies above each other) enable simultaneous loading of two cabins which increases the HC. For a circulating MCLS each entrance level may have an exchanger unit enabling a parallel exchanging of two cars (see Figure 10-2 – S3). The cycle time is now measured between two pairs of cars (see Figure 10-8), therefore, double the number of passengers can be transported per cycle time. The cycle time will increase slightly since the arrival time and the departure time of two cars at a double lobby/floor is longer compared to a single car stopping at a single floor. A parallel loading of multiple cabins in a horizontal arrangement is another option that could increase HC. This would require horizontal passenger transportation what is not considered in this research (see section 9.6).

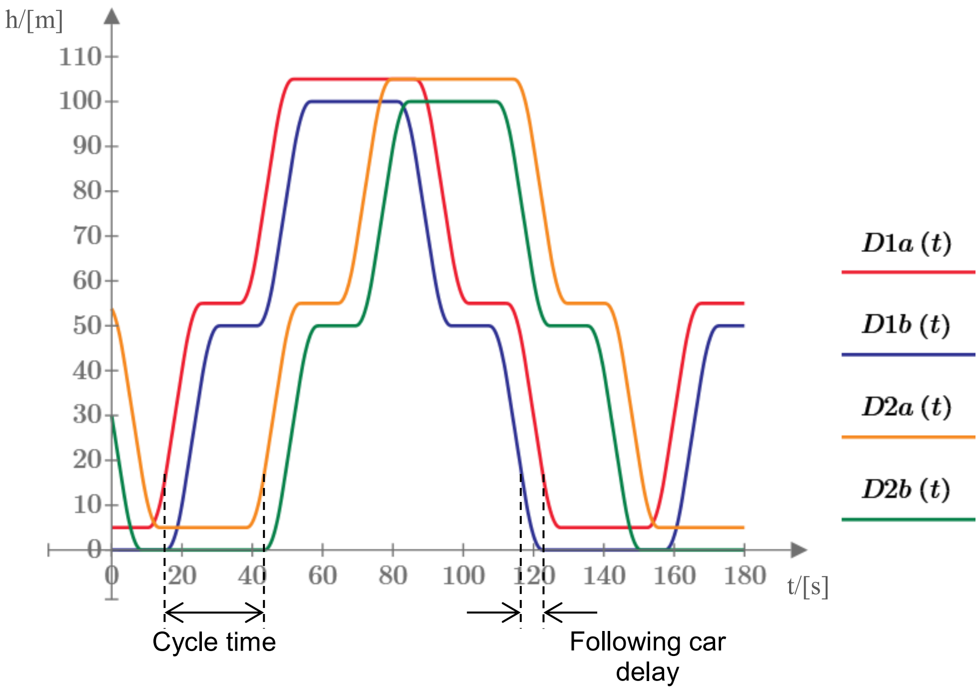


Figure 10-8: Cycle time between two pairs of cars

10.5 Quality of service for shuttle arrangements

As the major measure of QOS is waiting time (WT), the WT derived from the cycle time and interval may be the main measure (CIBSE, 2010), but travelling times and the number of stops need to be considered too. In multi car applications additional delays may be included as quality measures.

The maximum HC for conventional rope elevators is achieved in a two stop shuttle application. The RTT is kept to a minimum. Using RTT calculations the QOS, interval and WT can be optimised.

For a circulating MCLS the HC is independent from the number of (same) stops. The WT at the main entrance can be kept to a minimum, but additional delays during the journey will affect QOS. In applications where all cars have the same stops these additional delays can be reduced to a minimum, or completely avoided, through synchronisation of the cars. This can be compared with an underground train for urban transportation. Every train of a specific line has the same stops with a similar stop time. If one train cannot pass another train additional delays can be avoided during normal operation of the system. Allowing individual stops for each car, like in local groups, limits the options to avoid these delays without sacrificing HC as cars cannot pass each other. Therefore, the shuttle application with one or multiple sky lobbies is preferred as it ensures good QOS with maximum possible HC.

10.6 Comparison of shuttle lift systems

To assess the performance of a circulating MCLS it can be compared with traditional double deck lift systems in a shuttle lift application. Figure 10-9 shows the compared configurations. The comparison is based on the cycle time calculations for the MCLS described in this chapter and RTT calculations for the double deck system. Different travel heights (100m, 200m, 300m, 400m, 500m and 600m) are compared. Table 10-1 shows the parameters of both systems. It shows the number of passengers that fit in the car. The traffic mix is 80% incoming and 20% outgoing with passengers equally distributed to both lobbies. The MCLS has an advantage in higher total HC compared to 100% incoming traffic as the minimum interval or cycle time is independent from additional down traffic. For the double deck system the additional down travelling passengers increase the RTT. Therefore, the interval of the system is slightly increased compared to 100% incoming traffic because of longer total passenger transfer times during each stop (incoming and outgoing passengers). Figure 10-10 to Figure 10-13 shows the chosen velocity and number of cabins, the total HC in 5 minutes and the interval are dependent on the travel height.

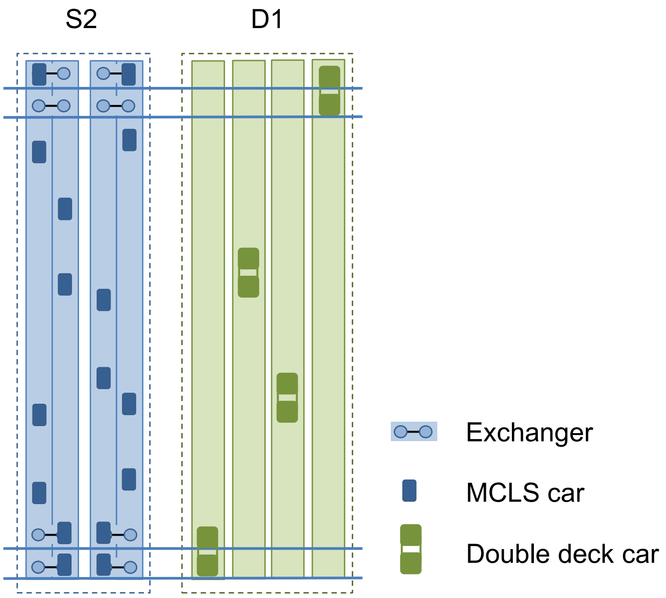


Figure 10-9: Comparison of a group of circulating multi car systems with a double deck group

Table 10-1: parameters of both systems

	Double Deck	MCLS
Shafts space	36 m²	24 m²
Waiting area	18 m²	12 m²
Passenger/car	2x16	8
Number of cabins	2x4	variable
Velocity	variable	variable

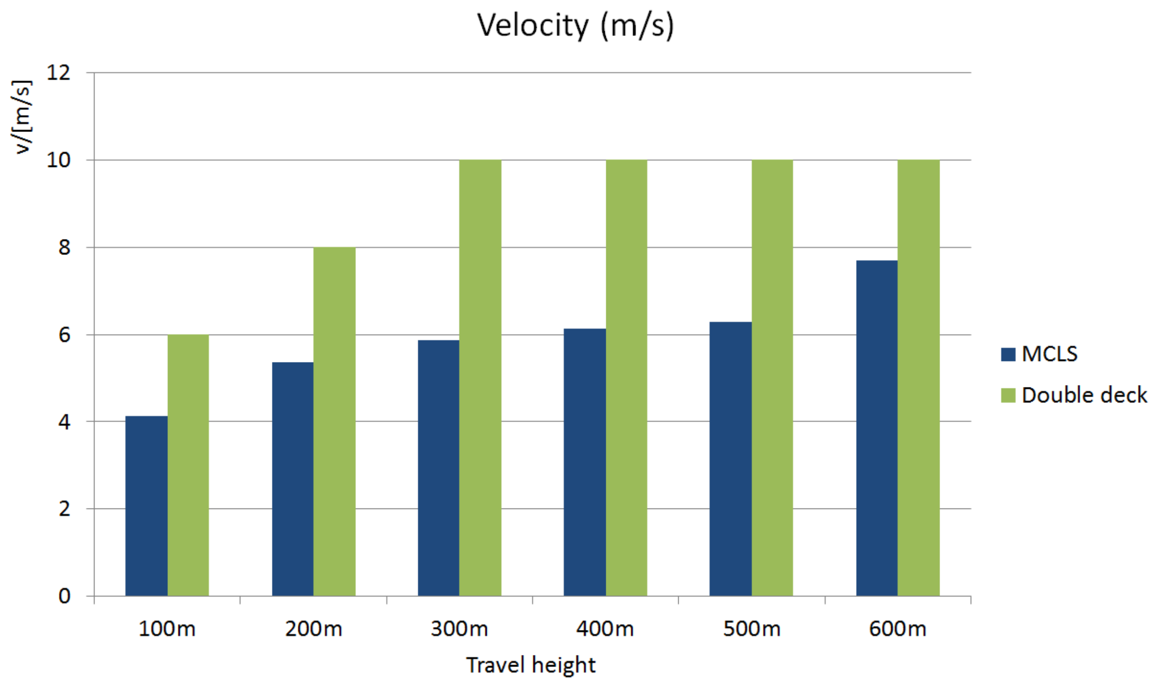


Figure 10-10: Comparison MCLS vs. double deck depending on travel height: velocity

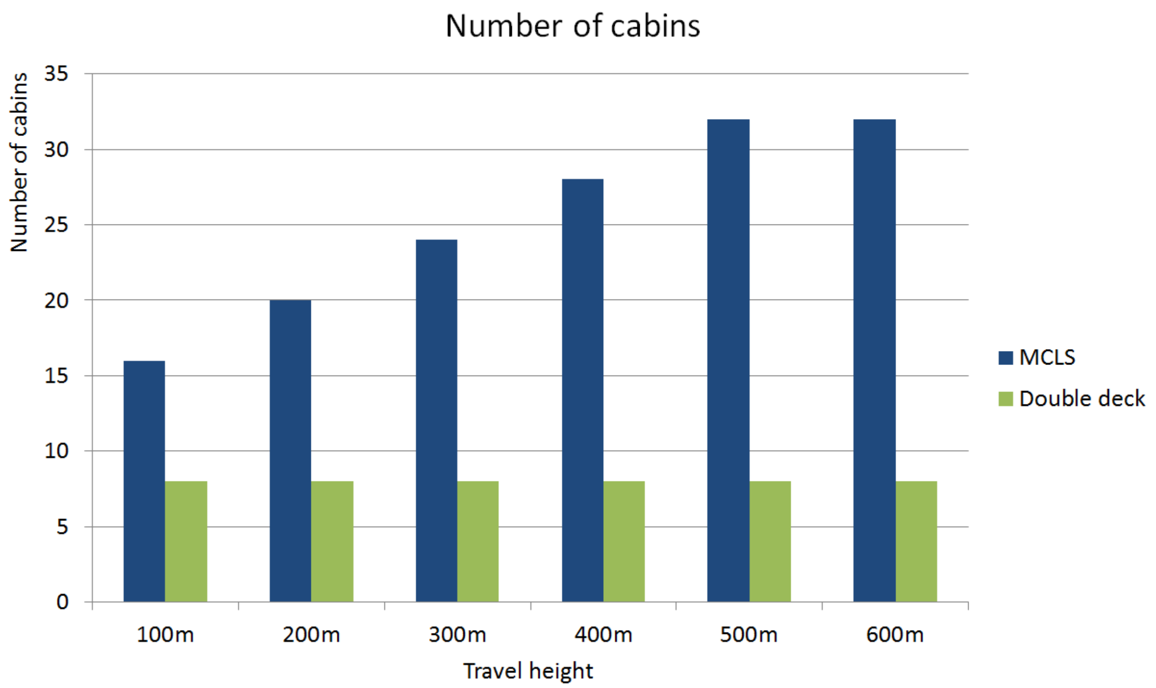


Figure 10-11: Comparison MCLS vs. double deck depending on travel height: number of cabins

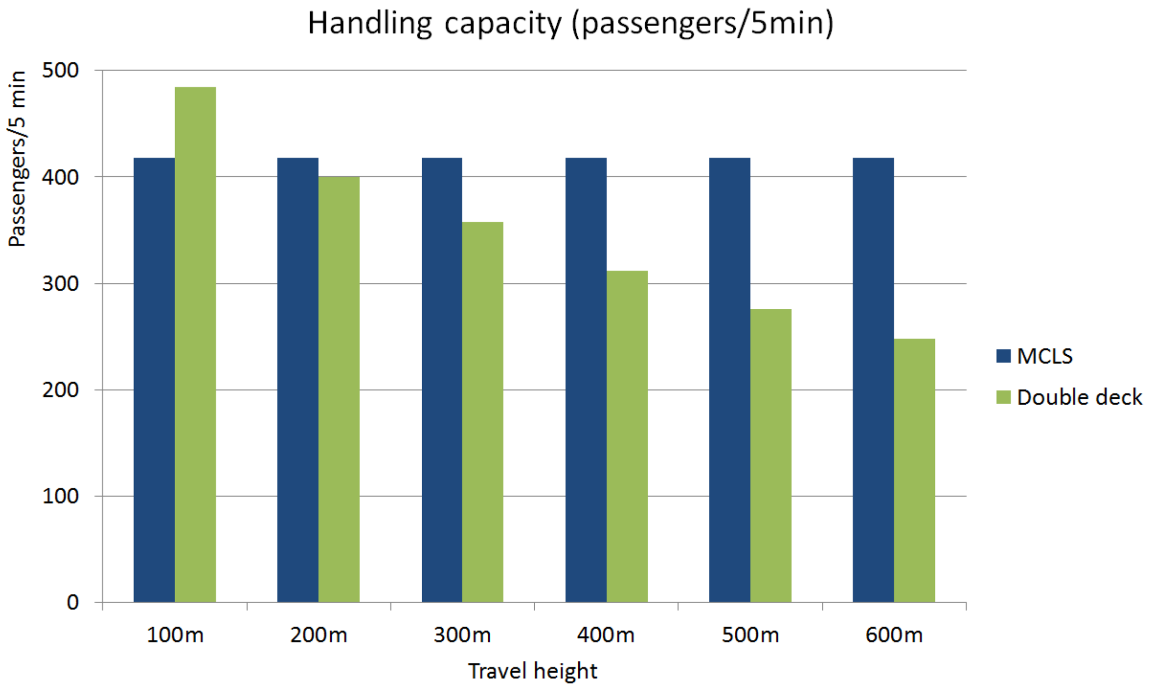


Figure 10-12: Comparison MCLS vs. double deck depending on travel height: HC

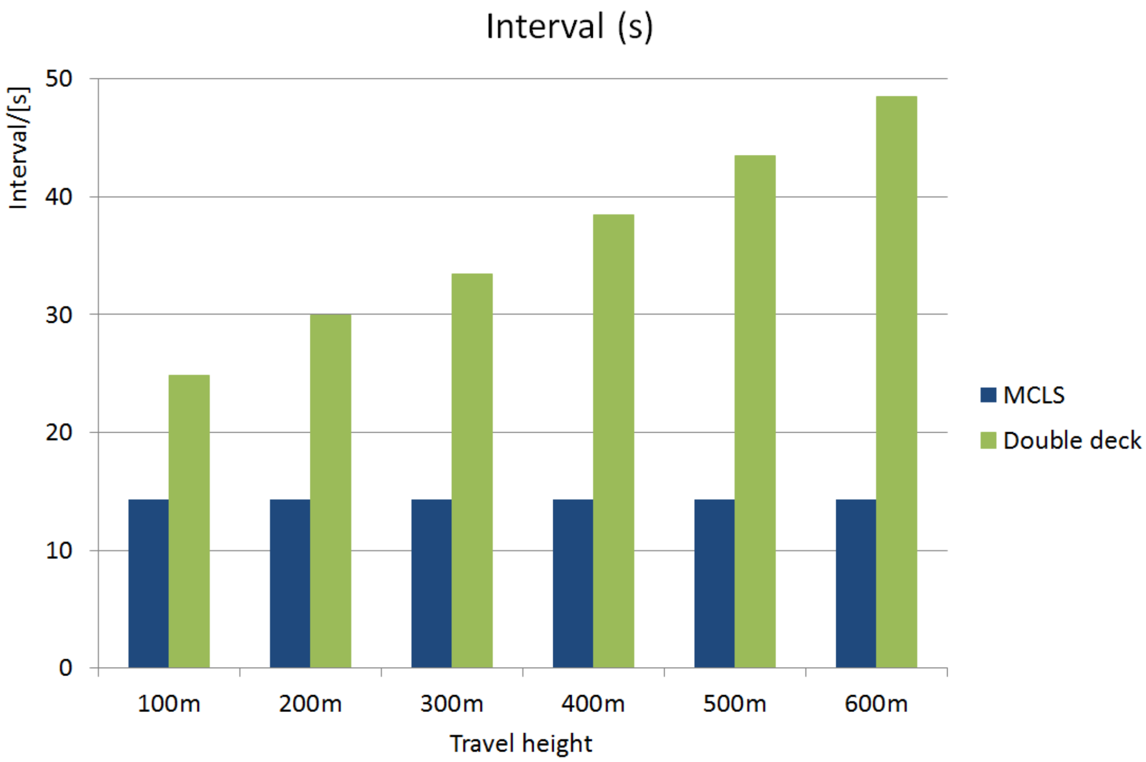


Figure 10-13: Comparison MCLS vs. double deck depending on travel height: interval

The HC of the MCLS is constant, independent from the travel height. Starting with a travel height of about 200m, it is going to be higher than the compared double deck system. With increasing travel height, the benefit of the circulating MCLS can be seen. To keep the HC constant at the MCLS for every travel height, the number of cars required needs to be adapted for the MCLS without additional shafts. Without adding any shafts the number of cars and thus the cabins for the four double deck shafts is constant. With increasing travel height, the rated velocity is increased for both systems. The velocity of the MCLS is lower than the velocity of the double deck.

The average WT and average transit time (TT) of both systems is compared in Figure 10-14. The relationship between interval and WT is complex (Peters, 2013a). For simplicity, in these results the average WT of RTT calculations is taken as 50% of the interval.

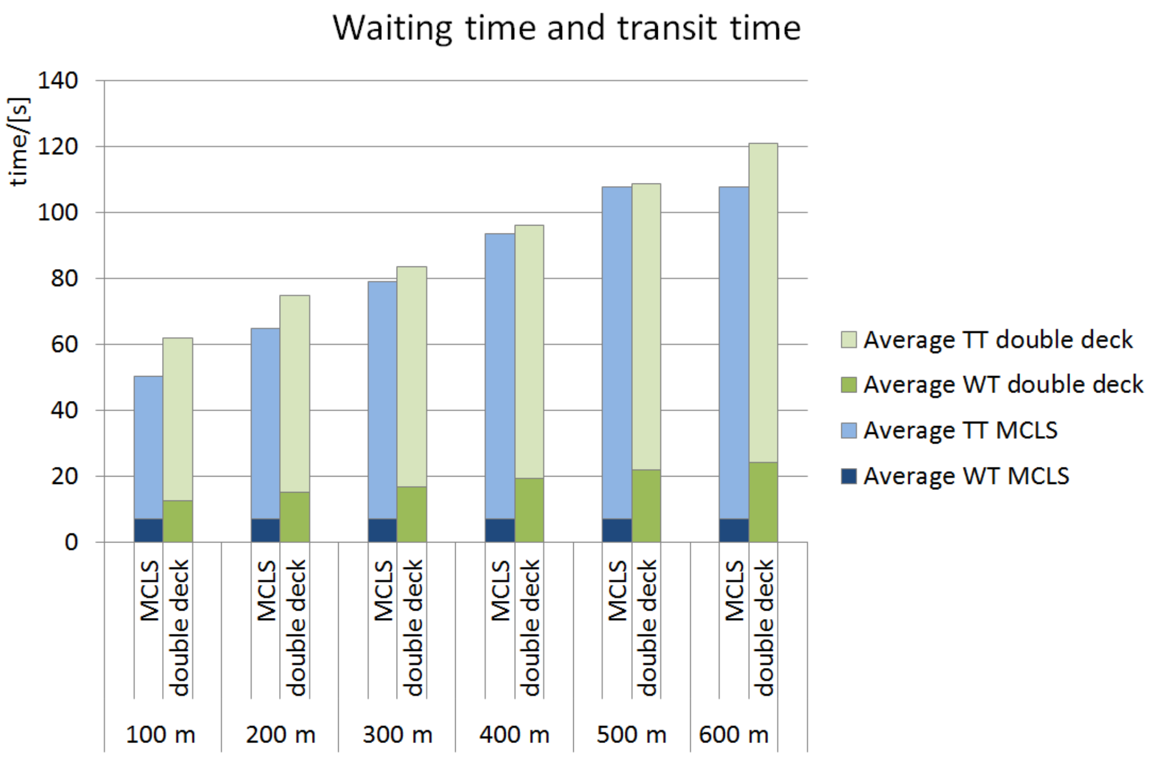


Figure 10-14: Comparison MCLS vs. double deck depending on travel height: average WT and average TT

Since the interval of the MCLS is constant, the average WT is constant. Although the chosen velocity of the MCLS is less than the double deck, the average time to destination of the MCLS provides better values. This is caused by lower average WTs and shorter passenger loading/unloading times.

10.7 Summary

The maximum possible HC for a circulating MCLS is based on the minimum possible cycle time of the system. The minimum possible cycle time of circulating MCLS were discussed and defined in this chapter, for the case of a circulating MCLS being used as a shuttle lifts where all cars have the same stops. If the average RTT of a MCLS increases, the number of cars has to be adapted in order to keep the minimum possible cycle time and a constant HC. To achieve the minimum possible cycle time without “traffic jams” the velocity also needs to be adapted. Safety distances and stopping distances need to be considered in order to calculate reasonable values for the minimum possible cycle time.

Flexible arrangements using MCLSs as shuttle lifts can be included in the vertical transportation concept for tall buildings; this approach is shown and described.

Based on a cycle time and RTT calculations a circulating MCLS and a double deck system were compared with different travelling heights in a shuttle application. The MCLS provides constant values for HC and average WT with increasing travelling heights by adding more cars to the system. Also a short cycle time enables short average WT.

These values need to be proven by simulation. Advanced control algorithms may enable additional MCLS applications.

In a shuttle application all cars have the same stops enabling a minimum possible cycle time between cars. This is different in local groups where cars have individual stops according to their passengers’ individual destinations. The average cycle time needs to be increased if “traffic jams” shall be avoided in a local group. This is analysed in chapter 11.

11 MCLS as local group

List of symbols

Delaying stops:

d_{Accel}	Distance [m] travelled during to acceleration
d_{Decel}	Distance [m] travelled during to deceleration
t_{Accel}	Time [s] necessary to accelerate to rated velocity
t_{Cy}	Minimum possible cycle time [s]
t_{CyD}	Additional cycle time delay [s]
t_{Decel}	Time [s] necessary to decelerate from rated velocity
t_s	Time [s] consumed when making a stop
t_{Stand}	Standing time [s]

Stop sequences:

L_u	Set of landings that can be served in the up direction shaft of a MCLS
l_i	Landing number i
N	Number of landings of a MCLS shaft
s_i	Stop number i
S_{LC}	Number of stops of the leading car that cause an additional delay for the following car
$S_{SafeFloor}$	Ordered sequence of safe floors in an up direction shaft of a following car
S_u	Ordered sequence of stops at landings in an up direction shaft of a car

Z Number of stops of a car in the up direction shaft of a MCLS

Comparison of stop sequences:

k Index indicates the stop of the following car to check

S_{fc} Stopping sequence of the following car

S_{lc} Stopping sequence of the leading car

S_{sl} Sequence of safe floors for the following car

Results:

d_{f2f} Floor to floor distance [m]

d_{min} Minimum distance between cars [m]

11.1 Introduction

A circulating multi car lift system (MCLS) is not limited to shuttle applications (see chapter 10). It can also be used for a local lift group to distribute passengers to their final destination floors.

To control the operation of a circulating MCLS, the general “rules of call control” and the additional “rules of MCLS control” (see section 9.2) need to be considered. This affects the handling capacity (HC) of a circulating MCLS loop. This chapter explores the average cycle time in up direction in a 100% incoming traffic situation and the average up direction HC in a local MCLS group considering quality of service (QOS) constraints. The traffic analysis is established by applying Monte Carlo simulation that calculates an additional cycle time avoiding “traffic jams”.

11.2 Lift arrangements

General lift arrangements with single entrance floors are shown in Figure 11-1. Multiple cars are circulating in 2-shaft loops (A and B). Express zones are possible (B) similar to lift arrangements of traditional lift systems. Lower exchanger levels can be at the entrance level or below. Upper exchanger levels are most likely at the top floor served by the lift group. Intermediate exchanger levels are possible on every other floor.

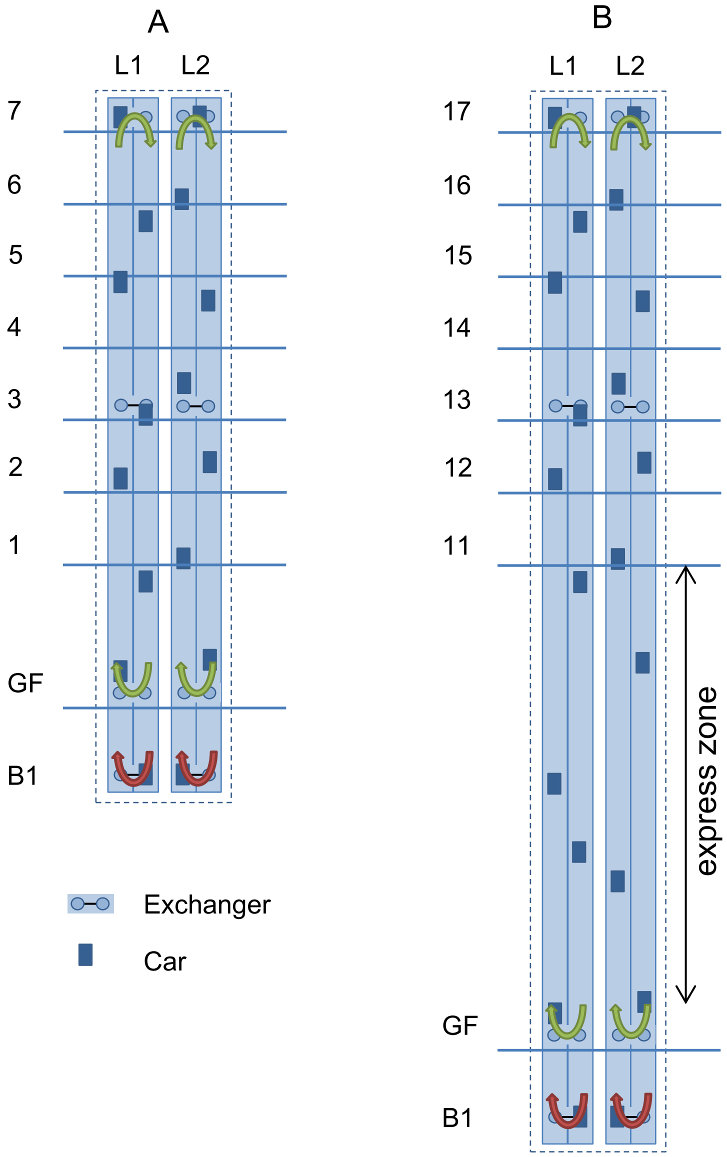


Figure 11-1: Arrangements of a MCLS as local group

11.3 Cycle time in local MCLS groups

To calculate the incoming HC the average cycle time of a local circulating MCLS needs to be determined considering existing constraints like safety distance and avoiding departure delays. In a local group lift cars have different stops during a round trip depending on its passengers' individual arrival and destination floors. Lift cars in the described circulating MCLS cannot bypass each other as they are using the same shaft(s). The minimum possible cycle time can be achieved in shuttle applications where all MCLS cars have the same stops (see chapter 10). If cars have individual stop sequences an additional time needs to be added to the minimum possible cycle time to avoid “traffic jams” and to fulfil the “rules of call control” and the “rules of MCLS control”.

11.3.1 Assumptions

As a MCLS has multiple options the following assumptions are the basis of this local group traffic analysis.

- Bottom floor is the main entrance level and each car is able to stop at that level.
- Top floor is the exchanger level to change from the up direction to the down direction shaft. Every car has to stop there. This is a served floor and landing where the lift car can open its doors in order to let passengers transfer in and out.
- As there is the same stop at the bottom floor for every car there is a minimum possible cycle time between two subsequent cars that is equal to the shuttle application (see section 10.2).
- Cars are running with their rated speed pattern/travelling curve (speed patterns are not adapted e.g. to depart earlier).
- The “rules of call control” and “rules of MCLS control” are satisfied.
- Required distances between cars are considered.

11.3.2 Additional cycle time delay

11.3.2.1 Delaying stops

Stops of a leading car can block the shaft and delay the processing of a following car stop sequence. A longer cycle time between cars can avoid these “traffic jams” of lift cars. Therefore, an additional time needs to be added to the minimum possible cycle time. The additional time between two subsequent cars avoiding any departure delays for the following car in an up direction shaft depends on the stop sequence of the leading car and the following car. Figure 11-2 shows a general example of a spatial plot of two subsequent cars with longer distance runs between stops. The leading car 1 ($D1(t)$) has one “delaying stop” that causes a safety distance violation if car 2 ($D2x(t)$) departs from the bottom landing after the minimum possible cycle time (t_{cy}).

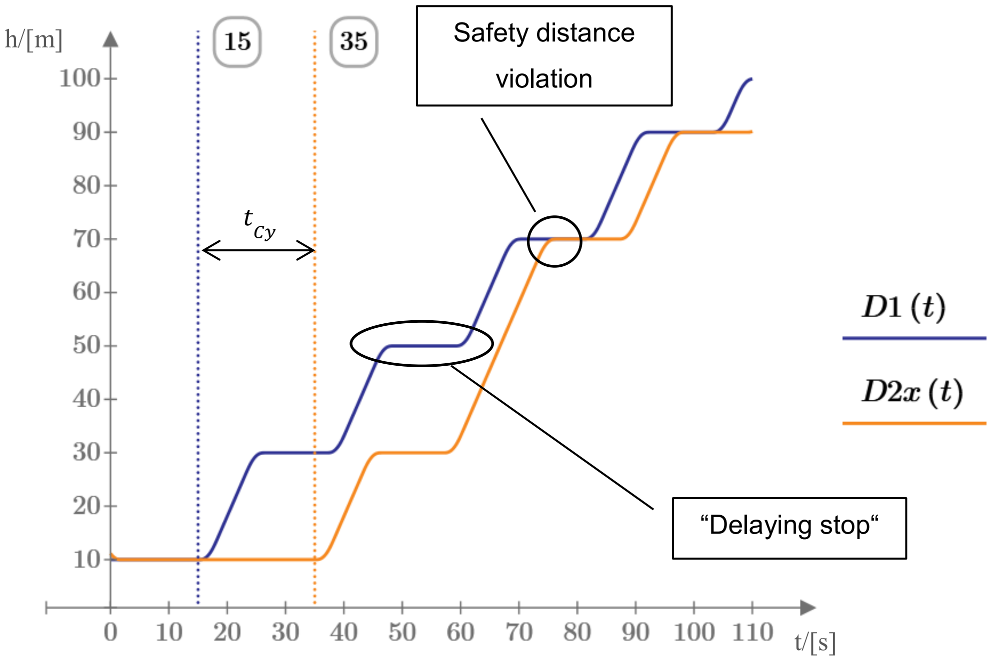


Figure 11-2: Spatial plot with the stopping sequence of two subsequent cars violating the safety distance

An additional cycle time delay (t_{CyD}) for the following car 2 ($D2(t)$) results in a delayed departure from the main entrance floor and avoids the safety distance violation (see Figure 11-3). “Delaying stops” needs to be calculated to derive the additional cycle time. Both stopping sequences (the leading car stopping sequence and the following stopping car sequence) need to be analysed and compared.

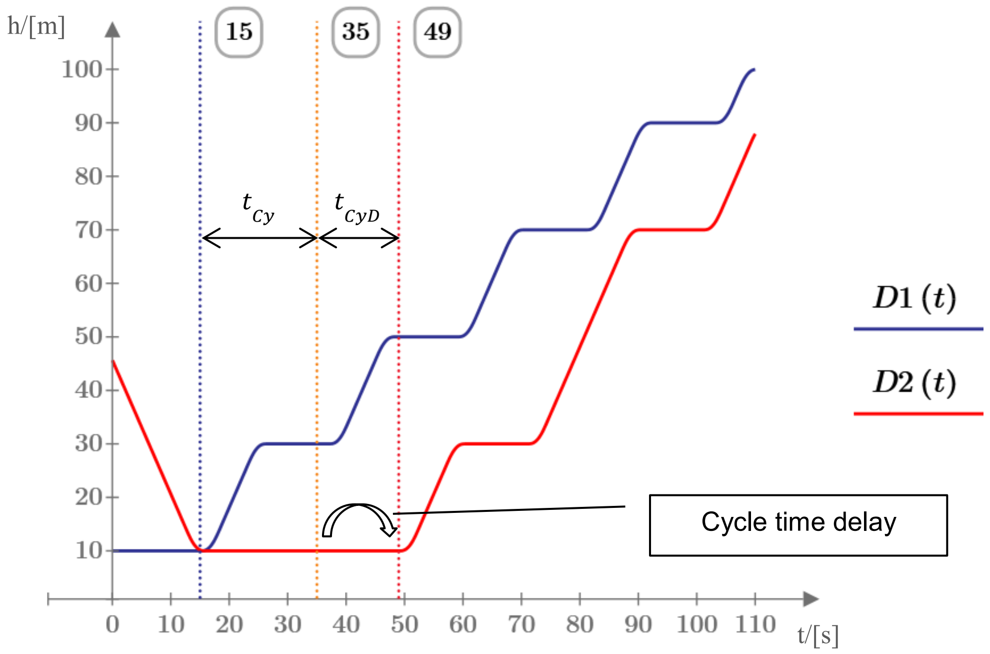


Figure 11-3: Spatial plot with the stopping sequence of two subsequent cars with an additional cycle time delay

The cycle time delay (delayed departure) can be determined if the following car has a later arrival at the bottom landing. Another option is that the following car has a delayed door opening for loading passengers. That increases the WT for passengers but reduces experienced departure delays inside the cabin. Waiting for a lift to arrive is an expected scenario for passengers in opposite to departure delays. The delayed door opening should only be applied if passengers are not aware of a car already waiting behind the shaft door.

An additional cycle time can be reduced if flexible speed patterns are used. A principle example is shown in Figure 11-4. Car 2 ($D2x(t)$) is using a slower velocity to avoid delays. This has a bigger effect if travel distances are longer as there is a lower limit in parameters for the travelling curve. Adaption of the speed pattern is not considered in this chapter's analysis.

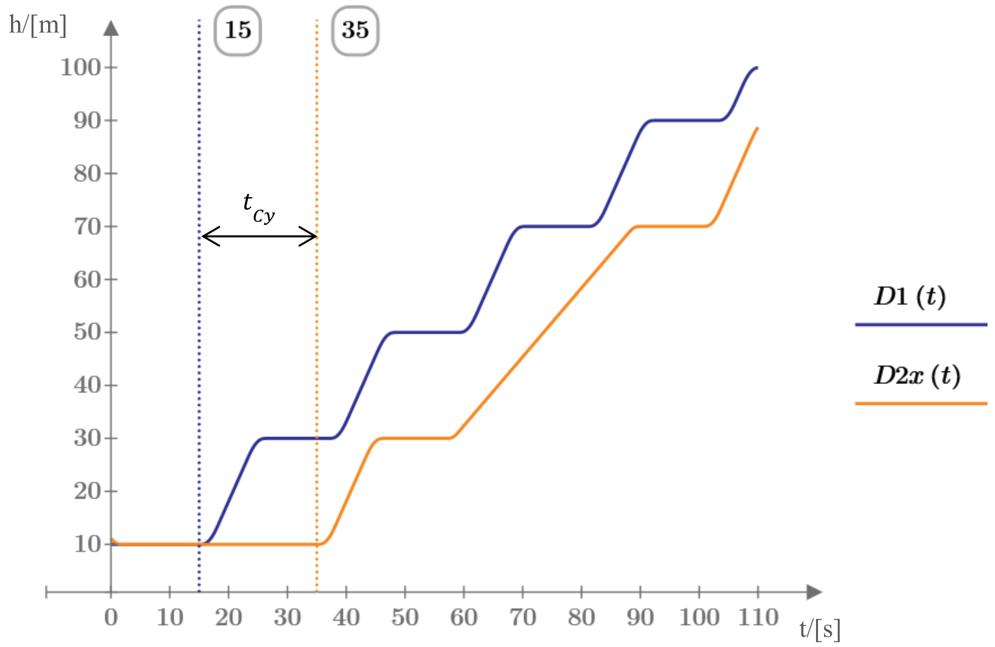


Figure 11-4: Adapted speed to avoid an additional cycle time delay and violation of safety distances

11.3.2.2 Additional cycle time delay

There is a necessary cycle time delay for each delaying stop. This additional delay depends on “time consumed when making a stop” (t_s) (Peters, 1998) for all intermediate stops. This includes the time for standing (t_{Stand}) at the floor itself but also includes the longer time for acceleration (t_{Accel}) and deceleration (t_{Decel}) compared to the time passing the same distance ($d_{Accel} + d_{Decel}$) with rated velocity. If rated velocity is reached the time consumed when making a stop can be calculated with equation (11-1).

$$t_s = (t_{Accel} + t_{Decel} + t_{Stand}) - \frac{(d_{Accel} + d_{Decel})}{v} \qquad (11\text{-}1)$$

The standing time (t_{Stand}) includes passenger transfer times. For simplicity in this analysis the time consumed for each intermediate stop (t_s) is calculated with the same duration of time although the number of transferring passengers may be different for each stop. Assumptions are that rated velocity is reached and the same average number of passengers are unloading.

The additional cycle time delay (t_{CyD}) can be calculated with equation (11-2). S_{LC} is the number of delaying stops of the leading car, t_s the average time consumed when making a stop. For each delaying stop the cycle time needs to be delayed by the time consumed for a stop.

$$t_{CyD} = S_{LC}\, t_s \quad (11\text{-}2)$$

11.3.2.3 Stopping sequences and safe floors

To calculate the number of “delaying stops” in order to derive the additional cycle time, the stopping sequences of the leading and the following cars are necessary. It is also important to know the floors the following car is able to stop at depending on the leading car stops and safety distance constraints.

A MCLS has a given number of landings per shaft where lift cars can stop. L_u is a set of landings (l_i) in the up direction shaft of a MCLS loop (see equation (11-3)).

$$L_u = \{l_0, l_1, \dots l_{N-1}\} = \{1,2, \dots , N\} \quad (11\text{-}3)$$

Depending on assigned calls every lift car in a MCLS has an ordered sequence (S_u) of stops (s_i) at landings in the up direction shaft (see equation (11-4)).

$$S_u = (s_0, s_1, \dots , s_{Z-1}) \quad (11\text{-}4)$$

Each stop is associated with a landing of the up direction shaft: $s_i \in L_u$

The sequence of stops needs to be a continuously rising order of landings: $s_{i+1} > s_i$

For all cars the first stop needs to be the bottom landing ($s_0 = l_0$). The stop at landing l_0 is for passenger loading at the main entrance floor. The last stop must be the top landing ($s_{Z-1} = l_{N-1}$) of the up direction shaft. The last stop at landing l_{N-1} can be for passenger unloading but is also necessary for the horizontal shaft changing of a car using the exchanger unit. The stops at landings $l_1 \dots l_{N-2}$ are for unloading passengers at intermediate landings ($N > 2$). This is shown in equation (11-5).

$$S_u = (s_0, s_1, \dots , s_{Z-1}) = (l_0, \{l_1, l_2, \dots , l_{N-2}\}, l_{N-1}) = (1, \{2,3, \dots N-1\}, N) \quad (11\text{-}5)$$

From the leading car stops sequence a safe floor sequence ($S_{SafeFloor}$) for the following car can be derived. The safe floor for the following car is defined by the minimum (safety) distance between cars and the landing levels measured in meter.

$$S_u \xRightarrow{calc\_safe\_floors} S_{SafeFloor}$$

It is possible that there is no safe floor for a specific stop of the leading car for the following car in the same shaft. In this case the safe floor needs to be marked as not applicable (n/a).

Example:

$N = 10$

The landing levels (meters above reference level) are:

$l_0 = 0m$; $l_1 = 5m$; $l_2 = 10m$; $l_3 = 15m$; $l_4 = 20m$; $l_5 = 25m$, $l_6 = 30m$; $l_7 = 35m$; $l_8 = 40m$; $l_9 = 45m$; $l_{10} = 50m$;

if the minimum distance between cars is 6m the safe landing sequence is:

$$S_u = (l_0, l_3, l_7, l_8, l_{10}) \xRightarrow{calc\_safe\_floor} S_{SafeFloor} = (n/a, l_1, l_5, l_6, l_8)$$

If the leading car is at l_0 no safe floor for the following car in the same shaft exists (n/a). If the leading car has a stop at landing l_7 and the minimum distance between cars is 6m then the safe floor for the following car is l_5.

11.3.2.4 Comparison of stop sequences

There is at least the minimum possible cycle time between the first stop $S_{lc}(0)$ of the leading car and the first stop $S_{fc}(0)$ of the following car. To calculate the delaying stops a stop of the following car $S_{fc}(k)$ needs to be compared with the safe floor for the following car $S_{sl}(k+1)$ belonging to the leading car's stop ahead. The movement in the whole up direction shaft needs to be analysed. Figure 11-5 shows the algorithm to calculate the delaying stops. (Accessing a stop in the stop sequence: $S_{fc}(x) = s_x$).

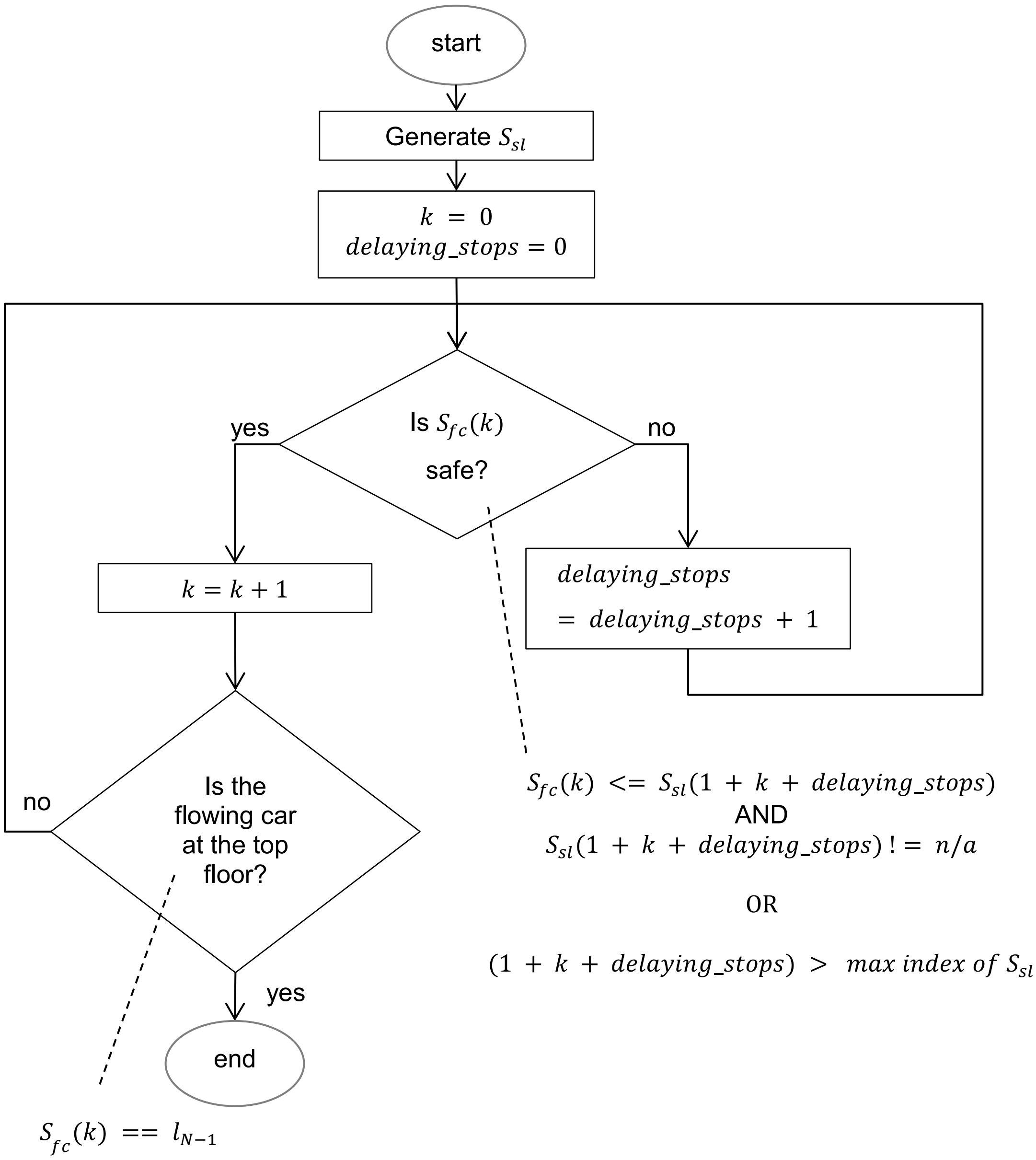


Figure 11-5: Algorithm to calculate the delaying stops

11.3.3 Simulation/Calculation

The average cycle time for a local MCLS is expected to be higher than the minimum possible cycle time if "traffic jams" shall be avoided. To calculate an average cycle time in a pure incoming traffic the stopping sequences of multiple subsequent cars need to be compared. The stopping sequences of the cars are depending on the passengers destinations. To calculate the average cycle time of multiple subsequent cars the method of Monte Carlo simulation is used. This method was introduced to evaluate the round trip time (RTT) of conventional single car lift systems in pure incoming situations (see section 2.1.3.3). To evaluate the average cycle time in local circulating MCLSs the general structure is shown in Figure 11-6.

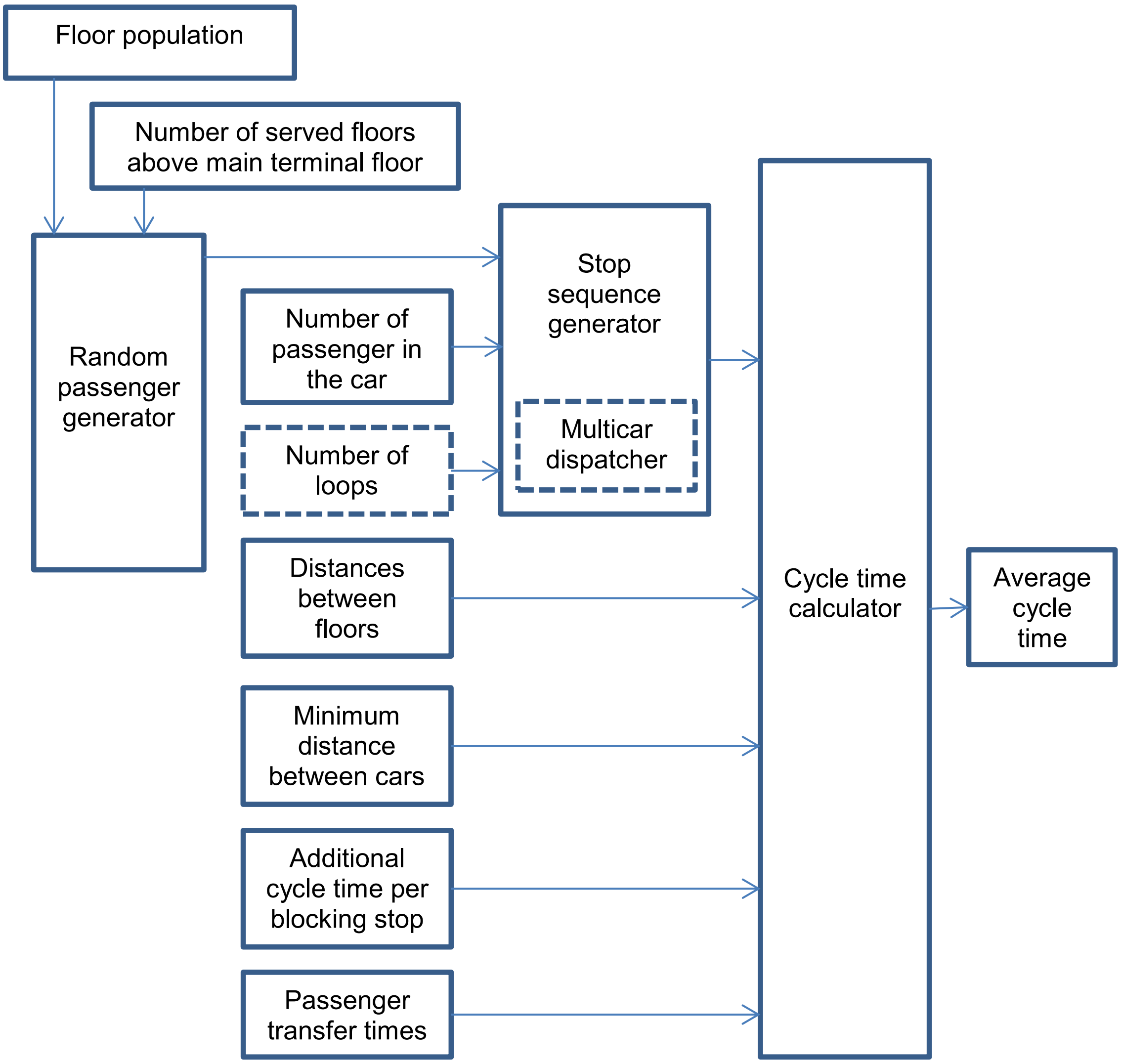


Figure 11-6: Structure of the Monte Carlo simulation to calculate the average cycle time

Random passenger generator: The file output of the passenger generator from the lift traffic simulation software ELEVATE (Peters Research Ltd., 2014) is used to generate an ordered passenger list with an arrival floor and a destination floor for each passenger. As input the number of floors and the floor population is necessary. The same population on each floor and a traffic mix of 100/0/0 for “in/out/interfloor” is used.

Stop sequence generator: The stop sequence generator assigns passengers from the ordered list to the next arriving lift car(s). Every car is filled up to the number of passengers fitting into the car. Depending on the destinations of the passengers in the car a stop sequence of the car is generated. A stop at the top floor is mandatory as it is used to move the lift car horizontally to the down direction shaft. If multiple parallel loops are used as one group simple dispatcher logic may be applied to assign passengers to the next arriving cars of different loops.

Cycle time calculator: The cycle time calculator comparing the stop sequences of a leading and a following car is described above (see section 11.3.2). Two subsequent cars are analysed and delaying stops are calculated avoiding departure delays and “traffic jams”. A cycle time for the following car is calculated (minimum possible cycle time + additional cycle time delay). Input parameters for the cycle time calculator are distances between floors, minimum distances between cars, additional cycle time per blocking stop and passenger transfer times. The cycle times of multiple subsequent result in an average cycle time. An average pure incoming HC can be calculated.

The sequence of operations of the complete Monte Carlo simulation calculating the average cycle time and HC of multiple samples is shown in Figure 11-7.

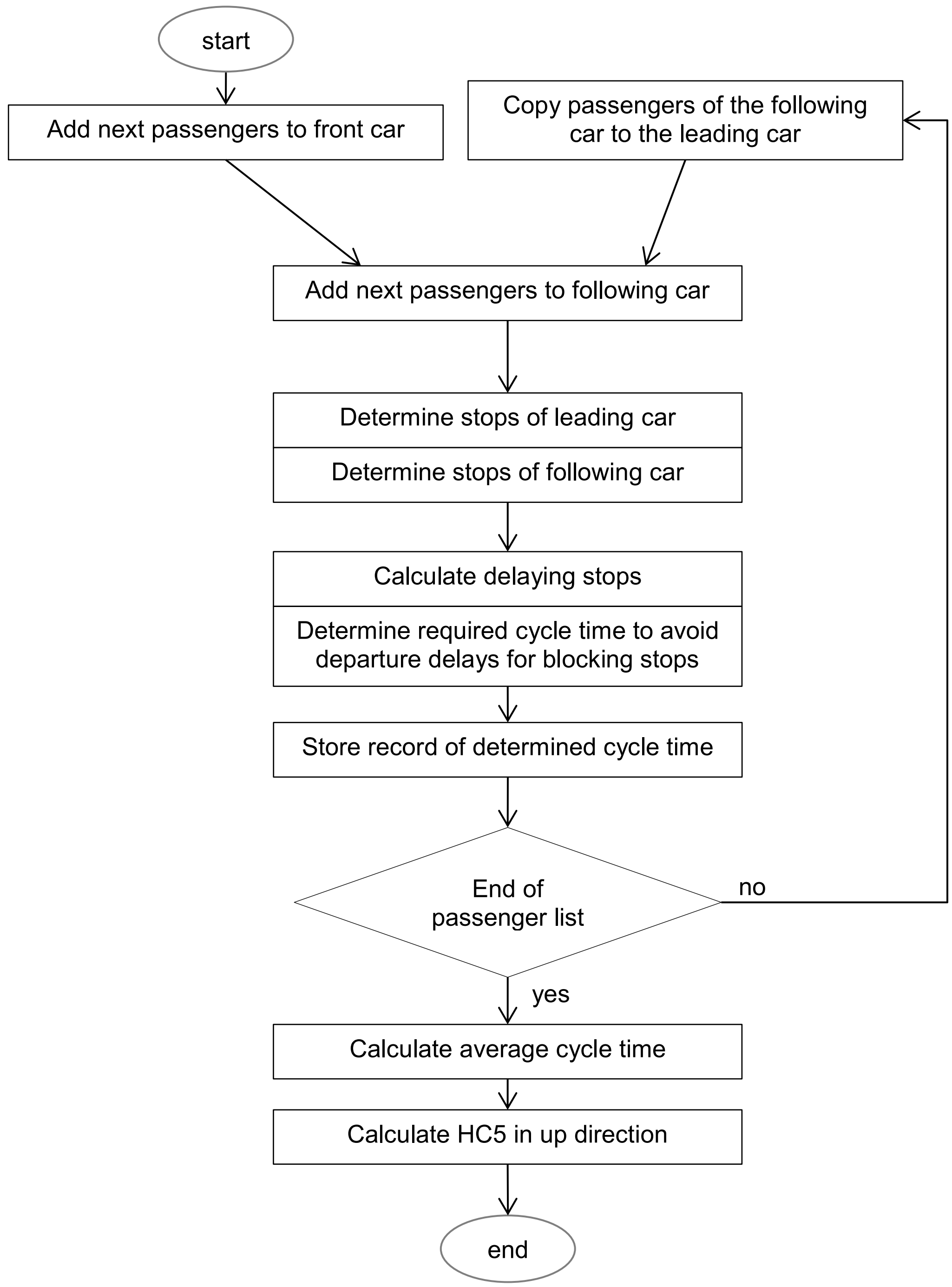


Figure 11-7: Monte Carlo simulation - sequence of operations

The software to execute the simulation/calculation is implemented in the C++ programming language using an integrated software development environment (Microsoft Corporation, 2007). A screenshot of the software is shown in Figure 11-8. A simple console input/output is used without the usage of a graphical user interface.

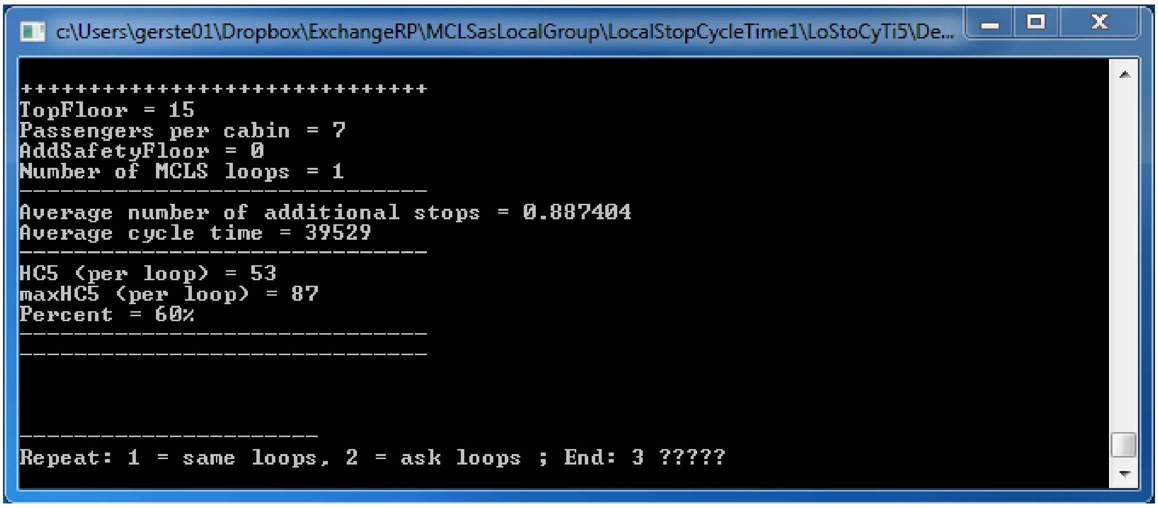


Figure 11-8: Screenshot of the software to calculate the average cycle time and handling capacity of a local circulating MCLS

11.4 Results

11.4.1 $d_{min} < d_{f2f}$

The average incoming HC derived from the average cycle time depends on the number of passengers per car and the number of served floors above the main entrance level. In case the minimum distance between cars is shorter than the floor to floor distances ($d_{min} < d_{f2f}$) the results depend on the number of passengers per car is shown in Figure 11-9. The diagram shows the results of one MCLS loop serving all calls in a 100% incoming traffic situation. If the number of served floors increases the probability of different stop sequences increases and therefore the probability of delaying stops increases. But there is a minimum HC. If number of served floors is high the impact of additional served floors is less.

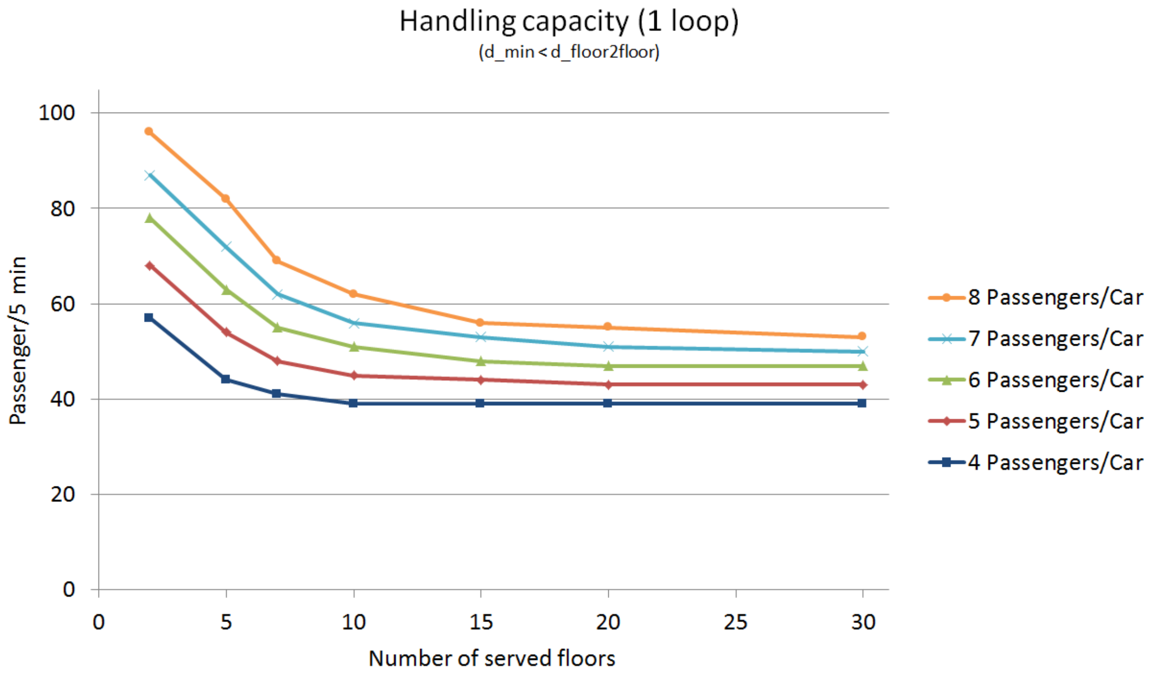


Figure 11-9: Average incoming HC5 for one local circulating MCLS loop

The average delaying stops per pair of leading and following car is shown in Figure 11-10. A shuttle application with two floors has no delaying stops. With a higher number of floors passengers can travel to, the probability of delaying stops increase. If the number of floors is low (<~7 floors) a higher number of passengers in the car reduces the number of delaying stops. Cars are probably stopping often at every floor which reduces the number of delaying stops. As a result a circulating MCLS should serve as few stops as possible.

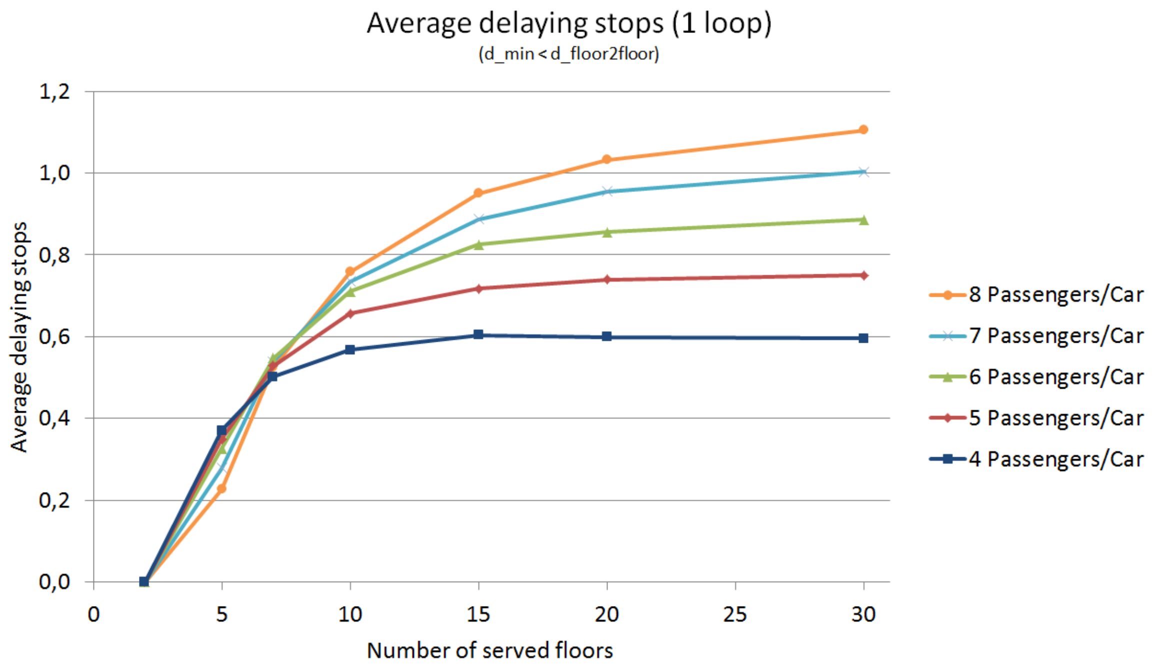


Figure 11-10: Average delaying stops for one local circulating MCLS depending on number of floors

A different view on the same data shows the benefit of limiting the number of served floors (see Figure 11-11).

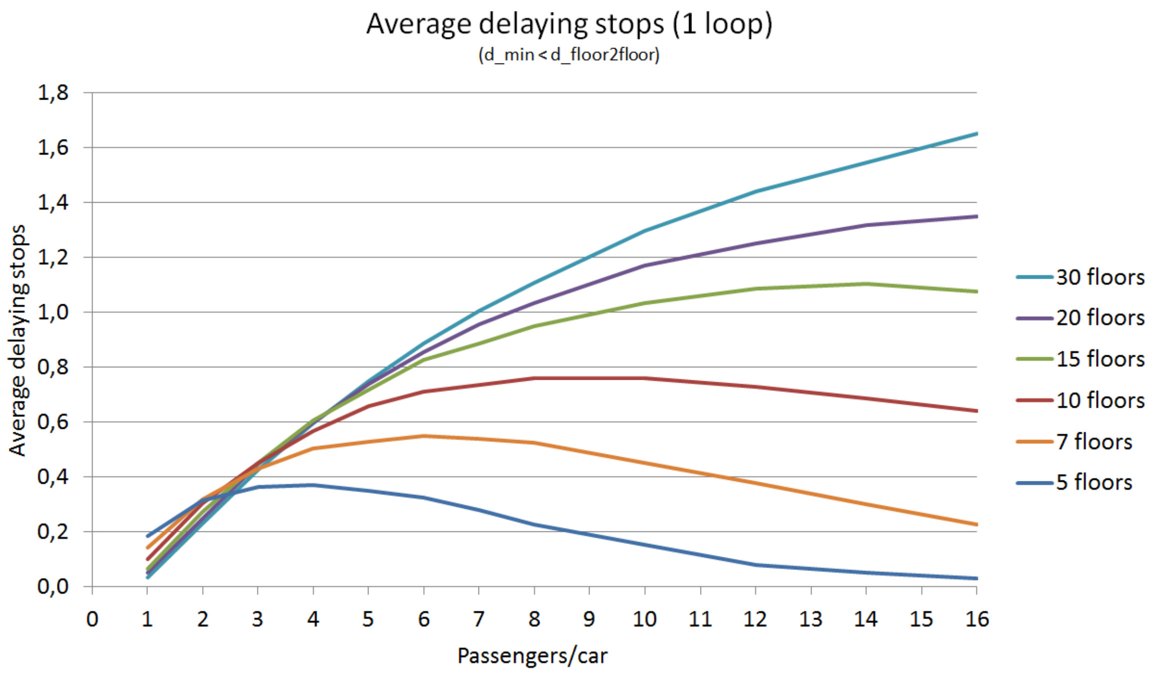


Figure 11-11: Average delaying stops for one local circulating MCLS depending on passengers per car

11.4.2 $d_{f2f} < d_{min} < 2\ d_{f2f}$

It is very likely that the minimum distance between cars is longer than the floor to floor distances ($d_{min} > d_{f2f}$). HC will be affected if a following car has to stand at least two floors below a stopped leading car ($d_{f2f} < d_{min} < 2\ d_{f2f}$). Figure 11-12 compares the results with 8 passengers per car with two cars able to stand next to each other ($d_{min} < d_{f2f}$) and an additional floor required between two stopped cars ($d_{f2f} < d_{min} < 2\ d_{f2f}$). It is assumed that the distance from the main entrance floor to the floor above is longer than the minimum distance. This is a reasonable assumption because main entrance floors are often high.

The additional safety distance constraints reduce the HC. If a leading car is standing at a floor it blocks the landing below. If the lift system serves a low number of floors the negative effect is higher than serving more floors.

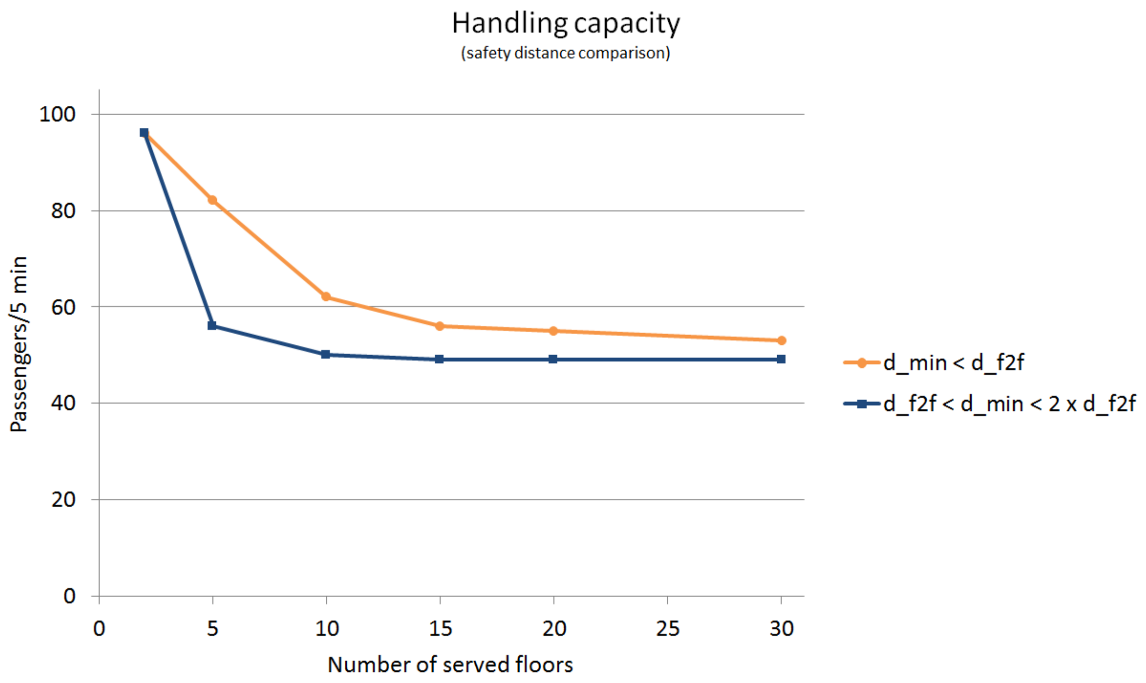


Figure 11-12: HC depending on the safety distance constraints

11.4.3 Express zones

High rise lift groups serve upper floors of a building bypassing lower floors as shown in Figure 11-1. For traditional rope lifts, number of shafts, car velocities or cabin sizes need to be increased in order to achieve similar lift group performances compared to lift groups without an express zone. For a circulating MCLS with an express zone, the number of cars can be easily increased to maintain a low cycle time, so HC and average WT can be maintained. The express zone can be used to reduce additional delays as velocity can be reduced for the long travel distance runs and therefore cars may depart earlier.

11.4.4 3-shaft system

Loops with 3-shafts are also possible. In 3-shaft system two shafts are operating in the same direction and one shaft in the opposite direction. In a two shaft MCLS cabins are circulating. The cycle time that can be achieved between cars considering safety distance and QOS constraints defines the HC. The incoming and outgoing HC is equal as the down direction shaft feeds the up direction shaft with cars. If a significantly lower cycle time can be achieved in e.g. the down direction compared to the up direction shaft a third shaft supporting the up direction shaft can improve HC in both directions. As the cycle time in shuttle applications is close to the minimum possible cycle time the effect of a third shaft will be minimal or non-existent.

In lift groups with conventional control (collective control) the down peak HC can be 1.6 times higher than the up peak HC (Barney, 2003). The control system may choose where the cars stop in the down direction to collect passengers. Passenger with the same start floor are automatically grouped together to travel to the main entrance floor. Cars have fewer stops during a round trip. Less stops lead to fewer unequal stops which enable a reduction in the time between cars considering departure delays. In this scenario, a third shaft used in up direction can have a benefit in HC in both directions. The up direction shafts with higher cycle time are fed by the down direction shaft arriving cars with the lower cycle time. The down direction shaft with the lower cycle time is fed by two up direction shaft each with a higher cycle time.

11.5 Summary

This chapter introduces traffic analysis for a circulating MCLS used as local group. Based on a simplified additional cycle time calculation the HC for a 100% incoming traffic is calculated avoiding “traffic jams”. The Monte Carlo Simulation method is used. The result for different numbers of served floors and different numbers of passengers per car were calculated. In case of a higher number of served floors the probability of a different number of stops increases and the cycle time needs to be increased to avoid “traffic jams”. This reduces HC compared to a shuttle application. Furthermore safety distance and distance between served floors affects results. If cars cannot stand next to each other at two adjacent floors the HC is further reduced.

Full traffic simulation including control algorithms are needed to prove the results. Concepts of control algorithms for circulating MCLSs are described in chapter 12. Control algorithms need to provide expected system behaviour. Interfloor traffic may affect the minimum possible cycle time if “traffic jams” shall be avoided. Interfloor traffic may cause additional stops. Additional stops can have a negative effect on calculated delaying stops but also can have a positive effect on calculated delaying stops.

12 Multi car control

12.1 Introduction

When a circulating multi car lift system (MCLS) is operated as shuttle, or local lift group, effective dispatching and control algorithms are necessary. The traffic control algorithms need to ensure high handling capacities (HCs) and must consider quality of service (QOS) aspects for passengers. This goes beyond traditional call dispatching and will affect different control levels related to traffic performance of lift groups: call dispatching/group control, system control, call control, motion commands and door commands. Additionally, system configuration affects control and dispatching strategies. This chapter addresses important concepts that are relevant for effective multi car control, optimising HC and considering QOS aspects.

12.2 Call dispatching with multiple loops

Multiple 2-shaft circulating MCLS loops can be operated as one common group serving calls for the same floors. If multiple MCLS loops are operated as one destination control system, call dispatchers have the option to find allocations that fit best to the overall group performance, considering the effective operation of each loop. Main considerations of a dispatcher are costs for (additional) delaying stops and coincident calls and stops (= grouping of passengers). This addressed QOS aspects of each MCLS loop.

The Monte Carlo simulation described in section 11.3.3 and Figure 11-6 is used to show the positive effect of destination control dispatchers in a 100% incoming traffic situation if multiple MCLS loops are operated as one group. Arriving passengers are allocated to the next arriving cars of multiple loops, considering effective operation of each loop. For simplicity, passengers are allocated to a set of cars, one car for each MCLS loop that are departing next from the main entrance floor before the next passengers are allocated to the following set of departing cars. As this is not a traffic simulation, it only gives an indication of possible improvements per loop. If multiple loops are operated as one group, the results of the HC per loop are shown in Figure 12-1. Each loop can be operated with a lower average cycle time and therefore higher HCs are reached without additional “traffic jams”. The minimum distance between cars is shorter than the floor to floor distance.

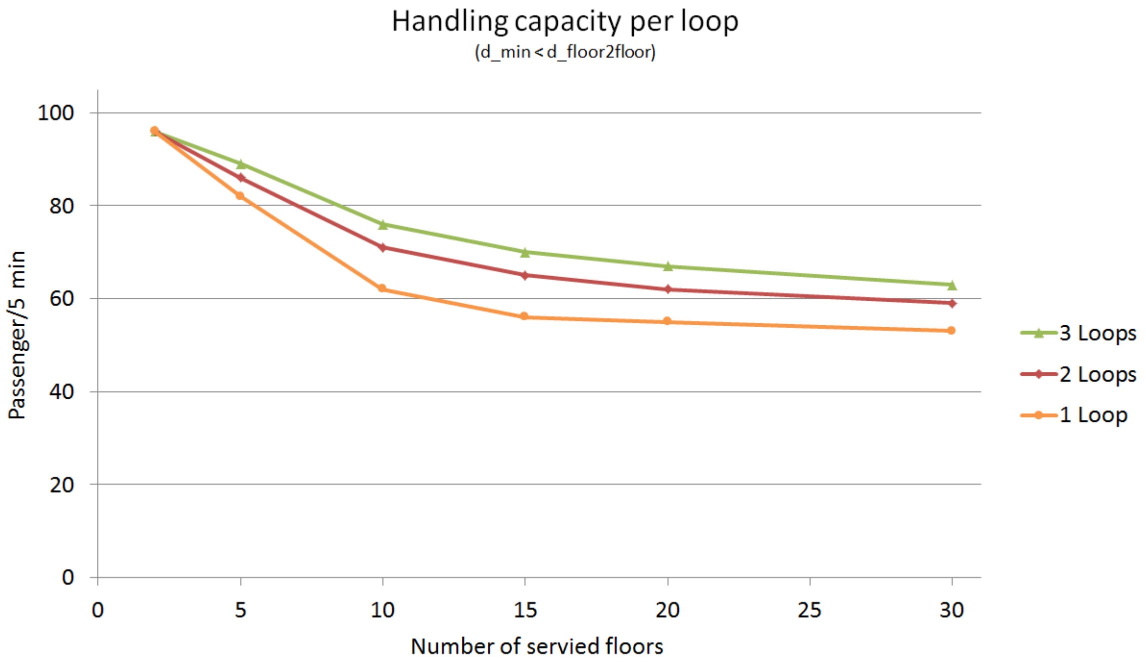


Figure 12-1: HC in 5 minutes per MCLS loop if multiple loops are operated as one group

The effective gain per loop using multiple loops as one group is shown in Figure 12-2.

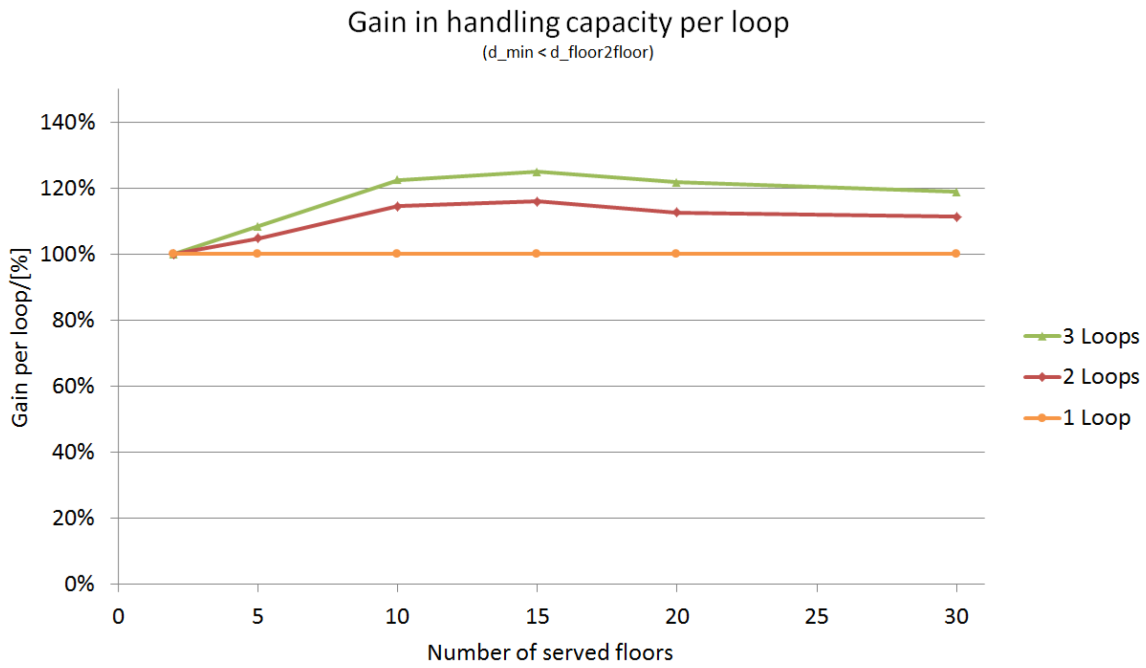


Figure 12-2: HC in 5 minutes gain if multiple MCLS loops are operated as one group

12.3 Served floors assignment

In conventional lift groups, sub zoning increases the HC in up peak situations (Barney, 2003). A lift group is divided into sub groups and are temporarily assigned to buildings zones. Each lift in a sub group serves fewer floors. This reduces the round trip time (RTT) and the interval that increases the HC. If “traffic jams” are avoided, a higher number of served floors also reduces HC in circulating MCLS (see section 11.4.1 and Figure 11-9). Reducing numbers of served floors can improve HC. But in a MCLS the distance between served floors has also a significant impact. There is a negative effect on HC if the distance between served floors is shorter than the minimum distance between cars (see section 11.4.2 and Figure 11-12). In a 100% incoming traffic situation the served floors from the main entrance lobby can be split between loops in an alternating manner similar to interleaved zones (Barney, 2003). This reduces served floors per MCLS loop and increase distance between served floors. In a lift group with “n” MCLS loops served floors above the main entrance lobby are assigned to the MCLS loops as follows:

- Loop 1 serves every n-th floor starting with floor 1 above the entrance floor
- Loop x serves every n-th floor starting with floor x above the entrance floor
- Loop n serves every n-th floor starting with floor n above the entrance floor

It is likely and preferred that the distances between the served floors of a MCLS loop are longer than the minimum distance between floors. As an example in a 2 MCLS loop group the first loop serves odd floors and the second loops serves the even floors above the main entrance. This is illustrated in Figure 12-3.

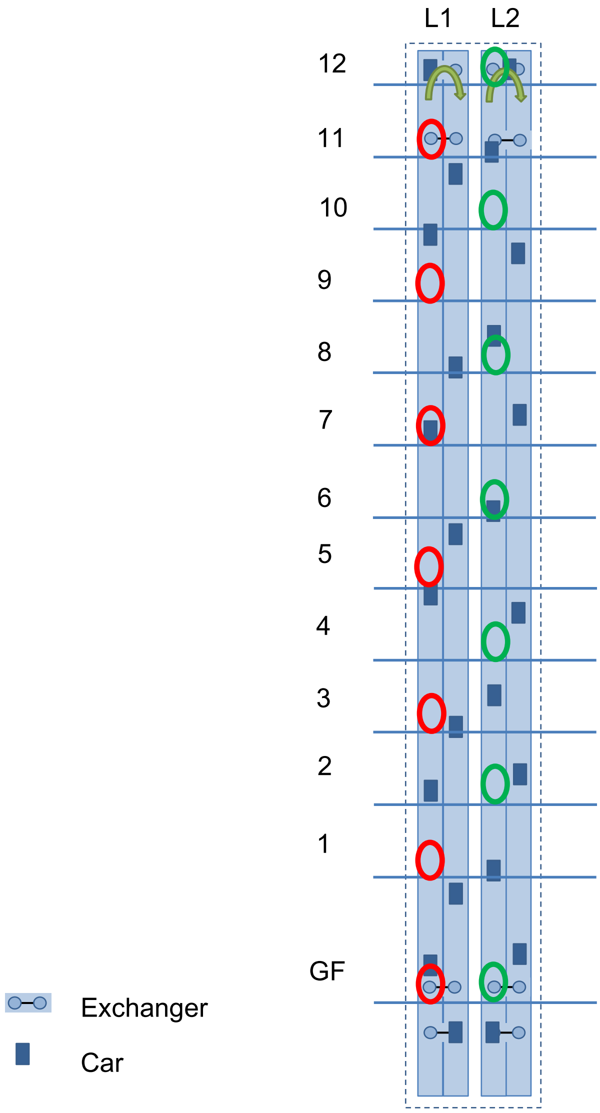


Figure 12-3: Alternating floor assignment of multiple MCLS loops

The advantage is obvious: Each loop has less possible served floors and the distances between served floors are higher than the minimum distance between cars. The positive effect of the floor assignment in a group of two MCLS loops serving 20 floors with conventional control is illustrated in Figure 12-4. It shows an increased HC for a pure incoming traffic of greater than 20% per loop. A fixed served floor assignment in a conventional control system requires appropriate signage to guide passengers. The served floor assignment is hidden from passengers if a destination control system is used. Passengers are guided as their destination calls are assigned to the right shaft to use. A flexible call dispatcher can vary for better allocations in special situations.

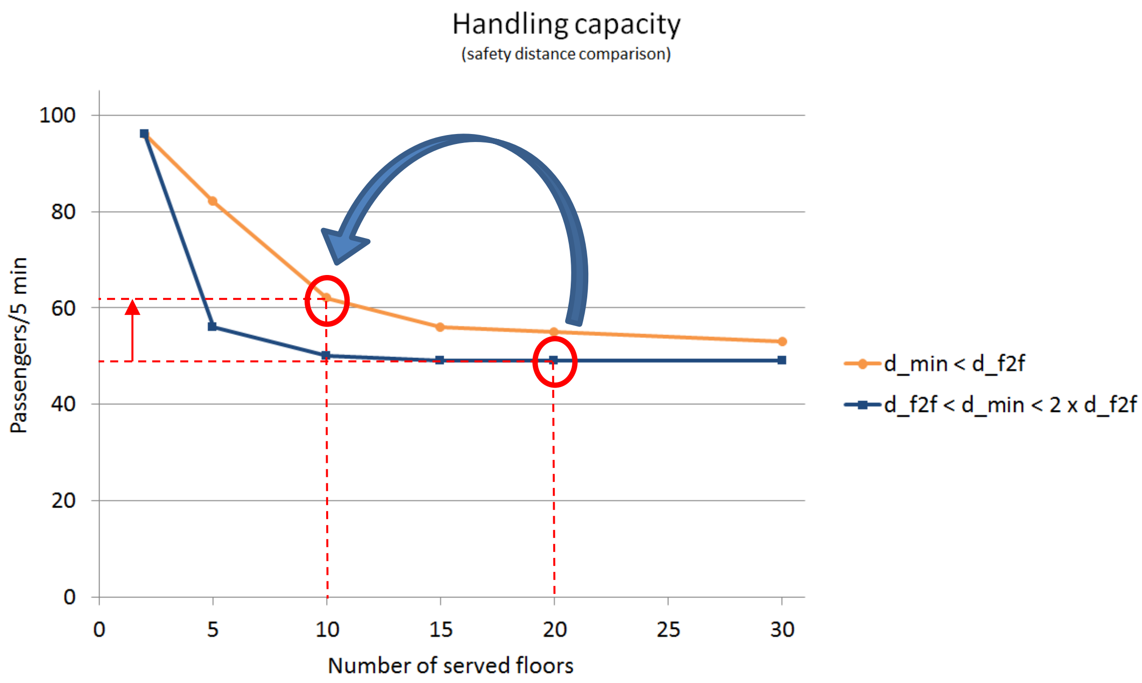


Figure 12-4: Effect of served floor assignment

A similar served floor assignment can be realised with double entrance floors. This is shown in Figure 12-5. The disadvantage of this is that passengers entering the building need to find the way to their dedicated entrance floor. In the given example, passengers travelling to floor 1 and 2 have to use the lower entrance floor, passengers to floor 3 and 4 the upper entrance floor, passengers to 5 and 6 have to use lower entrance floor, and so on.

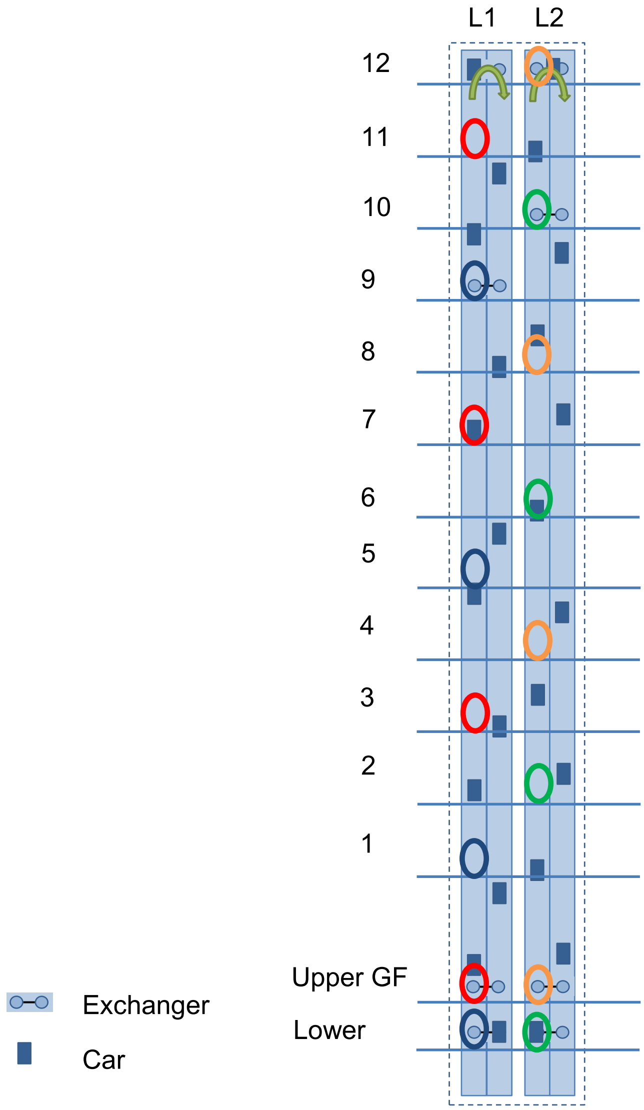


Figure 12-5: Alternating floor assignment of multiple MCLS loops with a double entrance lobby

12.4 Synchronisation within a single MCLS loop

Effective operation of a group of circulating MCLSs requires effective operation of cars within a MCLS loop. If a car is using a shaft exclusively there is no need for any coordination between cars to avoid "traffic jams" or departure delays. In a MCLS traffic control, algorithms need to synchronise and coordinate cars to avoid "traffic jams" and minimise departure delays. The bunching effect (Al-Sharif, 1993), seen in conventional roped lifts groups, causes "traffic jams" in a circulating MCLS as cars using the same shafts and cannot bypass each other. Cars need to be equally spaced with sufficient time between following cars. Early traffic controllers for conventional lift groups dispatched cars from the main entrance with a fixed time between departures (Barney, 2003). If the bunching effect is low and cars are even distributed a spatial plot of a 3-car lift group can look similar to 3 cars circulating in a MCLS, as shown in Figure 12-6.

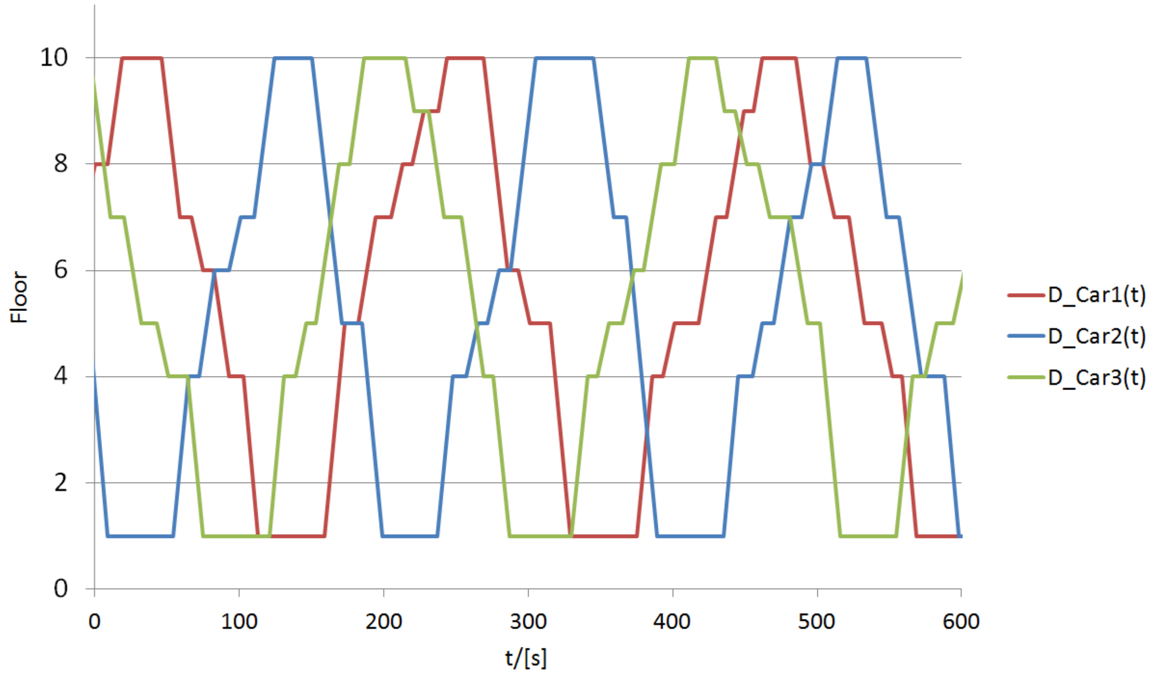


Figure 12-6: Spatial plot of three cars in MCLS

Anti-bunching mechanisms need to be applied to MCLS to coordinate cars within the same loop. These mechanisms should not confuse passengers by breaking the “rules of call control” and “rules of MCLS control” given in section 9.2. To achieve this, the traffic control needs to be able to give commands to modify the lift control standard behaviour as follows:

Flexible speed patterns: In order to delay or speed up a car the speed pattern may be modified. For example, if a car is ahead of schedule it can start a trip with lower velocity to delay the arrival at its next stop. Also velocity may be adapted during a trip.

Modify door opening/closing times: To delay or speed up a car departure the door opening and closing times may be slightly modified to vary the time of a stop without passengers noticing.

Modify door dwell: To change a departure of a car the door dwell time may be modified. This departure delay should be realised by an extension of the door dwell time when passengers are inside the car before the doors start closing. This will have a negative effect on experienced departure delays with open doors and should only be used as an exception and with information displays inside the cars.

If *no passengers* are in the car additional strategies can be applied:

Delay door openings: It is more confusing entering a lift car that does not depart than waiting in the lobby. So, although a car is already at an arrival floor of a waiting passenger, the door opening may be delayed. If the passenger is aware of the waiting car behind the shaft door this strategy will not work, but will confuse and annoy.

Additional stops: Additional stops can help to delay cars during their round trip.

Departure delays: Cars can be delayed by simply delaying their departure.

Additional means to control the synchronisation and coordinate multiple cars are:

Passive area/stock: With an exchanger below the main entrance lobby, a car can be ready to be dispatched to the main entrance lobby at any time. The landing below the main lobby is a passive area with no passenger transfer and can be used as car stock. If a car is delayed in the down direction shaft a waiting car can still be used to serve the main entrance lobby in the up direction shaft.

Middle exchangers: Exchanger units in the middle of the shaft enable cars to short cut the round trip. This can reduce the number active cars in a circulating MCLS loop.

12.5 Control levels

Traffic control can be divided into different control levels that are relevant for the performance of lift groups. Traditionally these are group control and call control. If multiple cars are sharing the same shaft a system control needs to be added (see section 2.2.2). To improve QOS, motion command (determining of speed profiles) needs to be considered in traffic control (see section 8.3). Further improvements are possible by including door commands (see Figure 12-7).

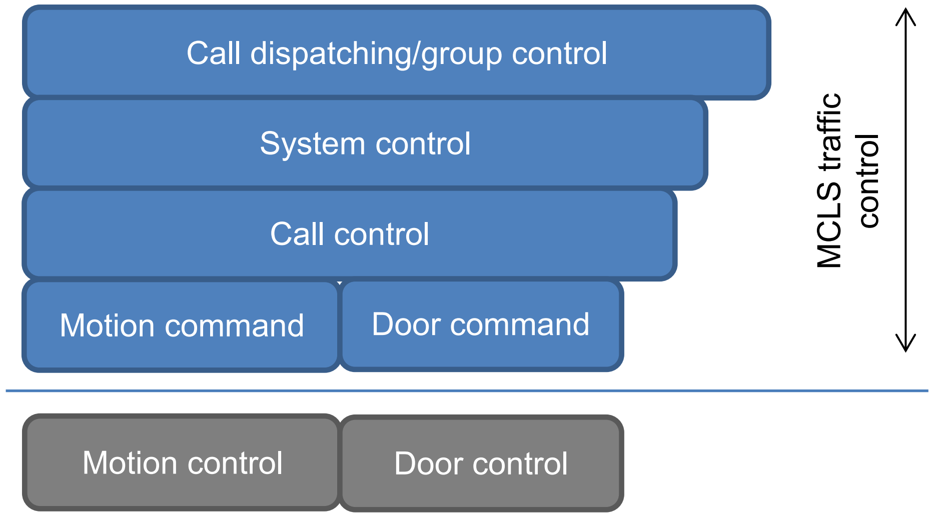


Figure 12-7: Traffic control levels of a MCLS

The tasks of the different control levels in a MCLS can be described as followed:

Call dispatching/Group control: Dispatching algorithms use cost functions to choose the most appropriate call allocation. Waiting time (WT) and transit time (TT) of passengers are known cost variables. New cost variables are considered as well (see chapter 6). The degradation cost of existing passengers caused by an allocation is considered. Mutual interactions between cars and departure delays caused by the system behaviour may affect costs as passengers waiting or travelling in all cars of a loop are affected. This control level allocates landing or destination calls to cars considering system control behaviour, call control behaviour, door commands and motion command. It indicates to the system control how many cars are needed and what cycle time is needed. It synchronizes different loops if necessary.

System control: System control ensures that safety distances (see chapter 7) are not violated. It controls the loop internal coordination and synchronization of the cars (see section 12.4). Therefore, it uses the door and motion command unit. System control considers the call control behaviour and adds additional journey and stop requests for cars if necessary. It also coordinates the process of bringing new cars in and out of the loop if the number of cars can be adapted due to traffic intensities.

Call control: Call control algorithms optimise the service for the allocated calls of a single car. Compared to conventional lift systems it is not limited to one vertical shaft and includes horizontal movement on exchanger levels. Additional constrains e.g. that shafts are used as one way tracks needs to be considered.

Motion command: Motion command is responsible to calculate parameters for speed pattern profiles considering safety distance constraints between cars and cars and exchanger units.

Door command: Based on served calls, transferring passengers at landings and synchronisation demands door dwell times and door closing profiles are calculated and adapted.

12.6 Summary

If multiple MCLS loops are operated as a common lift group the performance of each loop can be improved with destination control or “served floor assignment” (compare with sub zoning for conventional lifts) because the operation of each MCLS loop can be optimised. Cycle times between cars can be reduced as their individual stops can be controlled and distances between cars are used as input parameters. The operation of the cars of each loop needs to be supported by a “system control”. Motion and door command supports the coordination and synchronisation of cars implementing “rules of call control” and “rules of MCLS control” within a MCLS loop.

13 Conclusion

13.1 General

This research was focused on quality of service (QOS) experienced by lift passengers in lift systems where multiple cars are sharing same shafts (multi car lift systems) and destination control systems. New QOS criteria for traffic analysis were defined and addressed by lift control algorithms including variable speed profiles. Opportunities and constraints that impact handling capacity (HC) and passengers experience using these advanced vertical transportation systems were explored.

The overall aim of the research was to determine and analyse existing and new QOS criteria for multi car lift systems (MCLS) and destination control systems in terms of traffic handling and developing lift control concepts considering these QOS criteria.

13.2 Findings and application

13.2.1 Quality criteria

Existing QOS criteria are focused on conventional and traditional lift systems and are mostly defined by waiting time (WT). The overall experience of lift passengers using MCLSs and destination control systems was analysed and linked to the psychology of waiting. Lift architecture and user interfaces have an impact to non-reality aspects of QOS that are psychological phenomena like perception. Lift designers need to consider these aspects for passengers' satisfaction using lifts. Additionally, lift control functionality, which defines the lift behaviour, needs to support the perception of lift passengers. Lift control functionality is also responsible for the measurable reality. WT is the main quality measure that aligns with psychological of waiting concepts. In this thesis it has been proposed that, especially in destination control systems, waiting passengers can face situations that may be perceived as unfair. The probability of these situations depends on the optimisation objectives of the dispatching and control algorithms. Detailed analysis was completed for reverse journey and departure delay situations. Figure 13-1 shows an overview of the existing main quality criteria (waiting time and transit time) and the new quality criteria introduced in this thesis. Reverse journeys and departure delays are special parts of passengers' transit causing higher anxiety and frustration for passengers. The number of reverse journeys is a relevant criterion for destination control systems. Departure delays are mostly relevant for MCLS.

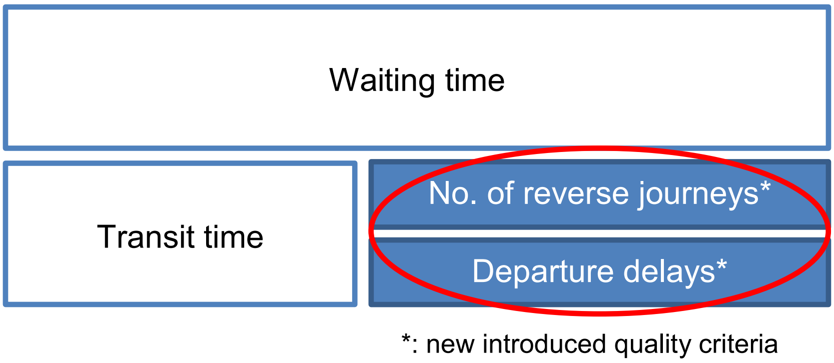


Figure 13-1: Overview quality criteria

In a reverse journey a passenger is initially taken into the opposite direction of his or her desired direction. Reverse journeys were introduced as new QOS criterion. An existing dispatching algorithm was extended to assess the impact of reverse journey situations in destination control systems using traffic simulation. Destination control systems are particularly susceptible to reverse journeys. A reverse journey violates the accepted "rules of call control" as it is confusing for passengers. This research proved that avoiding reverse journeys is a constraint for destination control systems and limits options for the dispatching algorithms. If reverse journeys are allowed, especially in mixed traffic situations, WT as main QOS criterion can be improved significantly. With proper indication (improved user interfaces) this is a possible configuration of lift control algorithms for real lift installations. There are also lift arrangements (e.g. unequal floors and multiple entrance floors) with a high susceptibility for reverse journeys. This should be considered when planning lifts.

Another new QOS criterion that was introduced is departure delays. Passengers who are on their journey to their destination expect the car to depart after passenger transfer has finished. In multi cabin and multi car lift systems, departure delays are likely as passenger transfer times or stops of cars can be different and one car can delay the departure of another car. Measures have already been requested by operators and clients of multi car and double deck lift installations to get a statistical and objective data. Also situations where departure delays can happen in conventional lift systems were indicated. For example longer door dwell times because of passengers still walking to the lift can delay a departure. Therefore, how to measure departure delays was defined independently from the lift system type. Measures that are passenger related (passenger departure delay) and cabin related (cabin departure delay) were introduced. Delays with open and closed doors were distinguished as they have different pain levels. Delays with closed doors are more painful as the situation is less under passengers' control. As the definition of how to measure departure delays was provided this may be used as additional quality criterion especially for MCLS and double deck lifts. The departure delay measures are necessary if lift systems and their control algorithm are to be improved in terms of passengers' satisfaction.

In general user interfaces play a key role in communicating unexpected scenarios for passengers while travelling in lifts. Unexplained waits feel longer than explained waits. Therefore, unexpected scenarios need to be explained using displays or voice announcements. Even if departure delays are explained the lift controller should consider the perception and expectation of lift passengers. Waiting situations need to be appropriate. Control algorithms beyond group control and dispatching algorithms need to take special situations into account.

13.2.2 Traffic control

Traffic control algorithms need to consider quality criteria. An overview of the main control levels involved are shown in Figure 13-2. Traditionally "call dispatching" and "call control" are the main traffic control levels. Additionally, these control levels need to consider reverse journey situations for destination control systems. To minimise departure delays, system control and motion control are also introduced as part of traffic control to optimise the operation of MCLSs.

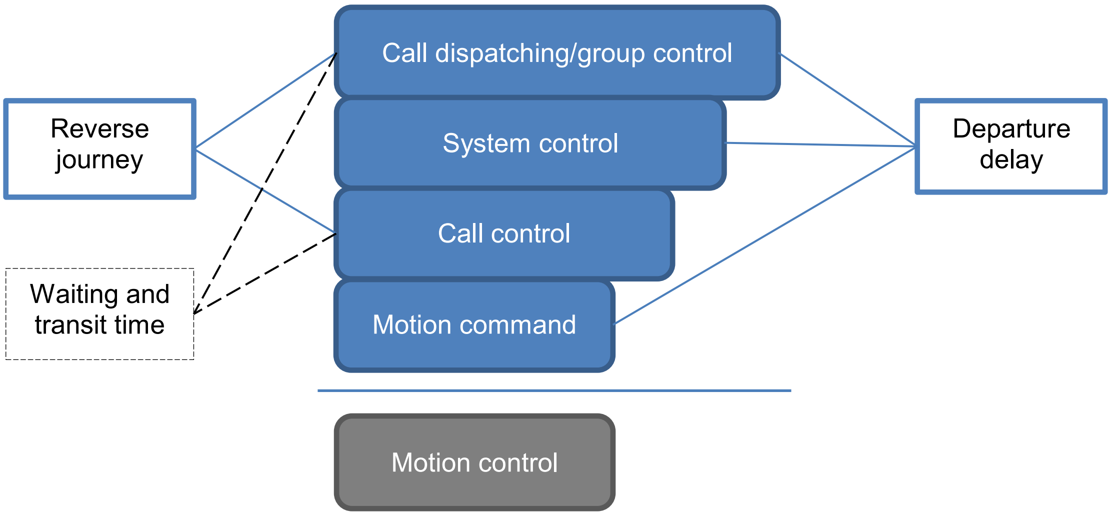


Figure 13-2: Traffic control levels considering QOS criteria

The existing Estimation Time to Destination (ETD) dispatching algorithm considers WT and transit time (TT) cost. Optimisation objectives can be biased by using different factors for WT and TT. New QOS parameters (e.g. departure delays, reverse journeys) were applied and added to the definition of the cost function to introduce a new QOS dispatching algorithm. An online survey (see section 6.2) supports the idea that different phases of a passenger's journey should be associated with different pain levels. The QOS dispatching algorithms can be applied to lift systems with single or multiple cars per shaft and double deck lifts. It needs to be implemented and further evaluated using traffic simulation.

If multiple independent cars are sharing the same shaft(s) not only dispatching algorithms (allocating calls to cars) can optimise departure delays. By optimising the movement of cars (kinematics) departure delays can be reduced as well. But required distances between cars need to be known in order to control and optimise the cars' operation. One aspect is the characteristics of existing certified safety systems that generate an operational distance while levelling at a floor. This affects minimum possible distances between cars. Equations to calculate this operational distance were derived. Another aspect is the required distance between cars while travelling. In unexpected situations, emergency stops from certified safety systems should be avoided by using a controlled deceleration. A controlled deceleration provides more comfort and is less concerning for lift passengers. Equations for controlled deceleration and stopping points were derived during this research. These are necessary if the kinematics of lifts are to be optimised in a MCLS.

To reduce departure delays and to optimise the movement of two following cars, equations for unsymmetrical travelling curves were derived. With adapted kinematics considering controlled stopping points it was shown that a following car could start a trip at the same time as the leading car. Also HC improvements can be achieved if cars can start earlier with reduced and adapted jerk and acceleration rates. This was confirmed by a case study for a shuttle application with two independent roped lift cars in one shaft. The equations of controlled stopping points and unsymmetrical travelling curve that were developed in this research have been used as input of a development project for a lift system with two independent roped cars in one shaft. Additionally, this can be used for ropeless lift systems.

13.2.3 Ropeless lift system

A ropeless circulating MCLS, currently under development, operates multiple independent cars in multiple vertical and horizontal shafts. It was analysed and shown that this new lift system has different characteristics compared to traditional roped lifts. There are new opportunities but also constraints that need to be understood and considered for traffic control algorithms and vertical transportation design in buildings. As shafts in the ropeless circulating MCLS are operated as one way tracks, reverse journeys are unlikely. However, departure delays are possible as cars may block each other's ways.

Operations of multiple lift cars in multiple shafts need to consider lift passengers' expectations and perceptions. Accepted "rules of call control" were expanded by the "rules of MCLS control" to cover situations with mutual interaction between the cars. In this research the usage of the systems was limited and focused in a way that the lift system can be used by passengers like in traditional lift systems. Destination or conventional control was assumed. This ensures that passengers' expectations using the lift system can be met, but at the same time it limits the system to not use additional opportunities for optimisation, especially if used as local group to distribute passengers to their destination in the building.

With the option of horizontal passenger transportation, a MCLS is no longer only a vertical transportation system, but enables additional ideas and concepts for transportation in buildings. Horizontal transportation of passengers was out of scope for this research. If applied, acceptable acceleration/deceleration and jerk rates for horizontal passenger transportation in lift cars need to be known. By excluding horizontal passenger transfer, the MCLS can be used as shuttle and as local lifts similar to traditional roped lift systems. These applications were explored in this research.

Similar to existing roped lift systems, the maximum possible HC of a MCLS can be achieved if the MCLS is used as express shuttle lifts, connecting entrance floors with sky lobbies. In this research traffic design principles for circulating MCLS were introduced with cycle time calculations. The cycle time in a MCLS is the time between the departures of two subsequent cars in one MCLS loop. Unlike conventional roped lift systems the HC is independent of the cars' round trip time (RTT) if there are enough cars in the system. If the lift cars have a long RTT because of high travel height or slow velocity it is possible to add additional cars to a MCLS loop. So the RTT is important to calculate the necessary and possible number of cars. A circulating shuttle lift system can serve more than one sky lobby without losing HC. The time between two subsequent cars what can be compared with the interval that defines the HC. The cycle time is affected by the standing time, arrival and departure time at floors and times for exchanger units to prepare for another orientation of the car movement.

A comparison between double deck lifts and a circulating MCLS in a double lobby shuttle arrangement showed that high velocities are not necessary for the MCLS to achieve good HCs, and to achieve comparable or even better times to destination (TTDs). The latter is because of short WTs and optimised passenger transfer. Although the ropeless cars were calculated only with half the passengers capacity compared to a double deck cabin, the HC is higher with a travel height above 200m.

The advantage of operating a circulating MCLS as a shuttle is that cars are stopping at the same floors. Departure delays can only be caused by different passengers' loading and unloading times. This is easily to compensate by adapting the velocity of the cars.

If a circulating MCLS is operated as a local group taking passengers to their desired destination floor, lift cars will have individual stops. As cars cannot bypass each other, delays and “traffic jams” are likely if too many cars are operated with too short cycle times. These delays can be reduced and avoided if cycle times are increased, however, this sacrifices HC. An algorithm was developed to compare the stopping sequences of two subsequent cars enabling the determination of additional cycle times. The average cycle time and HC without “traffic jams” was explored and calculated by developing and applying the Monte Carlo simulation. The Monte Carlo simulation method in lift traffic analysis is known for RTT calculations. In this research it was shown for MCLS that if the number of served floors increases the probability of different stops generating “traffic jams” increases. This requires additional cycle time to avoid “traffic jams” and departure delays for passengers. If the minimum distance between cars is longer than floor to floor distances, the cycle time needs to be increased as well to avoid “traffic jams”. The following car has fewer options to stop. The average cycle time calculation using Monte Caro simulation that was developed in this thesis has been applied for traffic analysis for planned new buildings that shall be equipped with ropeless lift systems.

An operation of multiple MCLS loops as one group was explored in this research. For such an arrangement the HC for each loop can be increased. Therefore, the served floors are assigned to the MCLS loops in a manner that the distances between served floors are longer than the minimum distance between cars. Additionally, a dispatcher that allocates calls to loops considering stops and consequent cycle time can increase the HC of each loop.

In this research, the analysis of the circulating MCLS used as a local group was focused on pure incoming traffic (100% incoming) to analyse the general characteristics. However, additional interfloor traffic may affect results. It was assumed that the user interface is the same as in existing lift systems. More sophisticated controls may allocate passengers not only to cars arriving next at a landing door. That can help improve the situation. This requires advanced passenger guidance, good indication (new user interfaces) and passenger awareness that cars loaded at the same landing door will travel to different destination floors. This is unexpected by most lift passengers and could be confusing; but it may be an option in the future.

To manage and control the new quality criterion “departure delays” in MCLS, multiple control levels and tasks are affected. Next to dispatching and call control a system control uses motion commands to adapt unsymmetrical travelling curves and door commands supporting the synchronisation of car operations.

13.2.4 Further work

The traffic analysis for the circulating MCLS, used as shuttle and local group, gives an indication of performance based on existing user interfaces of lift systems. This needs to be proven by implementing traffic control algorithms and computer traffic simulations. Making the traffic control algorithms available in real systems is a challenging task and a number of technical problems need to be solved. The impact on HC and QOS if advanced user interfaces are used in circulating MCLS (e.g. the allocation of the car after the next arriving car at a shaft door) needs to be explored. Additionally, the effect of interfloor traffic on system performance needs to be considered for local groups. The effect on traffic handling performance in special traffic situations needs to be explored. This includes traffic profiles for different building usages, restaurant traffic and special service functions.

Ropeless lift systems open a wide field of possibilities for passenger transportation in buildings. This research was focused on fundamental configurations and applications. The option of complex network of horizontal and vertical shafts within a building especially requires more work in the development of traffic analysis and control algorithms. For horizontal transportation of passengers information about horizontal acceleration/deceleration and jerk rates acceptable for passengers in lifts is necessary.

Dispatching algorithms need to consider QOS criteria not only in circulating MCLS. Proposed strategies need to be applied to real systems. It is important to weigh passengers’ preferences for the different criteria by psychology research.

13.3 Contribution to knowledge

The results of this research can be applied to traffic control algorithms and traffic designs for circulating MCLSs and destination control systems. If systems are assessed only by existing QOS criteria it can lead to systems passengers are not satisfied with. In this research, the focus is on passengers using the lifts so that their satisfaction level can be increased and frustration and confusion is reduced.

This research has contributed to the existing knowledge by:

- Better assessments of QOS for MCLSs, double deck lifts and destination control systems
- The introduction of new concepts of controlling QOS aspects in different traffic control levels
- The formulation of an improved model of car movement in MCLSs including required distance constraints
- The development of improved traffic analysis methods for circulating MCLSs
- Outlining opportunities and constraints in using and controlling circulating MCLSs

References

Al-Sharif, L. (1993) Bunching in lift systems. In: *Elevator Technology 5, Proceedings of Elevcon 1993.* Vienna/Austria: The International Association of Elevator Engineers.

Al-Sharif, L., Abdel Aal, O. F. and Abu Alqumsan, A. M. (2011) The use of Monte Carlo simulation to evaluate the passenger average travelling time under up-peak traffic conditions. In: *Symposium on Lift and Escalator Technologies.* Northampton: The Lift and Escalator Symposium Educational Trust.

Al-Sharif, L. and Abu Alqumsan, A. M. (2015) Stepwise derivation and verification of a universal elevator round trip time formula for general traffic conditions. *Building Services Engineering Research and Technology.* 36 (3), 311-330.

Al-Sharif, L., Abu Alqumsan, A. M. and Khaleel, R. (2014) Derivation of a universal elevator round trip time formula under incoming traffic. *Building Services Engineering Research.* 35 (2), 198-213.

Al-Sharif, L. and Al-Adem, M. (2014) The current practice of lift traffic design using calculation and simulation. *Building Services Engineering Research.* 35 (4), 438-445.

Al-Sharif, L., Aldahiyat, H. M. and Alkurdi, L. M. (2012) The use of Monte Carlo simulation in evaluating the elevator round trip time under up-peak traffic conditions and conventional group control. *Building Services Engineering Research.* 33 (3), 319-338.

Al-Sharif, L., AlOsta, E., Abualhomos, N. and Suhweil, Y. (2017) Derivation and verification of the round trip time equation and two performance coefficients for double-deck elevators under incoming traffic conditions. *Building Services Engineering Research.* 38 (2), 176-196.

Al-Sharif, L., So, A., AlZoubi, Q., Atallah, T., Hijazi, A. A. G. and T.Hammoudeh, A. (2016) Collision prevention procedure for a rectangular two-dimensional elevator traffic system using graphical methods. In: *Elevator Technology 21, Proceedings of Elevcon 2016.* Madrid/Spain: The International Association of Elevator Engineers.

Altenburger, Bernd. (Bernd.Altenburger@thyssenkrupp.com) 2015th. *TWIN.* e-Mail to S. Gerstenmeyer (Stefan.Gerstenmeyer@thyssenkrupp.com, 24.02.2015)

Andrew, P. and Kaczmarczyk, S. (2011) *Systems Engineering of Elevators.* Mobile, Alabama: Elevator World, Inc.

Baldwin, A.C., (2017) Framing up the future. *Elevator World,* 65(9), pp. 80-87

Barney, G. (2003) *Elevator Traffic Handbook.* London: Spoon Press.

Batey, D. and Kontturi, M. (2016) Traffic Analysis for High Rise Buildings to be Modernized. In: *Elevator Technology 21, Proceedings of Elevcon 2016.* Madrid (Spain): The International Association of Elevator Engineers.

Bird, C., Peters, R., Evans, E. and Gerstenmeyer, S. (2016) Your Lift Journey – How Long Will You Wait? In: *Symposium on Lift and Escalator Technologies.* Northampton: The Lift and Escalator Symposium Educational Trust.

CIBSE (2010) *CIBSE Guide D: 2010 Transportation Systems in Buildings.* London: The Chartered Institution of Building Services Engineers.

CIBSE (2015) *CIBSE Guide D: 2015 Transportation systems in buildings.* London: The Chartered Institution of Building Services Engineers.

CIBSE Lifts Group (2013) *Minutes of the CIBSE Lifts Group: Lift (US: Elevator) Traffic Analysis & Simulation Open Forum, 25 September 2013, Highgate House, Northampton* [online]. CIBSE lifts group. Available from: http://www.cibseliftsgroup.org/docs/September2013OpenForumMinutes.pdf [Accessed 04/12, 2017].

Closs, G. D. (1970) *The computer control of passenger traffic in large lift systems.* PhD Thesis, The University of Manchester Institute of Science and Technology.

Elevator World (2015) *The elevator museum - timeline* [online]. Available from: http://www.theelevatormuseum.org/timeline.php [Accessed 05/11, 2015].

Elevator World, (1996) An elevator go round. *Elevator World,* 44(1), pp. 42

EN 81-20:2014 (2014) *Safety rules for the construction and installation of lifts - Lifts for the transport of persons and goods - Part 20: Passenger and goods passenger lifts.* Berlin: DIN Deutsches Institut für Normung e.V.

EN 81-70:2003 (2003) *Safety rules for the construction and installation of lifts - Particular applications for passenger and goods passenger lifts - Part 70: Accessibility to lift for persons including persons with disability.* Berlin: DIN Deutsches Institut für Normung e.V.

facebook (2017) *facebook* [online]. Available from: https://www.facebook.com/ [Accessed 04/26, 2017].

Finschi, L. (2010) State-of-the-art traffic analyses. In: *Elevator Technology 18, Proceedings of Elevcon 2010.* The International Association of Elevator Engineers.

Fortune, J. (1995) Modern double deck elevator applications and theory. In: *Elevator Technology 6, Proceedings of Elevcon 1995.* The International Association of Elevator Engineers.

Godwin, A. (2010) Circular transportation in the 21st century (without the 'beautiful' counterweight!). In: *Elevator Technology 18, Proceedings of Elevcon 2010.* The International Association of Elevator Engineers.

Ikeda, K., Suzuki, H., Markon, S. and Kita, H. (2007) Traffic-sensitive controllers for multi-car elevators; design, multi-objective optimization and analysis. In: *SICE, 2007 Annual Conference.*

Jappsen, H. (2002) High Rise Elevators For The 21st Century. In: *Elevator Technology 12, Proceedings of Elevcon 2002.* The International Association of Elevator Engineers.

Thyssen Aufzugswerke GmbH (1998) *Linear motor for driving an elevator car.* Author/Inventor: R. D. Jessenberger. EP 0858965 B1. 26.04.2000.

Jetter, Markus. (markus.jetter@thyssenkrupp.com) 2015th. *CTBUH paper part 1, draft 1 (Next generation vertical transportation system).* e-Mail to S. Gerstenmeyer (stefan.gerstenmeyer@thyssenkrupp.com (25.04.2015))

Johnston, K. G. (1984) Hemingway and Freud: The Tip of the Iceberg. *The Journal of Narrative Technique.* 14 (1), 68-73.

Kaczmarczyk, S. (2008) The dynamic response of elevator compensating ropes in high-rise buildings. In: *Elevator Technology 17, Proceedings of Elevcon 2008.* The International Association of Elevator Engineers.

King, F., Hesselgren, L., Severin, P., Sveder, P., Tonegran, D. and Salovaara, S. (2014) The Articulated Funiculator. In: *Elevator Technology 20, Proceedings of Elevcon 2014.* The International Association of Elevator Engineers.

Lauener, J., (2007) Traffic performance of elevators with destination control. *Elevator World,* 55(9), pp. 86-94

Levinson, D., Harder, K., Bloomfield, J., Winiarczyk, K., Levinson, D. D., Engineering, D. O. C. and Harder, K. (2004) Weighting Waiting Evaluating Perception of In-Vehicle Travel Time Under Moving and Stopped Conditions. *Transportation Research Record Journal of the Transportation Research.* 1898 , 61-68.

Levy, D., Yadin, M. and Alexandrovitz, A. (1977) Optimal control of elevators. *International Journal of Systems Science.* 8 (3), 301-320.

Lin, Z., Qing, J., Jie, C. and Jianru, W., (2013) Elevator Group Control Method. *Elevator World,* 61(11), pp. 46-54

LinkedIn (2017) *LinkedIn* [online]. Available from: https://www.linkedin.com [Accessed 04/26, 2017].

Lu Yu, Mabu, S., Tiantian Zhang, Eto, S. and Hirasawa, K. (2009) Multi-car elevator group supervisory control system using Genetic Network Programming. In: *Evolutionary Computation, 2009. CEC '09. IEEE Congress on.*

Maister, D. (1985) *The Psychology of Waiting Lines* [online]. Available from: http://davidmaister.com/articles/the-psychology-of-waiting-lines/ [Accessed 02/12, 2014].

Microsoft Corporation. (2007) Microsoft Visual Studio 2008, Version 9.0

Motz, H. D. (1976) On the kinematics of the ideal motion of lifts (in German). *Foerdern Und Heben.* 26 (1), 38-42.

Motz, H. D. (1991) On the ideal kinematics of lifts (in English and Italian) part 1 and 2. *Elevatori.* Jan/Feb 1991 (part 1) and Mar/Apr 1991 (part 2), p. 41-46 (part 1) and 39-43 (part 2).

Müller, J. (2014) Lift Systems in High-Rise Buildings: Handling Capacity and Energy Efficiency. In: *Symposium on Lift and Escalator Technologies.* Northampton: The Lift and Escalator Symposium Educational Trust.

Norman, D. (2008) *The Psychology of Waiting Lines* [online]. Available from: http://www.jnd.org/dn.mss/the_psychology_of_waiting_lines.html [Accessed 05/07, 2014].

ThyssenKrupp Aufzugswerke GmbH (2006) *Aufzugsanlage.* Author/Inventor: W. Nuebling. EP 1698580.

Peters Research Ltd. (2014) ELEVATE, Version 8

Peters, R. (1990) Lift traffic analysis: Formulae for the general case. *Building Services Engineering Research.* 11 (2), 65-67.

Peters, R. (1996) Ideal Lift Kinematics: Derivation of Formulae for the Equations of Motion of a Lift. *The International Journal of Elevator Engineering.* 1 , 60-71.

Peters, R. (1998) *Vertical transporation planning in buildings.* Doctor of Engineering Thesis, Brunel University, Department of Electrical Engineering and Electronics.

Peters, R. (2002) Current technology and Future Developments in Elevator Simulation. *International Journal of Elevator Engineers.* 4 (2)

Peters, R. (2006) Understanding the Benefits and Limitations of Destination Dispatch. In: *Elevator Technology 16, Proceedings of Elevcon 2006.* The International Association of Elevator Engineers.

Peters, R. (2012) Lift Performance Time. In: *Symposium on Lift and Escalator Technologies.* Northampton: The Lift and Escalator Symposium Educational Trust.

Peters, R. (2013a) The Application of Simulation to Traffic Design and Dispatcher Testing. In: *Symposium on Lift and Escalator Technologies.* Northampton: The Lift and Escalator Symposium Educational Trust.

Peters, R. (2013b) *Elevator Traffic Analysis & Simulation 1st Edition, Chapter 7 Destination Control.* Draft,

Peters, R. and Evans, E. (2008) Measuring and Simulating Elevator Passengers in Existing Buildings. In: *Elevator Technology 17, Proceedings of Elevcon 2008.* The International Association of Elevator Engineers.

Peters, R., Mehta, P. and Haddon, J. (1996) Lift traffic analysis: General formulae for double-deck lifts. *Building Services Engineering Research.* 17 (4), 209-213.

Peters, R. and Mehta, P. (1998) Green Lift Control Strategies. *International Journal of Elevator Engineers.* 2

Peters, R., Smith, R. and Evans, E. (2011) The appraisal of lift passenger demand in modern office buildings. *Building Services Engineering Research & Technology.* 32 (2), 159-170.

Pletschen, I., Rohr, S. and Kennel, R. (2011) Simulation und Analyse des Energiebedarf von Aufzugssystemen, Simulation and analysis of the energy consuption of elevator systems. In: *Internationaler ETG-Kongress Würzburg.* Berlin: VDE Verlag GmbH.

Powell, Bruce. (bruce.powell@comcast.net) 2015th. *TWIN simulation.* e-Mail to S. Gerstenmeyer (Stefan.Gerstenmeyer@thyssenkrupp.com, 07.07.2016)

PTC Inc. (2013) PTC Mathcad, Prime 3.0

Sakita, M. (2010) Elevator system with multiple cars in one hoistway. *Elevator World.* 58 (8), 79-88.

Scott, A. (2016) *Are we ready for the ropeless lift?*[online]. Available from: http://www.cibsejournal.com/technical/engineers-cut-lose-as-ropeless-lifts-enter-space-race/ [Accessed 01/08, 2016].

Siikonen, M. (1997a) Customer service in an elevator system during up-peak. *Transportation Research Part B: Methodological.* 31 (2), 127-139.

Siikonen, M. (1997b) *Planning and Control Models for Elevators in High-Rise Buildings.* Research Reports A68. Helsinki University of Technology, Systems Analysis Laboratory.

Siikonen, M. (2000) On Traffic Planning Methodology. In: *Elevator Technology 10, Proceedings of Elevcon 2000.* The International Association of Elevator Engineers.

Siikonen, M. (2013) Traffic Patterns in Hotels and Residential Buildings. In: *Symposium on Lift and Escalator Technologies.* Northampton: The Lift and Escalator Symposium Educational Trust.

Kone Elevator GmbH (1995) *Determination of the number of persons entering and leaving and elevator car.* Author/Inventor: M. Siikonen and N. Roschier. US 5435416.

Smith, A. (2016) *Engineers cut lose as ropeless lifts enter space race* [online]. Available from: http://www.cibsejournal.com/technical/engineers-cut-lose-as-ropeless-lifts-enter-space-race/ [Accessed 01/08, 2016].

Smith, R. (2011) *Determination of Lift Traffic Design Requirements based on New Technologies and Modern Traffic Patterns.* PhD Thesis, The University of Northampton, unpublished.

Smith, R. (2014) Under Lifted Buildings in the MiddleEast. In: *Symposium on Lift and Escalator Technologies.* Northampton: The Lift and Escalator Symposium Educational Trust.

Smith, R. and Peters, R. (2002) ETD Algorithm with Destination Control and Booster Options. In: *Elevator Technology 12, Proceedings of Elevcon 2002.* The International Association of Elevator Engineers.

Smith, R. and Peters, R. (2004) Enhancements to the ETD Dispatcher Algorithm. In: *Elevator Technology 14, Proceedings of Elevcon 2004.* The International Association of Elevator Engineers.

ThyssenKrupp (2009) *Saturation Control for Destination Dispatch Systems.* Author/Inventor: R. Smith and R. Peters. WO 2009032733.

Smith, Rory. (rory.smith@thyssenkrupp.com) 2013th. *Waiting.* e-Mail to S. Gerstenmeyer (stefan.gerstenmeyer@thyssenkrupp.com, 24.04.2013)

So, A., Al-Sharif, L. and Hammoudeh, A. (2014) Analysis of Possible Two Dimensional Elevator Traffic Systems in Large Buildings. In: *Elevator Technology 20, Proceedings of Elevcon 2014.* The International Association of Elevator Engineers.

So, A., Al-Sharif, L. and Hammoudeh, A. (2015) Traffic analysis of a simplified two-dimensional elevator system. *Building Services Engineering Research and Technology.* 36 (5), 567-579.

Sorsa, J., Ehtamo, H., Siikonen, M., Tyni, T. and Ylinen, J. (2009) *The Elevator Dispatching Problem.* Submitted to Transportation Science. September 2009.

Sorsa, J., Hakonen, H. and Siikonen, M. (2005) Elevator selection with destination control system. In: *Elevator Technology 15, Proceedings of Elevcon 2005.* Peking: The International Association of Elevator Engineers.

Sorsa, J. and Siikonen, M. (2006) Double-deck destination control system. In: *Elevator Technology 16, Proceedings of Elevcon 2006.* The International Association of Elevator Engineers.

Sorsa, J., Siikonen, M. and Ehtamo, H. (2003) Optimal control of double-deck elevator group using genetic algorithm. *International Transactions in Operational Research.* 10 (2), 103-114.

Steinhauer, Eduard. (eduard.steinhauer@thyssenkrupp.com) 2015th. *Stoppingdistances MC.* e-Mail to S. Gerstenmeyer (stefan.gerstenmeyer@thyssenkrupp.com, 15.01.2015)

Strakosch, G. and Caporale, R. (2010) *The Vertical Transportation Handbook, Fourth Edition.* Hoboken; New Jersey: John Wiley & Sons, Inc.

Tanaka, S. and Watanabe, M. (2009) Optimization-based collision avoidance in multi-car elevator systems. In: *ICCAS-SICE, 2009.*

Tanaka, S. and Watanabe, M. (2010) Improvement of the optimization-based collision avoidance method for reversal- and livelock-free operation in multi-car elevator systems. In: *SICE Annual Conference 2010, Proceedings of.*

Tanaka, S., Uraguchi, Y. and Araki, M. (2005) Dynamic optimization of the operation of single-car elevator systems with destination hall call registration: Part I. Formulation and simulations. *European Journal of Operational Research.* 167 (2), 550-573.

Thumm, G. (2004) A breakthrough in lift handling capacity. In: *Elevator Technology 14, Proceedings of Elevcon 2004.* The International Association of Elevator Engineers.

ThyssenKrupp Elevator AG (2014) *New era of elevators to revolutionize high-rise and mid-rise construction* [online]. Available from: http://www.urban-hub.com/ideas/new-era-of-elevators-to-revolutionize-high-rise-and-mid-rise-construction/ [Accessed 04/20, 2015].

KONE (2001) *Method and apparatus for allocating passengers by a genetic algorithm.* Author/Inventor: T. Tyni and J. Ylinen. WO 01/65231.

Vogel, R. (1889) *Elevator Systems of the Eiffel Tower, 1889* [online]. Available from: http://www.scientificlib.com/en/Technology/Literature/RobertMVogel/ElevatorSystemsEiffelTower.html [Accessed 05/05, 2015].

Yu, L., Mabu, S. and Hirasawa, K. (2011) Multicar elevator group supervisory control system using genetic network programming. *IEEJ Transactions on Electrical and Electronic Engineering.* 6 (S1), 65-73.

Appendices

Appendix A: List of own publications

Choleau, P., Gerstenmeyer, S. and Jetter, M. (2016) MULTI - a variable lift system for modern buildings. In: *7th European Lift Congress Heilbronn 2016.* Heilbronn: Technical Academy of Heilbronn e.V.

Gerstenmeyer, S. and Peters, R. (2014) Reverse Journeys and Destination Control. In: *Symposium on Lift and Escalator Technologies.* Northampton: The Lift and Escalator Symposium Educational Trust. Available from: https://liftsymposium.org/9-past-events/23-4th-symposium-on-lift-and-escalator-technologies-2014
Republished:
Gerstenmeyer, S. and Peters, R. (2015) Reverse Journeys and Destination Control. In: *Elevator World*, 63(1), pp. 90-96

Gerstenmeyer, S. and Peters, R. (2015) Lifts without ropes: how many shafts and cars are needed? In: *Symposium on Lift and Escalator Technologies*. Northampton: The Lift and Escalator Symposium Educational Trust. Available from: https://liftsymposium.org/9-past-events/27-5th-symposium-on-lift-and-escalator-technologies-2015
Republished:
Gerstenmeyer, S. and Peters, R. (2016) Lifts without ropes: how many shafts and cars are needed? In: *Elevator World*, 64(1), pp. 114-128
Republished:
Gerstenmeyer, S. and Peters, R. (2016) Lifts without ropes: how many shafts and cars are needed? In: *Lift Report*, 42(2), pp. 41-47

Gerstenmeyer, S. and Peters, R. (2016a) Safety distance control for multi-car lifts. *Building Services Engineering Research and Technology*. 37 (6), 730-754. Available from: http://journals.sagepub.com/doi/abs/10.1177/0143624416642266

Gerstenmeyer, S. and Peters, R. (2016b) Multicar dispatching. In: *Symposium on Lift and Escalator Technologies*. Northampton: The Lift and Escalator Symposium Educational Trust. Available from: https://liftsymposium.org/9-past-events/54-6th-symposium-on-lift-and-escalator-technologies-2016

Gerstenmeyer, S. and Peters, R. (2017) Circulating multi car lift system – traffic concept and analysis. *Transportation Systems in Buildings - Special Issue 2016 [online]*, Available from: http://journals.northampton.ac.uk/index.php/tsib/article/download/107/88 [Accessed 03/03, 2017].

Gerstenmeyer, S., Peters, R. and Smith, R. (2017) Departure delays in lift systems. In: *Symposium on Lift and Escalator Technologies*. Northampton: The Lift and Escalator Symposium Educational Trust. Available from: https://liftsymposium.org/9-past-events/65-7th-symposium-on-lift-and-escalator-technologies-2017

Jetter, M. and Gerstenmeyer, S. (2015) A Next Generation Vertical Transportation System. In: *Wood, A. & Gabel, J. (eds.), The Future of Tall: A Selection of Written Works on Current Skyscraper Innovations. Addendum to the Proceedings of the CTBUH 2015 International Conference, New York, 26–30 October 2015*. Chicago: Council on Tall Buildings and Urban Habitat. Available from: http://global.ctbuh.org/resources/papers/download/2408-a-next-generation-vertical-transportation-system.pdf

Smith, R. and Gerstenmeyer, S. (2013) A review of Waiting Time, Journey Time and Quality of Service. In: *Symposium on Lift and Escalator Technologies*. Northampton: The Lift and Escalator Symposium Educational Trust. Available from: https://liftsymposium.org/9-past-events/8-3rd-symposium-on-lift-and-escalator-technologies-2013
Republished:
Smith, R. and Gerstenmeyer, S. (2014) Waiting Time, Journey Time and Quality of Service. In: *Elevator World*, 62(1) pp. 106-111

Appendix B: Operational distance

This appendix shows detailed equations of section 7.3.

Local absolute maximum during period p6:

The stopping point of the safety system while the lift is in period p6 of the travelling curve can be calculated relative to the destination with equation (A-1).

$$D_{URS6}(t) = D_6(t) + d_{URS}\left(V_6(t)\right) - d$$

yields

$$D_{URS6}(t) = x_c - \mathrm{d} - \frac{a\,t^2}{2} + x_b\left(v + \frac{a^2}{2\,j} - a\,t + \frac{a\,d}{v}\right) - \frac{a^3}{6\,j^2} - \frac{v^2}{2\,a} + t\,v$$
$$+ x_a\left(v + \frac{a^2}{2\,j} - a\,t + \frac{a\,d}{v}\right)^2 - \frac{a\,v}{2\,j} - \frac{a\,d^2}{2\,v^2} + \frac{a^2\,t}{2\,j} - \frac{a^2\,d}{2\,j\,v} + \frac{a\,d\,t}{v} \qquad \text{(A-1)}$$

To find the local maximum absolute value differentiation is necessary and shown in equation (A-2).

$$\frac{d}{dt}D_{URS6}(t) = v + \frac{a^2}{2\,j} - a\,t - a\,x_b + \frac{a\,d}{v} - 2\,a\,x_a\left(v + \frac{a^2}{2\,j} - a\,t + \frac{a\,d}{v}\right) \qquad \text{(A-2)}$$

The time of the maximum absolute value can be calculated with setting the differentiation to 0 and solving for t:

$$t_{lma6} = \frac{a}{2\,j} + \frac{v}{a} + \frac{d}{v} + \frac{x_b}{2\,a\,x_a - 1} \qquad \text{(A-3)}$$

Finding the maximum absolute value at time t_{lma6} is determined from equations (A-1) and (A-3), yielding equation (A-4)

$$d_{lma6} = D_{URS6}(t_{lma6})$$

$$d_{lma6} = \frac{a^3 - 2\,a^4\,x_a}{24\,j^2\,(2\,a\,x_a - 1)} - \frac{12\,a\,{x_b}^2 + 24\,x_c - 48\,a\,x_a\,x_c}{48\,a\,x_a - 24} \qquad \text{(A-4)}$$

The result is valid only in the range

$$t_5 \le t_{lma6} \le t_6 \qquad \text{(A-5)}$$

of the travelling curve.

If the local maximum absolute value is not within period p6, the peak value of period p6 will be at the end of period p6 ($D_{URS6}(t_6)$).

$$d_{ma6} = \text{if}\big(t_5 \le t_{lma6} \le t_6, d_{lma6}, D_{URS6}(t_6)\big) \qquad \text{(A-6)}$$

Local absolute maximum during Period p7:

Period p7 of the travelling curve can be considered in a similar way to period p6.

The stopping point of an emergency stop in period p7 of the travelling curve can be calculated relative to the destination with the equation (A-7).

$$D_{URS7}(t) = D_7(t) + d_{URS}\big(V_7(t)\big) - d$$

yields

$$\begin{aligned} D_{URS7}(t) = x_c - d - \frac{a\,t^2}{2} + \frac{j\,t^3}{6} - \frac{a^3}{6\,j^2} - \frac{v^2}{2\,a} + t\,v - \frac{a\,v}{2\,j} - \frac{a\,d^2}{2\,v^2} + \frac{a^2\,t}{2\,j} - \frac{j\,v^3}{6\,a^3} - \frac{d^3\,j}{6\,v^3} - \frac{j\,t^2\,v}{2\,a} + \frac{j\,t\,v^2}{2\,a^2} \\ - \frac{d\,j\,t^2}{2\,v} + \frac{d^2\,j\,t}{2\,v^2} - \frac{d^2\,j}{2\,a\,v} - \frac{a^2\,d}{2\,j\,v} + \frac{d\,j\,t}{a} - \frac{d\,j\,v}{2\,a^2} + \frac{a\,d\,t}{v} \\ + \frac{x_b\,(a^2\,v - j\,t\,a\,v + d\,j\,a + j\,v^2)^2}{2\,a^2\,j\,v^2} + \frac{x_a\,(a^2\,v - j\,t\,a\,v + d\,j\,a + j\,v^2)^4}{4\,a^4\,j^2\,v^4} \end{aligned} \qquad \text{(A-7)}$$

After differentiation the time of a local maximum absolute value can be calculated with the equations (A-8):

$$t_{lma7} = \begin{bmatrix} \frac{a}{j} + \frac{v^2 + a\,d}{a\,v} \\ \frac{a}{j} + \frac{v}{a} + \frac{d}{v} - \frac{1}{4\,j\,x_a} + \frac{\sqrt{1 - 16\,j\,x_a\,x_b}}{4\,j\,x_a} \\ \frac{a}{j} + \frac{v}{a} + \frac{d}{v} - \frac{1}{4\,j\,x_a} - \frac{\sqrt{1 - 16\,j\,x_a\,x_b}}{4\,j\,x_a} \end{bmatrix} \qquad \text{(A-8)}$$

Solution 1 of equations (A-8) equals the end time of the journey (t_7).

Solution 2 of equations (A-8) gives the solution for the time of the maximum absolute value.

The local maximum absolute value can be calculated with equation (A-7) and (A-8) and results in equation (A-9).

$$d_{lma7} = D_{URS7}(t_{lma7})$$

yields

$$d_{lma7} = \begin{bmatrix} x_c \\ -\frac{(1 - 16\,j\,x_a\,x_b)^{\frac{3}{2}} - 3\sqrt{1 - 16\,j\,x_a\,x_b} - 768\,j^2\,{x_a}^3\,x_c - 48\,j\,x_a\,x_b + 192\,j^2\,{x_a}^2\,{x_b}^2 + 48\,j\,x_a\,x_b\sqrt{1 - 16\,j\,x_a\,x_b} + 2}{768\,j^2\,{x_a}^3} \\ \frac{(1 - 16\,j\,x_a\,x_b)^{\frac{3}{2}} - 3\sqrt{1 - 16\,j\,x_a\,x_b} + 768\,j^2\,{x_a}^3\,x_c + 48\,j\,x_a\,x_b - 192\,j^2\,{x_a}^2\,{x_b}^2 + 48\,j\,x_a\,x_b\sqrt{1 - 16\,j\,x_a\,x_b} - 2}{768\,j^2\,{x_a}^3} \end{bmatrix}$$

(A-9)

Each of the three results is valid only in the range

$$t_6 \le t_{lma7} \le t_7 \qquad \text{(A-10)}$$

of the travelling curve.

The maximum absolute value of period p7 is the maximum of these values that applies for period p7 and the value at the beginning of period p7.

$$d_{ma7} = \max(|d_{lma7}|, |\, D_{URS7}(t_6)|) \quad \text{(A-11)}$$

Overall operational distance:

The overall maximum absolute operational distance is the maximum absolute value of all valid local maximum absolute values of period p6 and p7.

$$d_{opU/D} = \max(|d_{ma6}|, |d_{ma7}|) \quad \text{(A-12)}$$

Appendix C: Controlled deceleration with jerk

This appendix shows detailed equations of section 7.4.3.

$t_x \leq t \leq t_{D3}$ (period D3) and $t_{D3} \leq t \leq t_{D5}$ (period D5):

Controlled deceleration starts with the constant negative jerk value.

$$J_{D3}(t_d) = -j_d \qquad \text{(A-13)}$$

Acceleration is the current acceleration added to the integration of the jerk:

$$A_{D3}(t_d) = a_x + \int_0^{t_d} J_{D3}(\tau_d) d\tau_d$$

yields

$$A_{D3}(t_d) = a_x - t_d\, j_d \qquad \text{(A-14)}$$

Velocity is the current velocity added to the acceleration integrated:

$$V_{D3}(t_d) = v_x + \int_0^{t_d} A_{D3}(\tau_d) d\tau_d$$

yields

$$V_{D3}(t_d) = a_x\, t_d - \frac{j_d\, {t_d}^2}{2} + v_x \qquad \text{(A-15)}$$

The distance travelled starting from the early deceleration process is the velocity integrated.

$$D_{D3}(t_d) = \int_0^{t_d} V_{D3}(\tau_d) d\tau_d$$

yields

$$D_{D3}(t_d) = \frac{a_x\, t_d^{\,2}}{2} - \frac{j_d\, t_d^{\,3}}{6} + v_x\, t_d \tag{A-16}$$

As the process started in D3 is continued in period D5 the equations (A-17) to (A-20) for period D5 are the same like the equations (A-13) to (A-16) in the previous period $D3$.

$$J_{D5}(t_d) = -j_d \tag{A-17}$$

$$A_{D5}(t_d) = A_{D3}(t_{D3}) + \int_{t_{D3}}^{t_d} J_{D5}(\tau_d)d\tau_d$$

yields

$$A_{D5}(t_d) = a_x - t_d\, j_d \tag{A-18}$$

$$V_{D5}(t_d) = V_{D3}(t_{D3}) + \int_{t_{D3}}^{t_d} A_{D5}(\tau_d)d\tau_d$$

yields

$$V_{D5}(t_d) = a_x\, t_d - \frac{j_d\, t_d^{\,2}}{2} + v_x \tag{A-19}$$

$$D_{D5}(t_d) = D_{D3}(t_{D3}) + \int_{t_{D3}}^{t_d} V_{D5}(\tau_d)d\tau_d$$

yields

$$D_{D5}(t_d) = \frac{a_x\, t_d^{\,2}}{2} - \frac{j_d\, t_d^{\,3}}{6} + v_x\, t_d \tag{A-20}$$

$t_{D5} \le t \le t_{D6}$ (period D6):

Period D6 is the period with a constant deceleration. This period only exists if the maximum deceleration (a_{dMax}) of the controlled deceleration can be reached. Otherwise the next period D7 is directly follows period D5.

Period D6 has no jerk:

$$J_{D6}(t_d) = 0 \tag{A-21}$$

Acceleration in period D6 is the acceleration at the end of the previous period added to the integration of the jerk:

$$A_{D6}(t_d) = A_{D5}(t_{D5}) + \int_{t_{D5}}^{t_d} J_{D6}(\tau_d) d\tau_d$$

yields

$$A_{D6}(t_d) = -a_d \tag{A-22}$$

Velocity in period D6 is the velocity at the end of the previous period added to the integration of the acceleration:

$$V_{D6}(t_d) = V_{D5}(t_{D5}) + \int_{t_{D5}}^{t_d} A_{D6}(\tau_d) d\tau_d$$

yields

$$V_{D6}(t_d) = v_x + \frac{{a_d}^2 + 2\, a_d\, a_x + {a_x}^2}{2\, j_d} - a_d\, t_d \tag{A-23}$$

Distance travelled in period D6 is the distance at the end of the previous period added to the integration of the velocity:

$$D_{D6}(t_d) = D_{D5}(t_{D5}) + \int_{t_{D5}}^{t_d} V_{D6}(\tau_d) d\tau_d$$

yields

$$D_{D6}(t_d) = \frac{v_x\,(a_d + a_x)}{j_d} - \frac{(a_d + a_x)^3}{6\,{j_d}^2} - \frac{(a_d + a_x - j_d\,t_d)\,({a_x}^2 + a_d\,a_x + 2\,v_x\,j_d - a_d\,j_d\,t_d)}{2\,{j_d}^2} + \frac{a_x\,(a_d + a_x)^2}{2\,{j_d}^2} \qquad \text{(A-24)}$$

$t_{D6} \leq t \leq t_{D7}$ (period D7):

Period D7 decreases the deceleration rate of the lift car with a constant positive jerk value. This period ends with the standstill of the lift car.

Period D7 starts with the jerk:

$$J_{D7}(t_d) = j_d \qquad \text{(A-25)}$$

Acceleration in period D7 is the acceleration at the end of the previous period added to the integration of the jerk:

$$A_{D7}(t_d) = A_{D6}(t_{D6}) + \int_{t_{D6}}^{t_d} J_{D7}(\tau_d)d\tau_d$$

yields

$$A_{D7}(t_d) = j_d\,t_d - a_x - a_d - \frac{j_d\,v_d}{a_d} \qquad \text{(A-26)}$$

Velocity in period D7 is the velocity at the end of the previous period added to the integration of the acceleration:

$$V_{D7}(t_d) = V_{D6}(t_{D6}) + \int_{t_{D6}}^{t_d} A_{D7}(\tau_d)d\tau_d$$

yields

$$V_{D7}(t_d) = v_x + \frac{j_d\,{t_d}^2}{2} + \frac{{a_d}^2}{2\,j_d} + \frac{{a_x}^2}{j_d} - a_d\,t_d - a_x\,t_d + \frac{j_d\,{v_d}^2}{2\,{a_d}^2} + \frac{a_d\,a_x}{j_d} + \frac{a_x\,v_d}{a_d} - \frac{j_d\,t_d\,v_d}{a_d} \qquad \text{(A-27)}$$

Distance travelled in period D7 is the distance at the end of the previous period added to the integration of the velocity:

$$D_{D7}(t_d) = D_{D6}(t_{D6}) + \int_{t_{D6}}^{t_d} V_{D7}(\tau_d) d\tau_d$$

yields

$$D_{D7}(t_d) = \frac{j_d\, t_d^{\,3}}{6} - \frac{a_x\, t_d^{\,2}}{2} - \frac{a_d\, t_d^{\,2}}{2} - \frac{a_d^{\,3}}{6\, j_d^{\,2}} - \frac{a_x^{\,3}}{3\, j_d^{\,2}} + v_x\, t_d - \frac{a_d\, a_x^{\,2}}{2\, j_d^{\,2}} - \frac{a_d^{\,2}\, a_x}{2\, j_d^{\,2}} - \frac{a_x\, v_d^{\,2}}{2\, a_d^{\,2}} + \frac{a_d^{\,2}\, t_d}{2\, j_d} - \frac{j_d\, v_d^{\,3}}{6\, a_d^{\,3}} + \frac{a_x^{\,2}\, t_d}{j_d} - \frac{j_d\, t_d^{\,2}\, v_d}{2\, a_d} + \frac{j_d\, t_d\, v_d^{\,2}}{2\, a_d^{\,2}} - \frac{a_x^{\,2}\, v_d}{2\, a_d\, j_d} + \frac{a_d\, a_x\, t_d}{j_d} + \frac{a_x\, t_d\, v_d}{a_d} \quad \text{(A-28)}$$

Appendix D: Unsymmetrical travelling curve: times

This appendix shows derivations of equations in section 8.2.1.

To calculate and derive equations for distance travelled, velocity, acceleration and jerk of the different periods the time points a period ends and a next period starts needs to be calculated.

$$t_{G1} = \frac{a_1}{j_1} \quad \text{(A-29)}$$

Finding t_{G2} and t_{G3}:

The velocity at the end of period 3 (v_{tG3} equals the maximum velocity of a journey) can be calculated with equation (A-30).

$$v_{tG3} = \frac{a_1\, t_{G1}}{2} + a_1\, (t_{G2} - t_{G1}) + \frac{a_1\, (t_{G3} + t_{G2})}{2} \quad \text{(A-30)}$$

Solve t_{G3} and substitute t_{G2} with equation (A-31) yields in equation (A-33) ($v = v_{tG3}$). Equation (A-31) shows the simplified time point t_{G2}.

$$t_{G2} = t_{G3} - \frac{a_1}{j_2} \quad \text{(A-31)}$$

Using equation (A-33) and integrate it into equation (A-31) yields in equation (A-32) for to calculate t_{G2}.

$$t_{G2} = \frac{v}{a_1} - \frac{a_1\, (j_1 - j_2)}{2\, j_1\, j_2} \quad \text{(A-32)}$$

$$t_{G3} = \frac{v}{a_1} + \frac{a_1\, (j_1 + j_2)}{2\, j_1\, j_2} \quad \text{(A-33)}$$

Finding t_{G4}:

The distance travelled during acceleration is shown in equation (A-34). This equation is generated from $D_{G3}(t_{G3})$.

$$d_{accel} = \frac{v^2}{2\, a_1} + \frac{{a_1}^3}{24\, {j_1}^2} - \frac{{a_1}^3}{24\, {j_2}^2} + \frac{v\, a_1}{2\, j_2} \quad \text{(A-34)}$$

According to the equation (A-34) of the acceleration distance the distance travelled during deceleration is shown in equation (A-35). Substitute $a_1 = a_2$, $j_1 = j_4$, $j_2 = j_3$.

$$d_{decel} = \frac{v^2}{2\,a_2} + \frac{{a_2}^3}{24\,{j_4}^2} - \frac{{a_2}^3}{24\,{j_3}^2} + \frac{v\,a_2}{2\,j_3} \qquad \text{(A-35)}$$

The time of travelling constant velocity (duration of period 4 is t_{p4}) can be calculated with equation (A-36).

$$t_{p4} = \frac{d - d_{accel} - d_{decel}}{v} \qquad \text{(A-36)}$$

Equations (A-34), (A-35) and (A-36) yields in equation (A-37):

$$t_{p4} = \frac{d}{v} - \frac{v}{2\,a_1} - \frac{v}{2\,a_2} - \frac{a_1^3}{24\,v\,j_1^2} + \frac{a_1^3}{24\,v\,j_2^2} + \frac{a_2^3}{24\,v\,j_3^2} - \frac{a_2^3}{24\,v\,j_4^2} - \frac{a_1}{2\,j_2} - \frac{a_2}{2\,j_3} \qquad \text{(A-37)}$$

To calculate t_{G4} equation (A-38) can be used.

$$t_{G4} = t_{G3} - t_{p4} \qquad \text{(A-38)}$$

That yields in equation (A-39).

$$t_{G4} = \frac{d}{v} + \frac{v}{2\,a_1} - \frac{v}{2\,a_2} + \frac{a_1}{2\,j_1} - \frac{a_2}{2\,j_3} - \frac{a_1^3}{24\,v\,j_1^2} + \frac{a_1^3}{24\,v\,j_2^2} + \frac{a_2^3}{24\,v\,j_3^2} - \frac{a_2^3}{24\,v\,j_4^2} \qquad \text{(A-39)}$$

$$t_{G5} = t_{G4} + \frac{a_2}{j_3} \qquad \text{(A-40)}$$

$$t_{G6} = t_{G4} + \frac{v}{a_2} - \frac{a_2\,(j_3 - j_4)}{2\,j_3\,j_4} \qquad \text{(A-41)}$$

$$t_{G7} = t_{G4} + \frac{v}{a_2} + \frac{a_2\,(j_3 + j_4)}{2\,j_3\,j_4} \qquad \text{(A-42)}$$