BOOK 1 OF 2

VERTICAL TRANSPORTATION PLANNING IN BUILDINGS

A Portfolio Thesis for the Degree of Doctor of Engineering in Environmental Technology

by

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ABSTRACT

This thesis is submitted for the degree of Doctor of Engineering in Environmental Technology. The degree is awarded for industrially relevant research, based in industry, and supported by a programme of development courses.

This project aims to contribute to a reduction in the environmental burdens of vertical transportation systems. The author has carried out an environmental assessment showing that the dominating environmental burdens of vertical transportation systems arise from their use of electricity while in operation in buildings.

An assessment of traffic demand has concluded that we are probably over-sizing lifts, and are therefore installing systems that consume more energy than necessary. Traffic planning techniques for single and double deck lifts have been reviewed and developed.

The kinematics (motion) of lifts has been studied. New formulae have been derived that allow us to plot travel profiles for any input of journey distance, maximum velocity, maximum acceleration and maximum jerk. Taking these journey profiles as inputs, a mathematical model of a DC Static Converter Drive has been developed. The model can be used to calculate the energy consumption of any individual lift trip.

A lift simulation program has been developed. The program uses the research in traffic, kinematics and motor modelling as a basis for developing energy saving lift control strategies.

DECLARATION

This portfolio thesis is the result of my own work and, except where explicitly stated in the text, includes nothing which is the outcome of work done in collaboration. No part of this thesis has been or is currently being submitted for a degree, diploma, or any other qualification at any other university.

ACKNOWLEDGEMENTS

The author would like to thank his supervisors, Dr Pratap Mehta of Brunel University and Mr John Haddon of Ove Arup & Partners for supervising this work. The author is also grateful to colleagues at Brunel University, Ove Arup & Partners and the CIBSE Lifts Group for sharing their knowledge and experience which have provided an excellent basis for the research.

The author gratefully acknowledges financial support of this research from the Engineering and Physical Sciences Research Council, The Ove Arup Partnership, and the Chartered Institution of Building Services Engineers.

CONTENTS BOOK 1

EXECUTIVE SUMMARY

0.1 INTRODUCTION

The Engineering Doctorate is a 4 year research degree, awarded for industrially relevant research, based in industry and supported by a programme of development courses. The combined Brunel and Surrey Programme is unique in that it has the specific theme of “Environmental Technology”.

This project aims to contribute to a reduction in the environmental burdens of vertical transportation systems. The most widely used vertical transportation system is the lift or elevator. It was originally assumed, and subsequently demonstrated that the predominant environmental burdens of lift systems are due to their energy consumption while in use in buildings. Reduction of the energy consumption of lift systems has therefore been the main project objective.

0.2 GREEN LIFTS?

Is there such as thing as a “green” lift? Can we design a lift system that delivers good passenger service at an acceptable cost while incurring minimum environmental impact?

To assess the environmental impact of vertical transportation systems, we first need to have some measure of environmental burdens. The science of assessing environmental impact is still in its infancy. However, increasingly companies are quoting and applying Life Cycle Analysis (or Assessment), known as LCA. LCA attempts to quantify the environmental burdens of a product or process during its entire life cycle. It considers components such as

- resource extraction of materials for manufacture
- manufacture and installation
- use of product

- re-cycling and re-use
- waste
- transportation at all stages

Consider a hypothetical eight floor, four lift system manufactured and installed in the United Kingdom, whose life cycle could be represented in a diagram as shown in Figure 0.1

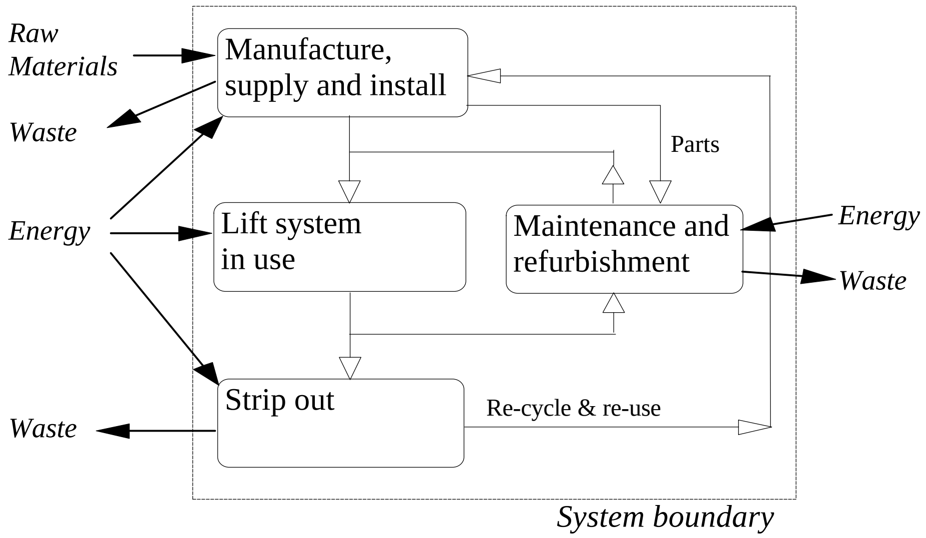

Figure 0.1 Hypothetical lift system Life Cycle Assessment

A computer database from the PEMS[(2.2)] Life Cycle Analysis program has been used to analyse this lift configuration. A summary of the results from the PEMS analysis is given in Figure 0.2. This shows that the dominating environmental burdens in the life of this hypothetical lift system are the non-renewable resources depleted, the waste created and the emissions generated through the production of electricity for operation of the lifts while in use. The environmental burdens associated with other stages in the life cycle are relatively small.

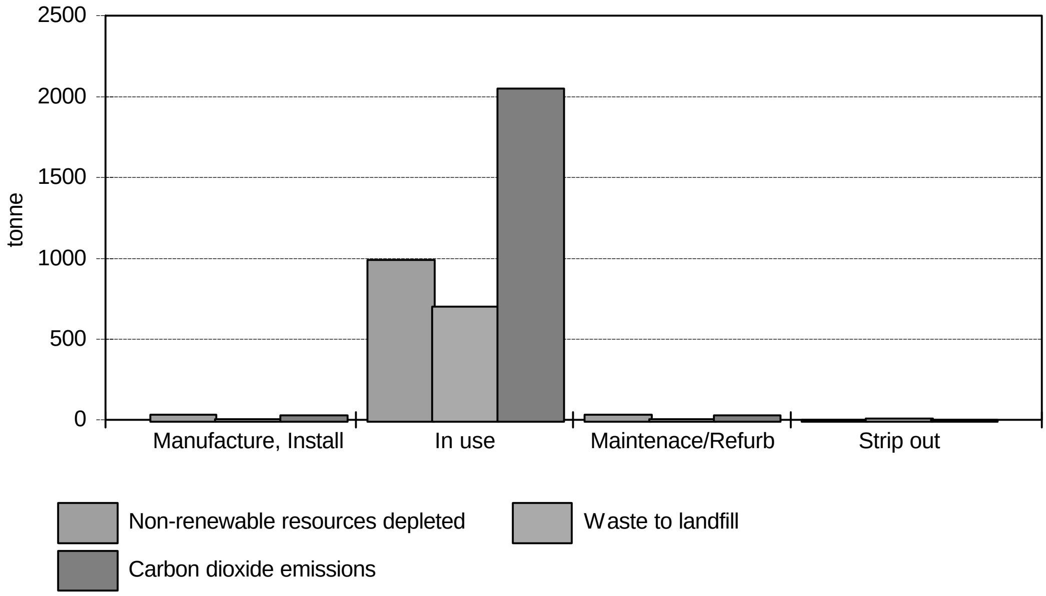

Figure 0.2 Lift Life Cycle Assessment results - impact over entire life cycle

The results are for lift systems, but the findings can be generalised to all vertical transportation systems, all of which have a high energy usage and a long design life.

Use of renewable resources in manufacture, recycling and re-use, efficient transport, disposal/spillage of hydraulic oil, etc. are all important, but secondary issues. Alone they cannot be the basis of claims for a green lift installation.

Where they are installed, lifts and escalators are a significant proportion of the building load; the draft CIBSE Energy Efficiency Guide(2.3) suggests 4 to 7%. Kone sales documentation suggests 5 to 10%. The importance of energy efficient Heating, Ventilation, Air Conditioning (HVAC) and lighting systems is generally accepted; the wealth of related research and development in both these fields reflects this. The author suggests that vertical transportation systems should be among the next in line for "greening".

The use of electricity at current levels is unsustainable, and damaging to our environment. As responsible stewards of the earth, we should be reducing our energy consumption and seeking to develop sustainable energy sources.

There are a number of "basic" principles for green lifts that should be considered by designers before adopting advanced strategies. These include:

- selection of energy efficient lift drives
- minimising inertia and other resisting forces
- efficient lift car lighting
- accessible stairs

Some manufactures promote their products as green because they include energy efficient drives; others promote their use of re-cycled packaging. This project should put these, and other environmental claims in context. For maximum effect in reducing the environmental burdens of lifts, we should concentrate on researching ways of reducing their energy consumption. Although they are not the largest energy user in a building, the potential savings are worthwhile.

0.3 ASSESSMENT OF TRAFFIC DEMAND

Assessment of performance is a crucial element in lift design. If lifts are too small, slow, or insufficient in number, passengers have to wait for excessive periods for a lift to arrive in response to landing calls. On the other hand, the luxury of an over-lifted building is an expensive one - floor area that could be let to tenants is lost to additional or larger lift lobbies and shafts; capital, maintenance and energy costs of the installation are higher.

The need to specify appropriate numbers of lifts, their capacity and speed, etc. has led to the study of lift traffic analysis. But lift performance results from lift traffic analysis are of no better quality than the estimated passenger traffic patterns that are used in the calculations or simulations.

A typical traffic flow for an office building is given by Barney and dos Santos[(3.1)], reproduced in Figure 0.3. Conventional procedure is to base the design of the lift systems on the morning up peak traffic situation.

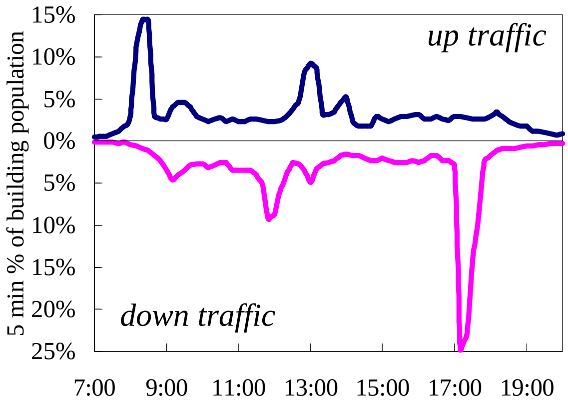

Figure 0.3 Typical office traffic, Barney(3.1)

Passenger traffic surveys have been carried out by the author at a range of buildings. A typical result is given in Figure 0.4.

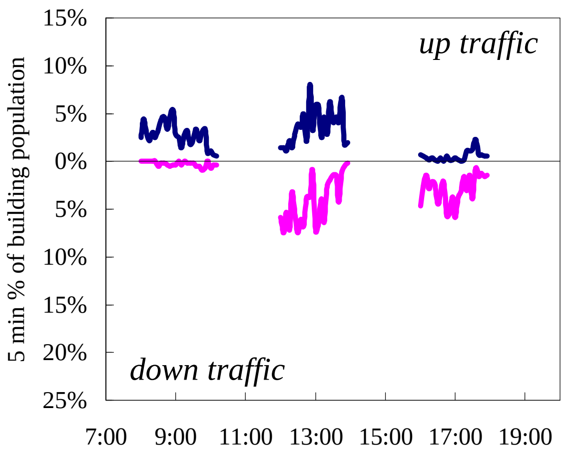

Figure 0.4 Typical office traffic survey

The traffic survey results suggest that the morning traffic peaks are less marked in buildings than they were when traditional up peak design criteria were formulated. In work-related buildings occupied during the day, the busiest time appears to be over the lunch period.

If the traffic studies of commercial buildings made during this research are representative, designers are allowing too much handling capacity during the morning up peak, and not giving enough attention to the waiting times for passengers during the lunch peak.

It would be dangerous to disregard established up peak design criteria without a wider study of building traffic flow peaks; more data must be collected. Thus means of representing and collecting traffic data have been reviewed and developed. The author favours an infra-red beam counting system as the best available technology for data collection.

The research suggests that we need to revise our design criteria. This is unlikely to result in fewer lifts, but would reduce car sizes, and therefore lead to energy savings.

0.4 TRAFFIC ANALYSIS

To realise any savings made through revising our design criteria, we need the appropriate traffic analysis tools. In this thesis we look at analytical traffic techniques, which are currently the most popular and widely applied.

Most lift designs are based on up peak calculations. The up peak is not always the most appropriate choice of peak period for the analysis. Nevertheless, the up peak calculation is important as an industry standard benchmark calculation, and a good starting point for assessing the handling capacity of a lift system.

The up peak lift calculation is based on estimating the time taken for a lift to make a single "round trip" of the building. The calculation assumes that people load the lift at the lowest floor, and get dropped off as the lift stops off at upper floors. The lift then expresses back to the ground floor. The round trip time is calculated for a single lift, so results for two of more lifts are extrapolated accordingly.

Improvements to the "standard" up peak calculation have been proposed. These include:

i. Introduction of formulae for the calculation of flight times. These formulae can be used for any travel distance and lift dynamics; the original calculation is based on a look up table which fixed the floor height and limited the choice of speeds, etc.

ii. Formulation of adjustments made for lifts which do not reach rated speed in a single floor jump.

A sensitivity analysis on the adjustments made for (ii) has demonstrated that the variation between the original and "corrected" results are relatively small (less than 2%).

A computer program has been written to implement the up peak calculation. This program will be given away with CIBSE Guide D *Transportation Systems in Buildings.*

The standard up peak calculation is a valuable tool, but has a number of limitations. These include:

- the calculation only considers up peak traffic; as previously discussed, this is not believed to be the most onerous traffic flow in buildings
- in some instances up peak calculations are inappropriate, e.g. in shopping centres, car parks, airports or hospitals
- it is difficult to adjust the calculation to analyse up peaks for buildings with basements which are occupied

Prior to joining the EngD programme, the author developed an new lift traffic analysis calculation which overcame these limitations. The *General* calculation allows us to carry out a round trip time calculation analysing any peak passenger traffic flow for any practical configuration of conventional lifts. The calculations are implemented in the Oasys (Ove Arup Computer Systems) LIFT program.

To avoid the inefficiencies of over-design, we need improved selection and analysis techniques. The tools developed will help in realising the savings achievable by improving our assessment of traffic demand.

0.5 DOUBLE DECK LIFT TRAFFIC ANALYSIS

Double deck lifts have two separate cabs built into a single unit so that the upper and lower cabs serve adjacent floors simultaneously. During peak periods maximum operating efficiency is achieved by restricting the lower cabs to serving odd numbered floors, and the upper cabs to serving even numbered floors.

Double deck lifts provide greater handling capacity per shaft than conventional lifts. This is particularly attractive for high rise buildings. The sacrifice is that double deck lifts are less convenient for passengers.

The General analysis approach has been applied to double deck lifts. The research carried out allows us to analyse any practical configuration of double deck lifts and any peak traffic flow. The calculations are based on considering the probable number of stops and average reversal floors of a lift during its round trip. The arrival of passengers at a lift landing station is assumed to be approximated by a Poisson process.

The formulae have been implemented by the author in the Oasys LIFT program, and are being used at Arup in the design of high rise developments.

This section of the research arose primarily from the commercial need to analyse high rise buildings. Dependant on loading, double deck lifts may or may not be a “green” vertical transportation system.

0.6 LIFT KINEMATICS

Lift kinematics is the study of the motion of a lift car in a shaft without reference to mass or force. The maximum acceleration and jerk (rate of change of acceleration) which can be withstood by human beings without discomfort limits this motion. Ideal lift kinematics are the optimum velocity, acceleration and jerk profiles that can be obtained given human constraints.

For this research project, equations have been derived which allow ideal lift kinematics to be plotted as continuous functions for any value of journey distance, speed, acceleration and jerk. Supplementary results include journey time formulae for use in lift traffic analysis.

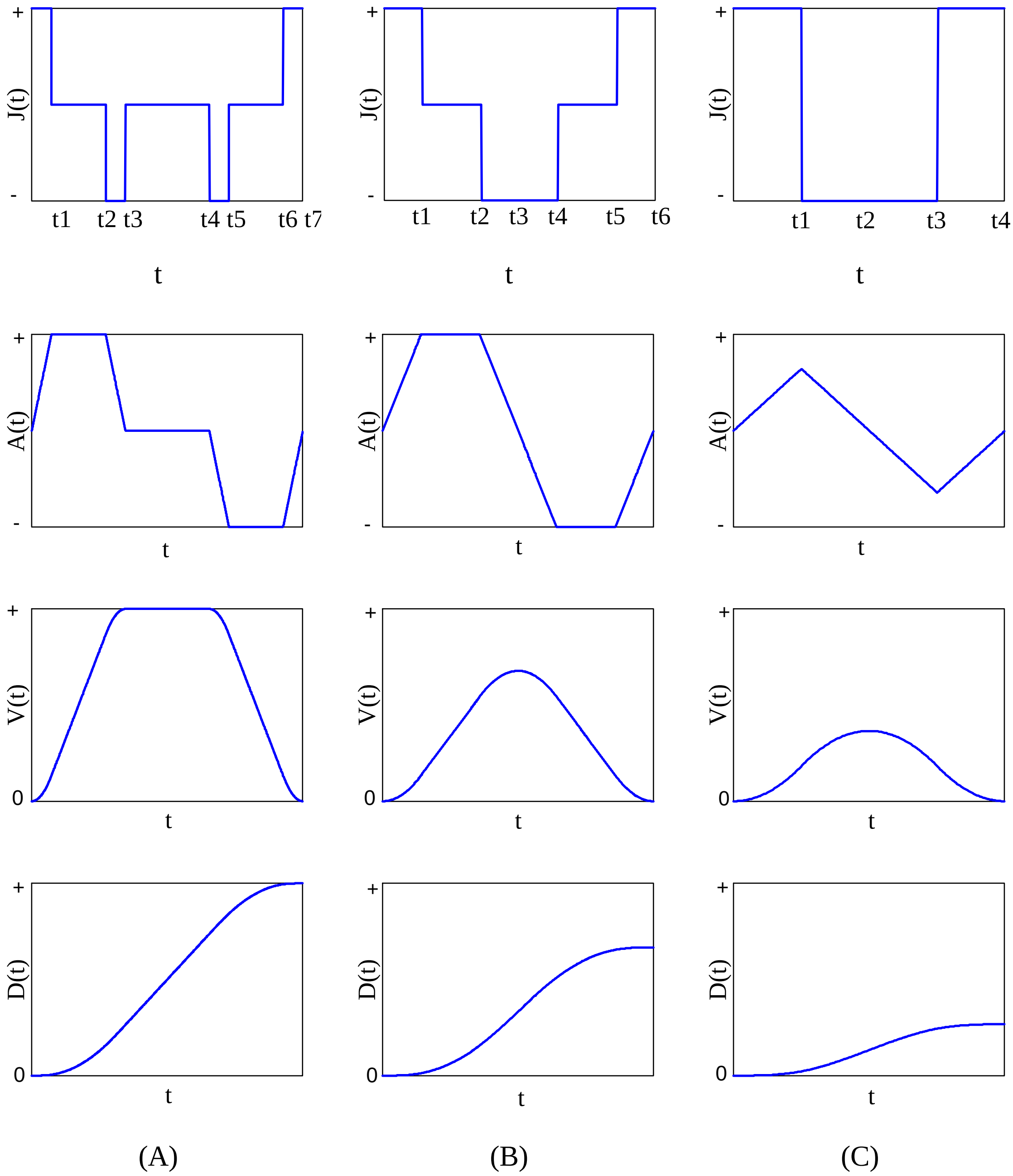

Figure 0.5 Ideal Lift Kinematics for: (A) lift reaches full speed; (B) lift reaches full acceleration, but not full speed; (C) lift does not reach full speed or acceleration

The derivation is divided into three major sections, corresponding to the journey conditions where: (A) the lift reaches full speed; (B) the lift reaches full acceleration, but not full speed; and (C) the lift does not reach full speed or acceleration. Conditions

A to C are represented graphically in Figure 0.5 Each of the three conditions is divided into time slices, beginning and ending at each change in jerk or change in sign of acceleration.

Microprocessor controlled variable speed drives can be programmed to match reference speed profiles generated through the study of lift kinematics. The research undertaken for this project is programmed in software, so these profiles can be generated quickly and easily. In later sections we will discuss how, by varying the kinematics for each trip, we can save energy.

0.7 MOTOR MODELLING

The purpose of this section of the research is to derive a motor model so that it can be built into a lift simulation program. We can then calculate the total energy consumption of a lift system for a given passenger traffic profile and lift control system. This will allow us to investigate possible energy savings.

A motor model based on work by other researches was implemented and extended. The drive is a separately excited DC motor, fed from a fully controlled 6 pulse converter. The model now uses, as an input, the motion profiles generated from the kinematics research. Equations for load torque and load inertia have been developed.

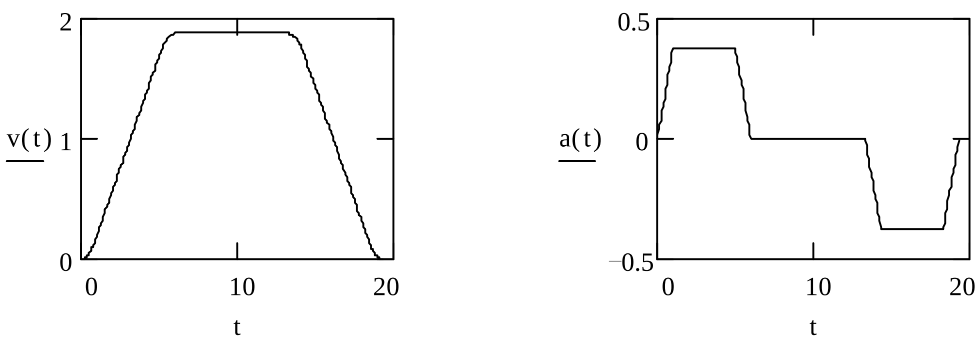

Figure 0.6 Velocity and acceleration profiles

Applying the ideal lift kinematics equations we can generate suitable velocity and acceleration plots, as shown in Figure 0.6.

Applying the motor model, we can calculate the power consumption and power factor during the trip, as plotted in Figure 0.7

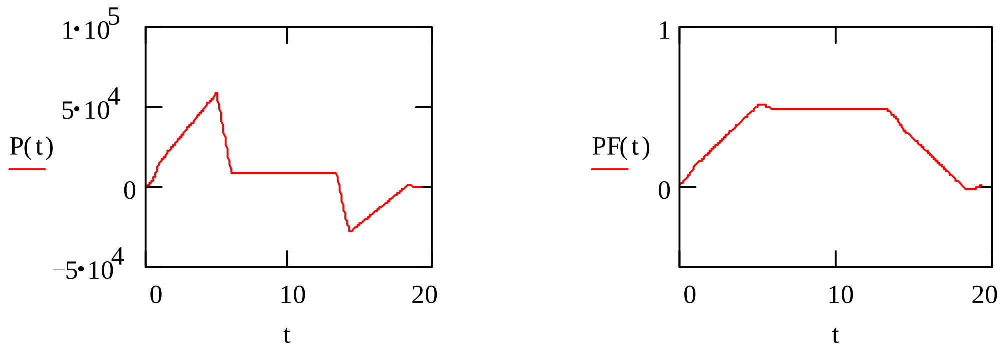

Figure 0.7 Power consumption and power factor during a lift trip

Results from the model are consistent with those presented by other researchers. Site tests suggest that the model is generating consistent power consumption profiles (some input variables could not be measures), and can at least not be rejected.

The motor model is an important component of the tools developed to test energy saving ideas. It has been implemented and applied in *Liftsim* as discussed in the following sections.

0.8 LIFT SIMULATION SOFTWARE

The lift simulation program, *Liftsim* has been written as development platform for "green" lift control systems. It will also have applications as an advanced lift traffic analysis tool.

The program has been written using Microsoft Visual C++ (for Windows 95 and Windows NT). C++ is a complex object oriented language, but it produces very fast programs, and easily reusable/portable code.

Liftsim has seven main simulation classes which define the behaviour of the system. These are:

- The *building* class defines the building in terms of number of stories and story heights.

- The *motion* class implements the ideal lift kinematics research carried out for this project. Programs using the class can specify the journey distance, rated velocity, etc. and output the current distance travelled, velocity, etc. at any time, t, since the journey began.

- The *lift* class defines a lift (rated speed, capacity, floors served, etc.) and its current status (position, speed, load, etc.). The *motion* class is applied to enable the lift to move according to the selected journey profile. The *lift* class includes algorithms to allow lifts to answer landing and car calls according to the principles of directional collective control.

- The *dispatcher* class defines rules for allocating which lift serves which calls. The default dispatcher logic has been based on conventional group control with dynamic sectoring.

- The *person* class defines a person, what time he/she arrives at the landing station, where he/she wants to go, their mass, etc. Once the journey is complete, the class provides details about passenger waiting and journey times.

- The *traffic* class converts arrival rate and destination probability data into a corresponding set of person objects.

- The *motor* class defines the characteristics of the drive. The class calculates the energy consumption and other characteristics of a DC six pulse static converter drive.

The *Liftsim* interface is Windows based, and allows the user to edit all the system data in dialogue boxes containing standard Windows controls (radio buttons, drop downs, etc.) and a spreadsheet-like control for tabular data entry. The program uses a multi-document interface, so the user can be working on a number of different simulations at the same time. A screen shot of the program is given in Figure 0.8.

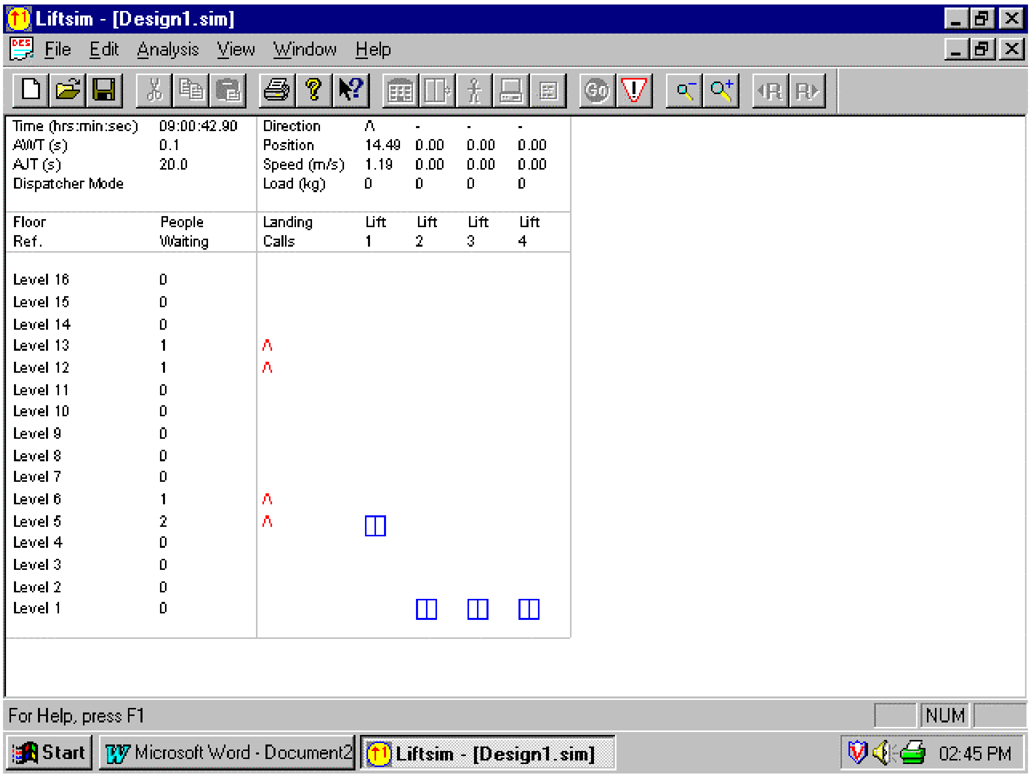

Figure 0.8 Simulation display

The program is a time slice simulation; it calculates the status (position, speed, etc.) of the lifts, increments the time, re-calculate status, increments time, and so on. As Windows is a multitasking operating system, the program cannot take full control of the computer's resources and run in a continuous loop. It must wait for a processing "thread" to become available, run one cycle of the simulation, then wait for the next thread to become available. Provided that there are not too many other demands on the computer's processor, the simulation will run faster than real time on a Pentium PC using a time slice of 0.01 seconds.

Once the simulation is complete, the results print preview includes:

- the input data

- results for average waiting time, longest waiting time, and a plot of the waiting time distribution

- results for average transit time, longest transit time, and a plot of transit time distribution

- the total power consumption for each lift, and total number of motor starts

Liftsim provides us with a power tool to test energy saving ideas. It also has applications as an advanced lift traffic analysis tool.

0.9 GREEN LIFT CONTROL STRATEGIES

Barney and dos Santos[9.1] define a group supervisory control system as *a control mechanism to command a group of interconnected lift cars with the aim of improving lift system performance*. Conventionally this system performance has concerned maximising the handling capacity of the lift system, and minimising passenger waiting and transit times.

It would be counterproductive to ignore conventional system performance criteria as excessive waiting for lifts is very frustrating for passengers. So let us define a green lift control system as a *group control system that considers conventional measures of system performance, as well as means to reduce energy consumption*.

Three strategies that are appropriate to a green lift control system have been considered. The strategies have been implemented, and tested using *Liftsim*.

Green Strategy No.1 - Control of Kinematics

Conventionally lifts have the same maximum velocity, acceleration and jerk for every trip. If the system does allow any variation, this is generally pre-set by the lift service engineer or building owner.

Research by the author in ideal lift kinematics has allowed us to generate, quickly and easily, motion profiles for any input of journey distance, velocity, acceleration and jerk. This allows us to consider control systems that vary all these parameters on line in lift system controllers.

An algorithm has been developed that tests a range of velocity and acceleration options (ranging ± 20% from rated velocity and acceleration) before the start of each trip. In tests a 33.4% saving in energy consumption has been achieved. The average journey time has increased by just 1.3 seconds.

Green Strategy No.2 - Reducing the Number of Stops

The energy consumption of a motoring lift peaks during the acceleration phase, and is relatively low once the lift reaches full speed. There is regeneration during the deceleration phase, but this is less in total than the energy expended during the acceleration phase. Thus it is reasonable to assume that there will be energy savings if we can transport the same number of passengers, with less stops, but without an increase in the overall distance travelled by the lifts.

One way to achieve this is by forcing the dispatcher to allocate a landing call to a lift when it is:

- already due to stop at that floor for a passenger's car call, and
- travelling in the right direction to serve the landing call.

This condition for a "forced" allocation may not occur for some time, e.g. it is unlikely during solely up peak traffic, or during light inter-floor traffic. But most lift systems are likely to benefit from the strategy at some time during their daily cycle.

In tests the "green" algorithm implementing this strategy caused a 3.2% reduction in the number of motor starts, leading to a 6.2% reduction in the energy consumption. The waiting time distribution remains very similar, but there is a minor improvement in transit times.

Green Strategy No.3 - Selective Parking Policies

When a lift has answered all its calls and becomes free, it can be “parked” at the floor it last answered a call, or sent to another floor in anticipation of future calls. From the energy saving viewpoint, we should apply parking policies selectively.

A simulation was set up for a fifteen storey building with very light inter-floor traffic. The simulation was run with and without a parking policy that implements a parking strategy.

The parking strategy improved passenger waiting and journey times, but increased the energy consumption by 43%. The results demonstrate that parking policies improve performance, but are not always appropriate.

Green control systems should place parking calls selectively. This could be achieved by the dispatcher reviewing the potential contribution to system performance of parking calls before deciding whether or not they should be made.

Simulation has demonstrated that each of these strategies will allow green control systems to reduce energy consumption without a significant deterioration in passenger waiting and journey times. The results are for a DC static converter drive, but it would be reasonable to assume that there would be similar savings in applying these strategies with other regenerative drives.

0.10 CONCLUSIONS AND FURTHER WORK

0.10.1 Green lifts

This project aims to contribute to a reduction in the environmental burdens of vertical transportation systems, primarily lifts. It has been shown that energy consumption is by far the most important factor. Further work in this area should be focused on communicating these findings. The lift system will not normally be the largest energy user in a building, but potential energy saving are still worthwhile.

A number of basic principles for green lifts have been identified. The choice of drive, position of stairs, etc. all have a major effect on the energy consumption of the vertical transportation system.

0.10.2 Planning issues

Lift designers need to have a good understanding of passenger traffic demand, and analysis techniques to assess the performance of possible lift configurations. If both of these are not in place, then there is a high probability that installed systems will be either inadequate or over-designed. The first alternative is unacceptable to passengers. The second is unnecessarily expensive, and will consume more energy.

The up-peak seen in commercial buildings is less marked than when current design criteria were formulated. The lunch time peak is now the busiest period. Further surveys need to be carried out to confirm these results, but it is likely that designers are often installing more capacity than is required.

Traffic analysis techniques based on Round Trip Time calculations have been developed and extended. The up-peak calculation has been implemented in a computer program which, it is intended, will be issued with the revised version of CIBSE Guide D, *Transportation systems in buildings*.

As we believe the lunch period is not the most onerous time for the lifts, it is important to be able to assess this period with traffic calculations. We can do this using the General Analysis calculation technique, which the author derived prior to joining the EngD programme. This is a relatively complex technique to implement and to apply. Therefore further research to determine the equivalent lunch time handling capacity relative to a given up-peak handling capacity would be beneficial.

Revising our design criteria is unlikely to result in fewer lifts, but would reduce car sizes, say from 1250 kg to 1000 kg. And therefore lead to energy savings.

0.10.3 Traffic analysis for double deck lifts

Double deck lifts provide greater handling capacity per shaft than conventional lifts. This is particularly attractive for high rise buildings. Formulae have been derived and implemented that allow analysis of any peak traffic flow for any practical configuration of double deck lifts. The approach taken for double deck lifts could be extended to cover triple and quadruple deck lifts if required.

This section of research has arisen primarily from commercial pressures to analyse the performance of lift systems in high rise buildings. A study of the relative energy consumption of double versus single deck lifts for a range of lift installations would be useful further work.

0.10.4 Mathematical models of lift motion and drives

In order to develop strategies for energy saving, we need models to experiment and test our ideas.

The ideal kinematics equations derived allow continuous, optimum functions of jerk, acceleration, speed and distance travelled profiles to be plotted against time. The ability to plot profiles for any input of jerk, acceleration and travel distance gives additional flexibility in the design of lift controllers. This functionality has been applied in the design of green control strategies.

Although there is some guidance already, it would be useful to study more fully the relative levels of ride comfort as the acceleration and jerk are changed.

A motor model based on work by other researches has been implemented and extended. The model now uses, as an input, the motion profiles generated from the kinematics research. Equations for load torque and load inertia have been developed. We can now model the operation and power consumption of a lift trip for any journey, direction and loading. Further research into the modelling of this and other lift drives would be valuable.

0.10.5 Liftsim and green control strategies

The simulation program, *Liftsim* implements the kinematics and motor model research, so provides a development platform for "green" lift control systems.
Liftsim is written in Microsoft Visual C++ using object oriented programming techniques.

Liftsim's passenger generator creates passengers, then the program performs a time slice simulation. The built in control system is based on conventional group control with dynamic sectoring. Additional control systems could be added, which would be worthwhile further work. Once the simulation is complete, *Liftsim* displays results on screen in a print preview format.

Three green lift control strategies have been developed and applied to the dynamic sectoring control algorithm:

(i) Control of kinematics
(ii) Reducing the number of stops
(iii) Selective parking policies

Simulation suggests that we can achieve an energy saving in excess of 30%. These results are for a DC static converter drive. It is reasonable to assume that there would be similar savings in applying these strategies with other regenerative drives. The development of additional drive models would enable us to confirm this assumption.

There is considerable scope for further development and testing of green lift control strategies using *Liftsim*. The performance of existing strategies needs to be tested across a wider range of installations and traffic flows. Other strategies are likely to arise as the simulation is applied and experimented with. It is envisaged that the research will ultimately lead to green lift control systems being implemented by control systems manufacturers.

The program also has applications as an advanced traffic analysis tool, and is being tested on some current Arup jobs.

Chapter 1

INTRODUCTION TO FINAL REPORT

1.1 ENGD REQUIREMENTS AND OBJECTIVES

The Engineering Doctorate (EngD) requirements and objectives are set out in the course handbook and regulations. In summary:

An EngD is a 4 year research degree, awarded for industrially relevant research, based in industry and supported by a programme of development courses.

The combined Brunel and Surrey Programme is unique in that it has the specific theme of "Environmental Technology". The overall Programme thesis is that the traditional practices of Industry are unsustainable. Its aim is to provide Engineering Doctors with the necessary skills to balance environmental risk along with all of the traditional variables of cost, quality, productivity, shareholder value, legislative compliance etc.

The EngD programme requires Research Engineers to submit course work assignments along with regular written evidence of progress on the research project. The research outcome needs to be at least to the same level as a PhD, i.e. the candidate has to make "a contribution to knowledge", as well as demonstrating competence in specified research and business skills.

1.2 BACKGROUND TO THIS PROJECT

The author joined Ove Arup & Partners as a graduate Electrical Engineer in 1987. In the following six years he completed the Arup graduate training programme, and went on to lead the design of electrical services for a number of major, national and international construction projects. His special interest in vertical transportation led to the publication of a number of research papers. With the backing of Ove Arup & Partners, the author joined the Environmental Technology Engineering Doctorate programme in 1993. This has provided an opportunity for him to research, in greater depth, topics that have arisen out of previous industrial experience.

The project was awarded a grant from the Engineering and Physical Sciences Research Council. In addition to sponsorship from Ove Arup & Partners, the Chartered Institution of Building Services Engineers has contributed to the research financially, and taken an active interest in the project.

1.3 PROJECT OBJECTIVES AND BOUNDARIES

This project aims to contribute to a reduction in the environmental burdens of vertical transportation systems. The most widely used vertical transportation system is the lift or elevator. It was originally assumed, and subsequently demonstrated, that the predominant environmental burdens of lift systems are due to their energy consumption, while in use in buildings. Reduction of the energy consumption of lift systems has therefore been the main project objective. Some references will be made to other vertical transportation systems, e.g. escalators. The case for why it is important to consider "Green Lifts" is presented in Chapter 2 of this thesis.

The energy consumption of a lift system is the function of many variables, ranging from the design of the motor, through to planning issues such as the number, size and speed of lifts, passenger traffic levels, and the position of the stairs. Ove Arup & Partners are consultants who specify, as opposed to manufacture engineering systems. Thus the approach taken has been to concentrate mainly on factors that Arup can specify, or may influence industry research and development through published material. These are mainly planning issues, thus the title of this thesis, "Vertical Transportation Planning in Buildings".

1.4 OVERVIEW OF CONTRIBUTION TO KNOWLEDGE

The project has yielded a "contribution to knowledge" in a number of areas which will be outlined in this thesis. These include:

Environmental Assessment

- applying life cycle assessment to demonstrate that “energy in use” is the most significant cause of environmental burden for vertical transportation systems

Lift System Models

- improving our understanding of passenger traffic flows in buildings to provide the basis for improved planning of vertical transportation systems
- development of new and enhanced traffic analysis calculations for better planning
- derivation of formulae to plot ideal lift kinematics
- enhancements to lift motor modelling techniques
- application of object oriented paradigm to lift simulation

Green Control Strategies

- development of energy saving lift control strategies

To date the project has yielded six conference papers and two journal papers. A further journal paper has been accepted for publication. Many of these papers, and other articles have been widely published in the national and international vertical transportation trade press.

Chapter 2

GREEN LIFTS?

2.1 INTRODUCTION

Is there such as thing as a “green” lift? Can we design a lift system that delivers good passenger service at an acceptable cost while incurring minimum environmental impact?

In this chapter we will investigate the environmental impact of vertical transportation systems, and introduce ways of reducing that impact. The discussion begins with Life Cycle Analysis, which enables us to quantify the environmental burdens associated with a product or process.

2.2 QUANTIFYING ENVIRONMENTAL BURDENS

To assess the environmental impact of vertical transportation systems, we first need to have some measure of environmental burdens. The science of assessing environmental impact is still in its infancy. However, increasingly companies are quoting and applying Life Cycle Analysis (or Assessment), known as LCA. LCA attempts to quantify the environmental burdens of a product or process during its entire life cycle. It considers components such as

- resource extraction of materials for manufacture
- manufacture and installation
- use of product
- re-cycling and re-use
- waste
- transportation at all stages

The LCA approach is very good at identifying the key environmental burdens. For example, The Economist reported[2.1]:

- In studies, one washing powder manufacturer has determined that 80% to 90% of the energy used in washing clothes is used once the powder has left the factory, in heating up water in the washing machine. A combination of washing powder and machine that used cold water could therefore be marketed as a truly green laundry product.

- It can be shown that the environmental burdens associated with transporting goods for re-cycling can sometimes outweigh the benefits of recycling the product in the first place. This type of evidence led the Danish government to lift its ban on non-refillable containers.

2.3 LIFT LIFE CYCLE ASSESSMENT

Consider a hypothetical eight floor, four lift system manufactured and installed in the United Kingdom, whose life cycle could be represented in a diagram as shown in Figure 2.1.

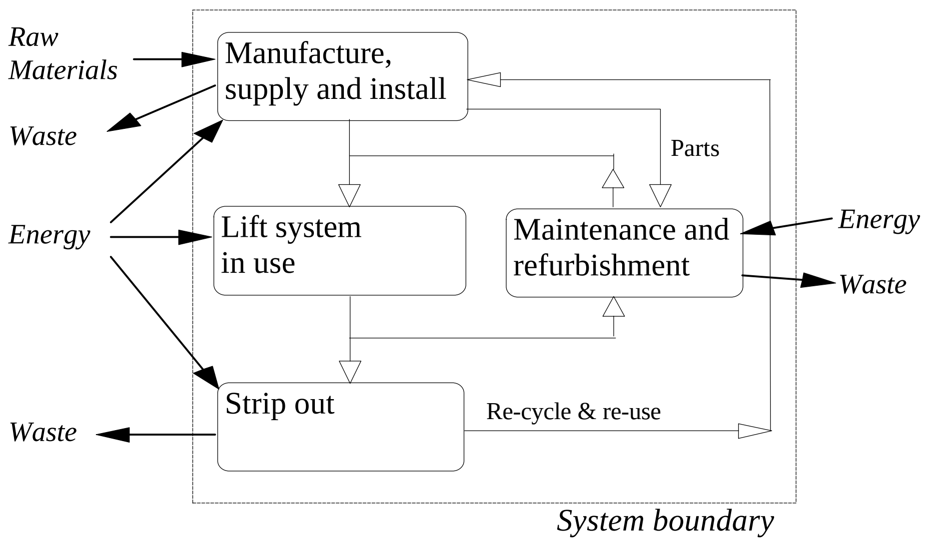

Figure 2.1 Hypothetical lift system Life Cycle Assessment

A computer database from the PEMS[2.2] Life Cycle Analysis program has been used to analyse this lift configuration, based on the following assumptions:

General assumptions

- Life cycle assessment flow diagram as in Figure 2.1
- UK manufactured lift system installed in London
- 4 No 1000kg lifts
- 30 year life with one major refurbishment at 15 years
- Use of PEMS database (The PEMS database is biased towards the packaging industry, so for instance, data for plastic is based on “plastic strap”.)

Manufacture, supply & install

- Estimates of materials used (where PEMS data available): 120 kg glass, 400 kg plastic, 7000kg steel, 20kg wood
- Transport of materials to factory/site: total of 300km for 7000kg of steel, using <16t truck via motorway
- All other personnel/material transport assumed negligible
- Electrical power consumption for manufacture, supply and install, 10000kWh

In use

- Assume 300kWh consumption per working day for complete lift system over 30 years

Maintenance/refurbishment

- Assume over lifetime is equal to total supply, manufacture and install
- Stripped out materials re-cycled, but not credited to system (no waste to landfill)

Strip out

- Power used during strip out, 100kWh
- Land-fill (including transport) of 120kg glass, 400 kg plastic, 7000kg steel, 20kg wood

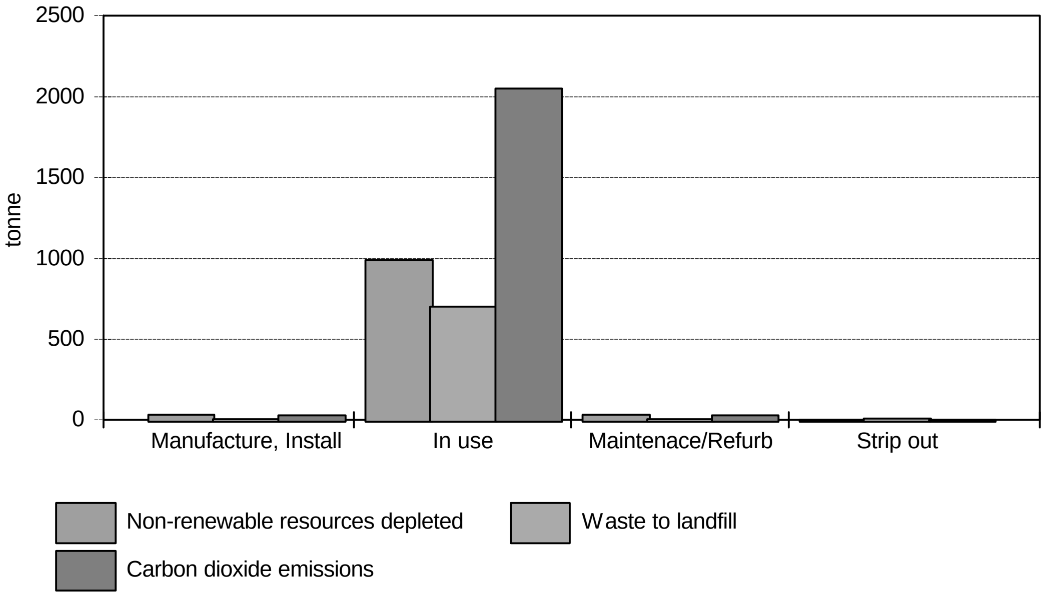

Figure 2.2 Lift Life Cycle Assessment results - impact over entire life cycle

A summary of the results from the PEMS analysis is given in Figure 2.2. This shows that the dominating environmental burdens in the life of this hypothetical lift system are the non-renewable resources depleted, the waste created and the emissions generated through the production of electricity for operation of the lifts while in use. The environmental burdens associated with other stages in the life cycle are relatively small.

The PEMS data for energy usage is not industry-specific. As this is by far the most dominant factor in the analysis, improvements in the (packaging biased) PEMS data for plastic, etc. would have minimal impact on the results.

The results are for lift systems, but the finding can be generalised to all vertical transportation systems, all of which have a high energy usage and a long design life.

Use of renewable resources in manufacture, recycling and re-use, efficient transport, disposal/spillage of hydraulic oil, etc. are all important, but secondary issues. Alone they cannot be the basis of claims for a green lift installation.

2.4 WHY IS ENERGY EFFICIENCY IMPORTANT?

2.4.1 Greenhouse effect

The greenhouse effect is caused by trace gases in the earth's atmosphere which absorb infra-red radiation emitted by the Earth's surface, causing a warming of the atmosphere. This natural effect is responsible for maintaining the temperature at the earth's surface which enables life. Man is upsetting the earth's natural balance by creating additional greenhouse gases. There is evidence to suggest that this is, and will cause global environmental effects such as droughts and floods.

The most important greenhouse gas is carbon dioxide, steadily increasing due to the burning of fossil fuels for energy generation and vehicles. Others include chlorofluorocarbons (CFCs). Half the carbon dioxide emitted in the UK results from the use of energy in buildings.

2.4.2 Pollution

Burning fossil fuels for energy generation produces nitrous oxide and sulphur dioxide which dissolves in the atmosphere creating acid rain. This is believed to have caused damage to lakes, plants, buildings, forests and fisheries. Nuclear electricity generation creates radioactive waste for which there is no satisfactory means of disposal.

2.4.3 Renewable resources and sustainable resources

If a resource can be regenerated it is said to be renewable, e.g. hardwood. If a renewable resource can be regenerated at a rate that matches the demand for it, it is said to be sustainable, e.g. softwood.

The use of fossil fuels for electricity generation is not sustainable. Sustainable energy sources such as wind, solar and hydroelectric do not, at this time, provide sufficient electrical power at a low enough cost to displace our dependence on non-sustainable sources.

2.4.4 Comment

The use of electricity at current levels is unsustainable, and damaging to our environment. As responsible stewards of the earth, we should be reducing our energy consumption and seeking to develop sustainable energy sources.

2.5 ARE LIFTS SIGNIFICANT ENERGY USERS?

Where they are installed, lifts and escalators are a significant proportion of the building load; the draft CIBSE Energy Efficiency Guide(2.3) suggests 4 to 7%. Kone sales documentation suggests 5 to 10%. The importance of energy efficient Heating, Ventilation, Air Conditioning (HVAC) and lighting systems is generally accepted; the wealth of related research and development in both these fields reflects this. The author suggests that vertical transportation systems should be among the next in line for “greening”. Apart from environmental concerns, the financial cost of the electricity used by lifts is a major incentive for adopting energy saving designs. A 20% saving on a system using 300 kWh per working day would save in excess of £1000 per year at 1997 electricity prices.

2.6 GREEN LIFT BASICS

2.6.1 General

There are a number of “basic” principles for green lifts that should be considered by designers before adopting advanced strategies. These are summarised as follows.

2.6.2 Lift drives

Hydraulic lifts are energy inefficient in comparison with electric lifts. In his site measurements, Doorlaard(2.4) concluded that *the energy consumption of hydraulic lifts travelling at the same nominal speed is over two times the consumption of conventional two-speed lifts*. Hydraulic lifts do have benefits (e.g. low structural building load, flexible motor room position, low capital cost). But they are not green.

Lift manufacturers offer a wide range of electric lift drives ranging from single speed AC machines to variable speed AC and DC machines. A summary of these drives and their applications is given in(2.5). Their energy efficiencies vary significantly. The most efficient electric lift drives are the modern fully controlled static converter DC and variable voltage variable frequency AC drives (including vector control drives); the AC drives provide better power factor control.

Green lift drives should be regenerative, i.e. return power to the mains when delivering negative torque (braking). The alternative, dissipating the energy in resistors can be doubly wasteful, as the waste heat introduces an additional cooling load in an air conditioned building. Installation of regenerative systems should be co-ordinated with the electrical building services design engineer as additional protection and harmonic filtering may be required.

2.6.3 Other installation issues

The torque, and therefore the energy, required of a motor to accelerate a lift can be reduced if we minimise inertia and other resisting forces. All rotating components (gear, brake, sheaths, etc.) and travelling components (lift car, counterweight, finishes, ropes, etc.) contribute to the inertia and to resisting forces in the system. Compared with the conventional worm gear, significant reduction in inertia and higher efficiencies have been demonstrated for by Zinke[2.6] for planetary gears, and by Stawinoga[2.7] for V-belt drives.

Lift car lighting should use efficient sources and be switched off automatically if a lift is not in use for long periods.

2.6.4 Planning issues

The total energy consumption of the installation is also dependant on planning issues. If stairs are accessible, attractive and adjacent to the lifts, there is likely to be a reduction in the use of lifts for short trips. It is also good to avoid over-sizing of lifts, as larger lifts result in greater inertia, larger motors and more energy use. While it is important to design spare handling capacity into a lift installation, over-sizing can be the result of:

- poor knowledge of probable traffic flows, leading to “safe” overestimates of required handling capacity.

- where traffic analysis suggests small lifts are acceptable, it is common to up-size the lifts selected. For instance, in a new office development where six, eight person lifts meet handling capacity and interval design criteria, ten or thirteen person lifts might be selected as larger lifts are perceived as prestigious.

2.7 OVERVIEW OF FOLLOWING CHAPTERS

In Chapter 3, the author reviews lift passenger traffic demand and data collection techniques. It is suggested that current lift design criteria need to be updated due to changes in working practices; and that these criteria result in the installation of excessive handling capacity. Having estimated prospective lift traffic, it is necessary to have analysis techniques to determine the number, size and speed of lifts required. In Chapters 4 and 5 traffic analysis techniques based on round trip time equations are reviewed and developed.

The developments in Chapters 3 to 5 are beneficial in the pursuit of improved design practice. From the environmental perspective, the benefit is that improved design criteria and analysis techniques will help avoid the over sizing of lift cars. Moving large, heavy lift cars up and down buildings when they are only partly loaded at peak times is not energy efficient.

In Chapters 6 and 7 tools are developed to model lift movement and corresponding energy consumption. These tools are implemented in a lift simulation program which is discussed in Chapter 8. The program is used to develop strategies for energy saving control systems which are discussed in Chapter 9.

Assuming that an installation has been designed with energy saving in mind, the developments in Chapters 6 to 9 provide a means by which we can reduce energy consumption further.

2.8 DISCUSSION

In this chapter we have used Life Cycle Analysis to identify the environmental burdens of lift systems. As was expected intuitively, the main burdens are caused by generating electricity to power the lifts while they are in use transporting passengers in buildings. Other environmental burdens are relatively minor. Thus, for maximum effect in reducing the environmental burdens of lifts, we should concentrate on researching ways of reducing their energy consumption.

Reducing energy consumption is important because of the environmental damage caused by the generation of electricity. The use of electricity at current levels is unsustainable. We need to reduce our current energy consumption as well as developing sustainable sources for the future.

The lift system will not normally be the largest energy user in a building. Other systems have higher loads and can offer greater energy savings. Nevertheless, there is correspondingly more research in environmental friendly HVAC, lighting, etc. systems. Energy saving lifts should not be disregarded as the potential savings are still worthwhile.

A number of basic principles for green lifts have been identified. The choice of drive, position of stairs, etc. all have a major effect on the energy consumption of the vertical transportation system. As a starting point, these choices should be made with energy saving in mind. We can then go on to consider more advanced strategies.

In the following chapters we will explore and develop these advanced strategies. We will show that savings can be made by improving the planning of vertical transportation systems using improved estimates of passenger demand. Furthermore, strategies for energy saving control systems will be developed through the application of motor and lift simulation models.

Some lift manufactures promote their products as being green because they include energy efficient drives; others promote their use of re-cycled packaging. Further work in defining green lifts should be focused on putting manufacturers' claims into context. This is primarily an exercise in communication, which has already begun through the publications arising from this project.

REFERENCES

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2.3 *CIBSE Energy Efficiency Guide*, (26 January 1994 draft), section 3.9, 1.

2.4 Doolaard D A *Energy Consumption by Different Types of Drive System* Elevator Technology 4, Proceedings of ELEVCON'92 (The International Association of Elevator Engineers)(1992)

2.5 Peters R D *Mathematical Modelling of Lift Drive Motion and Energy Consumption* Proceedings of CIBSE National Conference 1995 (The Chartered Institution of Building Services Engineers)(1995)

2.6 Zinke W *Planetary Gear and Frequency Inverter Set New Standards in Lift Drive Efficiency* Elevator World (January 1996)

2.7 Stawinoga R *New Mechanical Solutions for High Efficiency Gears* Elevator Technology 5, Proceedings of ELEVCON'93 (The International Association of Elevator Engineers)(1993)

Chapter 3

ASSESSMENT OF TRAFFIC DEMAND

3.1 INTRODUCTION

Assessment of performance is a crucial element in lift design. If lifts are too small, slow, or insufficient in number, passengers have to wait for excessive periods for a lift to arrive in response to landing calls. Furthermore, passengers travelling more than a few floors in under-lifted installations often endure long journey times - the result of the lifts having to stop to answer other calls at most of the intermediate floors. On the other hand, the luxury of an over-lifted building is an expensive one - floor area that could be let to tenants is lost to additional or larger lift lobbies and shafts; capital, maintenance and energy costs of the installation are higher.

The need to specify appropriate numbers of lifts, their capacity and speed, etc. has led to the study of lift traffic analysis. Lift traffic analysis allows us to assess the performance of a proposed lift installation based on estimates of building passenger traffic patterns. Lift traffic analysis techniques ranging from up peak calculations[3.1][3.2] to general analytical formulae[3.3] and simulation techniques[3.4] are widely applied. But lift performance results from lift traffic analysis are of no better quality than the estimated passenger traffic patterns that are used in the calculations or simulations.

In this chapter the author summarises current, published knowledge of lift passenger traffic patterns and compares this with survey results. Current design guidelines are questioned, and means of improving our knowledge of lift passenger traffic patterns are discussed.

3.2 CURRENT KNOWLEDGE OF TRAFFIC PATTERNS

3.2.1 General approach

In estimating prospective passenger traffic patterns, a designer might consult:

- Elevator Traffic Analysis Design and Control[(3.1)]
- Vertical Transportation, Elevators and Escalators[(3.2)]
- CIBSE Guide D, Transportation Systems in Buildings[(3.5)]
- Standards, e.g. in the UK, BS 5655 Part 6[(3.6)]

There are other sources of information, including manufacturers' planning guides, but these tend to re-iterate the recommendations of above. Barney, dos Santos[(3.1)] and Strakosch[(3.2)] present example diagrams of passenger traffic in a commercial, office building. These diagrams have been re-drawn in Figures 3.1 and 3.2.

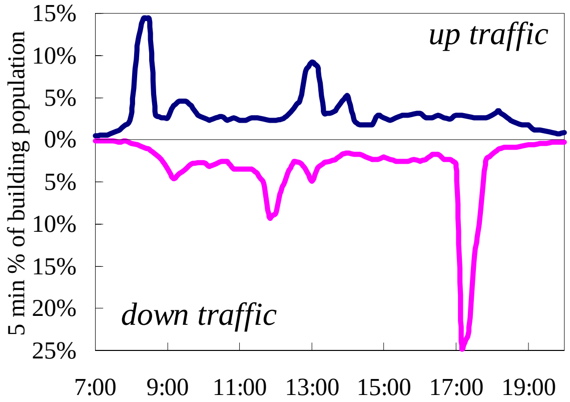

Figure 3.1 Typical office traffic, Barney[(3.1)]

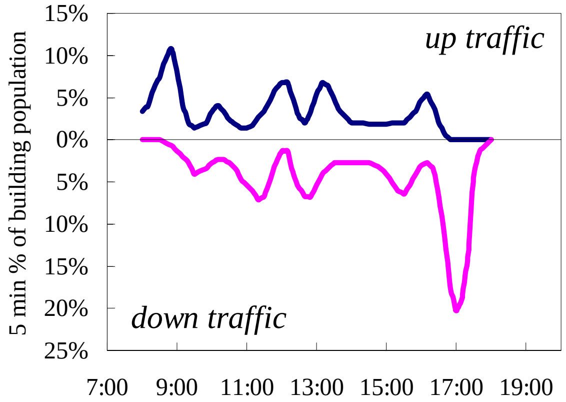

Figure 3.2 Typical office traffic, Strakosch[(3.2)]

According to Barney and dos Santos[(3.1)], conventional design procedure is to determine the performance of lift systems for the morning up peak traffic situation. This is consistent with the author's experience from reviewing consultants' and manufacturers' calculations. The common approach is probably because:

- the up peak traffic condition is relatively simple to analyse
- it is widely accepted that, if a lift system can cope efficiently with the morning up

peak, then it will cope with other periods in the day

- most traffic flow design recommendations are for up peak handling capacity

CIBSE Guide D[3.5] suggests the following up peak traffic flows for design purposes:

Building Type	*Arrival rate (% in 5 minutes)*	*Building Type*	*Arrival rate (% in 5 minutes)*
Hotel	10-15	Flats	5-7
Hospital	8-10	School	15-25
Office (multiple tenancy)	11-15 regular, 17 prestige	Office (single tenancy)	15 regular, 17-25 prestige

Table 3.1 CIBSE Guide D guidance on peak arrival rates

Strakosch[3.2] places most emphasis on the incoming up peak traffic, but also proposes two-way and outgoing traffic criteria. BS 5655 Part 6[3.6] offers only up peak design criteria.

3.2.2 Published lift traffic surveys

Detailed lift traffic surveys carried out by researchers, consultants and manufacturers are rarely published. One exception is *A survey of passenger traffic in two office buildings*[3.7] published by BRE in 1974. Results are summarised in Table 3.2.

Building	*Traffic period*	*Peak 5 min % building population using lifts*
Southbridge House	morning up peak	12.2
	evening down peak	8
Sanctuary Buildings	morning up peak	7.8
	evening down peak	6.7

Table 3.2 Summary of BRE traffic survey results

The BRE survey also concluded that lunch time traffic amounts to 12% of building population in both buildings, but this includes stair traffic.

3.3 TRAFFIC SURVEYS

Passenger traffic surveys have been carried out by the author at a range of buildings. Results are summarised in Figures 3.3 to 3.7 which record the traffic to and from the main terminal floor(s), except for Building E where the predominant traffic flow was inter-floor. Traffic was measured only during peak periods (normally morning, lunch and evening; morning and evening for the hotel).

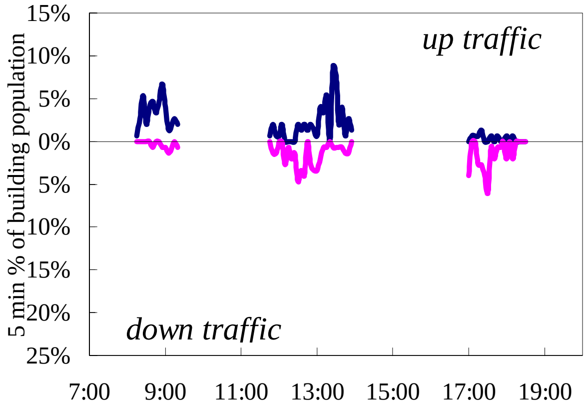

Figure 3.3 Building A traffic survey results for single tenancy office, engineering

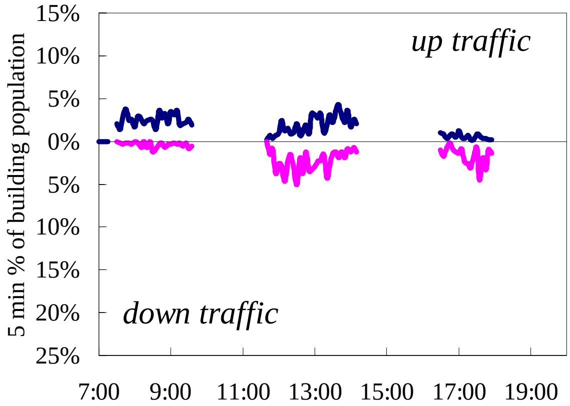

Figure 3.4 Building B traffic survey results for single tenancy office, banking/dealers (results based on nominal population of 1 person/10m^2 as actual occupancy not available)

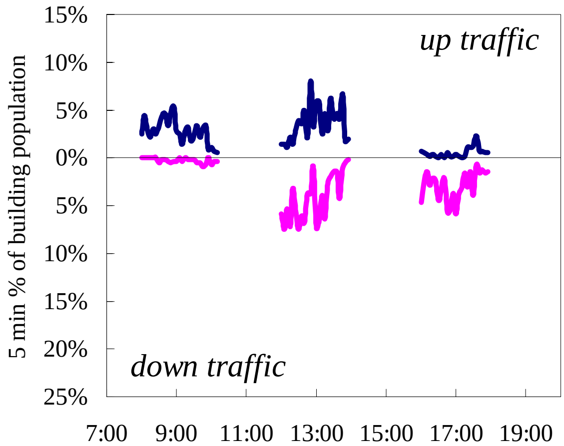

Figure 3.5 Building C traffic survey results for single tenancy office, general

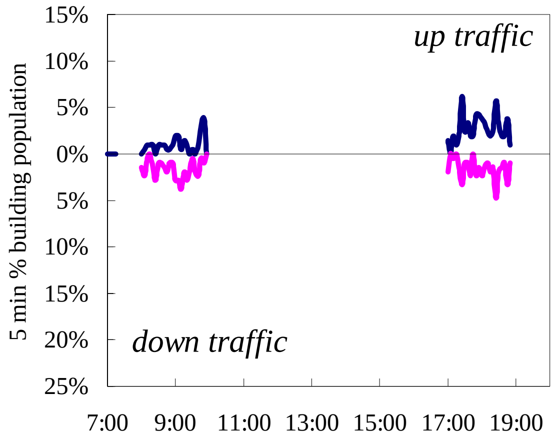

Figure 3.6 Building D traffic survey results for prestigious traditional hotel

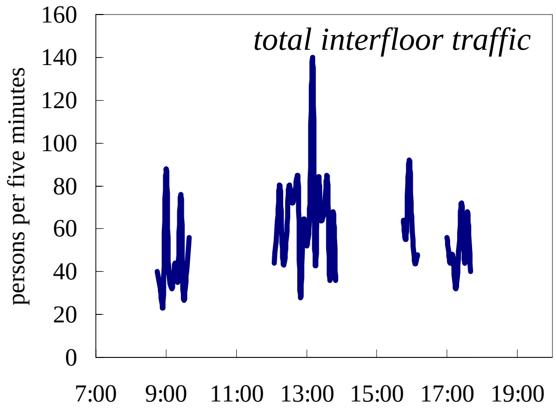

Figure 3.7 Building E traffic survey results for major high rise hospital

(results not shown as % as only one of two passenger lift banks available for survey)

3.4 REVIEW OF RESULTS

The traffic survey results suggest that the morning traffic peaks are less marked in buildings than they were when traditional up peak design criteria were formulated. In work-related buildings occupied during the day, the busiest period appears to be over the lunch period. Lunch traffic is a combination of up and down peak traffic to the main terminals, but often includes an element of inter-floor traffic. This inter-floor traffic is especially significant in buildings with restaurants, meeting rooms, etc.

A lift system has a greater passenger handling capacity during lunch time traffic than during a morning up peak. This is because during an up peak all the passengers are loaded at the ground floor. During lunch peaks, the lifts are loaded in both directions, and may carry up to twice as many passengers in a single round trip.

However, if the same total handling capacity is assumed, people wait longer for a lift at lunch time than they do during a morning up peak. This is because the combination of passengers travelling up and down the building results in more stops per round trip.

If the traffic studies of commercial buildings made during this research are typical, designers are allowing too much handling capacity during the morning up peak, and not giving enough attention to the waiting times for passengers during the lunch peak.

In testing these findings on Arup designs, it is apparent that revising our design criteria is unlikely to result in fewer lifts, but would reduce car capacities, say from 1250 kg to 1000 kg. And therefore lead to energy savings.

It would be dangerous to disregard established up peak design criteria without a wider study of building traffic flow peaks; more data must be collected. Thus the remainder of this chapter discusses means of representing and collecting traffic data so that, in due course, updated design criteria can be formulated for a wide range of buildings.

3.5 REPRESENTING LIFT TRAFFIC FLOWS

Traditionally lift traffic flows have been defined in terms of the percentage of the building population transported upwards and downwards in five minutes, as used in Figures 3.1-3.6. For more complex flows such as lunch peaks we need a more comprehensive way of describing lift traffic. The author presented an approach in his paper on *General Analysis Lift Calculations*(3.3) that allows us to describe traffic flow completely. Two terms are required:

μ_i the passenger arrival rate at floor i (defined for each floor at which passengers may arrive

d_{ij} the probability of the destination floor of passengers from floor i being the jth floor (defined for all possible i and j)

Using these terms, a simple up peak traffic flow in an office block could be represented as in Figure 3.8. And a more complex traffic flow could be represented as in Figure 3.9.

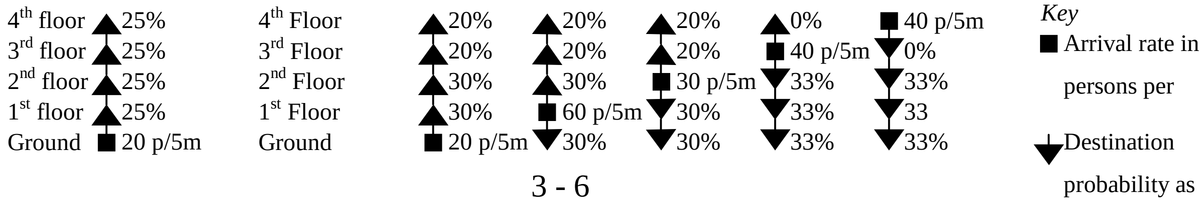

Figure 3.8 **Figure 3.9**

Future design criteria should enable the designer to estimate peak traffic flows in these terms from a knowledge of the office building population, number of hotel rooms, etc. dependant on the building type.

3.6 CARRYING OUT LIFT SURVEYS

3.6.1 Alternative survey techniques

The are a number of alternative approaches to collecting data on lift passenger traffic patterns. Those considered by the author are discussed in the following subsections. Other and new technologies may yield alternative approaches.

3.6.2 Manual surveys using observers

In manual surveys observers count passengers in and out of the lifts. Manual surveys are normally based on one of two approaches:

i. survey from the main terminal(s), where observers count passengers in and out of the lifts as they arrive/depart from the main terminal floor(s). Traffic between other floors is assumed to be negligible. Survey results given in Figures 3.3 to 3.6 where collected using this approach.

ii. the in-car survey, where observers are situated in the lift car, and count the passengers in and out at every floor the lift stops at. Survey results given in Figure 3.7 were collected using this approach.

Manual surveys are discussed in detail in [3.1] and [3.8]. The new generation of cheap, miniature video cameras (used with a video recorder) can be used to make observation unobtrusive; the recorded video is played back off site for counting.

The survey techniques do not allow us to describe traffic flow completely as:

- (i) only measures arrival rate at the main terminal floor(s) and requires assumptions to be made about arrival rates and destinations probabilities on other floors. These assumptions are generally based on the building floor populations.

- (ii) measures arrival rates at all floors, so provides superior data to (i). Overall destinations probabilities (averaged over all arrival floors) can be approximated from the count of passengers as they leave the lift. Collecting data to enable traffic to be described completely is impractical for the human observer unless traffic is light - to achieve a full data set of destination probabilities, the observer would have to track every passenger, e.g. passenger 53 entered the lift at floor 3 and alighted at floor 6; passenger 54 entered the lift at floor 4 and alighted at floor 10, etc.

3.6.3 Control system and traffic analyser surveys

Conventional systems

Traffic analysers are linked to the lift control system, and record the time every landing and car call is made and cleared. They analyse this data and provide a range of performance results and graphs. Modern control systems incorporate similar functionality.

A range of traffic and performance measures can be determined, for example:

- average response time to landing calls by time of day
- distribution of response times
- distribution of car calls by floor

Traffic analysers give a good indication of a lift system's performance, but very limited information about the actual passenger traffic flow. This is because they have no means of determining the number of people transported on each trip, e.g. a landing call at floor five and corresponding car call to floor seven could equally be a single person, or a group of people travelling together. The use of accurate weighing devices would provide a guide to passenger load.   But ambiguities occur if people are loading and unloading at the same floor, e.g. five people loading and three people unloading would provide the same weight differential as two people loading.

Therefore, on its own, traffic analyser data does not give us the information we require.

Inverse S-P method

Al-Sharif suggested a means of interpreting data that is available to traffic analysers. The Inverse S-P method[(3.9)] applies conventional up peak traffic analysis formulae "backwards" to estimate the number of passengers using a lift from the number of car calls and lift movements. The Inverse S-P method is effective, yet applies only to up and to down peak traffic.

Estimation of complete traffic flow

The author reported having derived a method for extrapolating (complete) traffic flow from control systems data in[(3.10)]. The development of this method has been halted after successful preliminary tests as further work is impractical without taking data directly from lift system controllers. Manufacturers have proved unable or unwilling to provide access to the necessary data for research purposes. The proposed method is outlined as follows:

- The passenger arrival rate, μ_i, is a function of [the average time between a lift leaving floor i travelling up and the up landing call being pressed by the next passengers arriving at the landing station] and [the average time between a lift leaving floor i travelling down and the down landing call being pressed by the next passengers arriving at the landing station].

- This function can be derived by applying the assumption that the arrival of passengers at a lift landing is reasonably modelled by a Poisson process. (This assumption has previously been applied in lift traffic analysis[(3.1)(3.3)].)

- Destination probabilities can be estimated by analysis of car calls registered as the lift leaves each landing. Not every passenger will register a car call (as other passengers will have pressed the button first). But over time the relative frequency of unregistered car calls being pressed will provide a good indication of the average destination probabilities from each floor.

Figure 3.10 records some results from the preliminary tests where control system data was collected "manually" by observation.

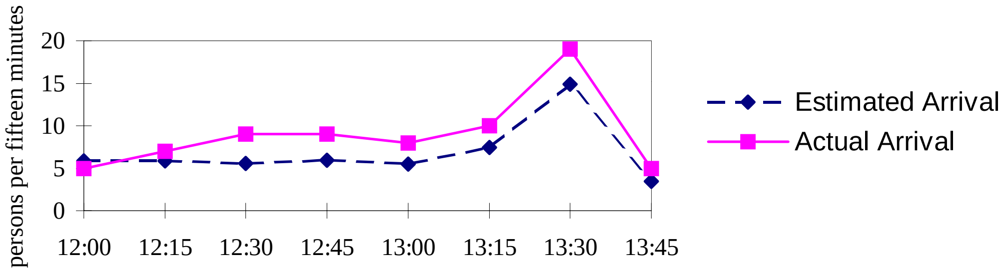

Figure 3.10 Poisson based estimate of traffic flow

3.6.4 Computer vision

Researchers[3.11][3.12] have applied image processing techniques to video pictures of lift lobbies to determine the number of people waiting for the lifts. This lobby count aids the control system by enabling it to prioritise calls from busy floors.

A spin off from the lobby count system developed at Brunel University was a prototype "traffic surveyor" to count the passengers as they loaded and alighted the lifts. The system applies similar image processing techniques to the lobby count system, but compares each video frame in sequence to track people across the scene. If people join or leave the scene from the areas defined as the lift doors, they are counted as having loaded or alighted the lifts. In tests the system was found to be 80-85% accurate, errors being due mainly to a tendency to miss-track people from one image to the next.

This Brunel University research project has now concluded, so no further development is envisaged. But image processing is an active research area and improved pedestrian tracking systems are likely to be developed in the future, probably initially for security applications. In due course, we are likely to be able to purchase general purpose pedestrian tracking systems that will provide us with the basis for complete measurements of traffic flow.

3.6.5 Infra-red

Infra-red technology is widely applied, particularly in the security industry. Traffic surveys using photocells or infra-red beams were suggested in [3.13][3.14]. The approach requires a minimum of two horizontal beams to count people passing through the detection field in single file. The sequence of beam states enables direction to be determined. If people are walking side by side, horizontal beams will detect only a single person. This can be overcome by mounting beams vertically - a system believed to be using this approach is installed in a London department store monitoring escalator traffic.

Initial lab and site tests suggest that, although system logic can be fooled, in practice the overall counting accuracy of infra-red counting systems is high. The infra-red detectors effectively replace observers in manual surveys, so the data collected does not describe traffic flow completely (as in 3.6.2 ii we can only calculate average destination probabilities). But infra-red technology is available and relatively inexpensive to implement.

3.6.6 Written surveys

Written surveys, where people record the times of lift trips on a form, have been found to be unreliable[3.7]; this was confirmed from the results of a written survey at Building A (Figure 3.3). This is probably due to a tendency for people to record their arrival and departure times as the fixed working hours of a company.

3.6.7 Security systems

Various security systems are applied to control access in buildings, some of which are integrated with the lift systems. Systems that use swipe cards to call the lift, or a key pad to control access to specific floors, do not yield useful traffic flow data. Where they are installed, systems that identify passengers individually as they arrive and depart lift lobbies, will enable traffic flow to be monitored completely.

3.7 OTHER ISSUES

3.7.1 Use of stairs

In planning lift installations, some designers make allowance for the use of stairs. The author's survey experience suggests:

- the number of people using the stairs in lieu of the lifts drops off sharply as the journey travel increases
- people are less likely to walk up than down
- an attractive staircase sited adjacent to the lifts is far more likely to be used than a back staircase

In the Building C (Figure 3.5) survey, use of the staircase was virtually nil in spite of the lifts being heavily loaded and long passenger waiting times; the main staircase was an unattractive fire escape sited well away from the lift lobby. Figure 3.11 shows the associated stair usage for the BRE[7] and Building A (Figure 3.3) surveys.

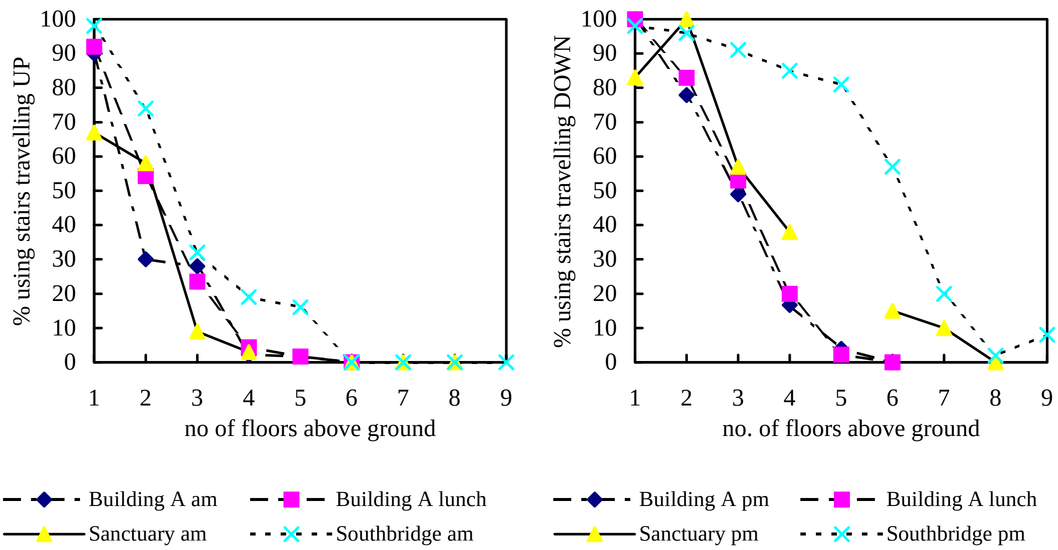

Figure 3.11 Example stair usage for up and down travel

In lift traffic surveys we need to assess stair usage, otherwise generalised recommendations will be inappropriate to:

- high rise buildings where the relative use of stairs is far less significant
- buildings where stair access is poor

3.7.2 Occupancy

If the results of traffic surveys are to be applied in the design of other buildings, it is important that traffic is recorded relative to the actual building population - plotting survey results of a partly occupied building relative to nominal building population can suggest misleadingly low traffic flows.

3.8 DISCUSSION

It is important for lift designers to have a good understanding of passenger traffic demand. A poor knowledge of demand will often result in either an inadequate or an over-designed system. The first alternative is unacceptable to passengers. The second is unnecessarily expensive, and will consume more energy.

Most lift installations in commercial buildings are designed on the basis that the morning up peak is the most onerous traffic condition for the lifts. Surveys carried out for this research project suggest that this is not the case, and that the lunch time is now the busiest period. Further surveys need to be carried out to confirm these results. However, they are consistent across the office buildings surveyed by the author, and with anecdotal evidence from designers to whom this work has been presented.

The findings on passenger traffic demand are important as a lift installation has a greater total handling capacity at lunch time than it does in the morning. This is because, during a lunch time peak, passengers are being transported during both the up and down journey of the round trip. During an up peak, the lift is normally empty during the down trip.

Thus revising our design criteria to take these findings into account is unlikely to result in fewer lifts, but would reduce car sizes, and therefore lead to energy savings.

It is recognised that large lifts are often associated with prestige. And that in order to improve environmental performance, we need to forego this luxury. As for many other products and processes, consumers will have to accept some changes if they want to support green issues.

In carrying out further surveys, researchers should use automated people counting techniques as it is very time consuming to collect large amounts of data manually. A range of surveying techniques has been reviewed. Currently the author favours an infra-red beam system as the best available technology, although further research in passenger counting techniques would be beneficial. The author continues to collect data, and has been encouraging others to publish their results so that improved design criteria can be established.

In planning new lift installations, it would be dangerous to disregard conventional up peak design criteria completely until a wider study of other traffic flow peaks is complete.

Major elements of the research discussed in this chapter were presented at the International Elevator Technology Conference, ELEVCON '96 and again at an IAEE London Lift Seminar.

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Chapter 4

TRAFFIC ANALYSIS

List of symbols

a	acceleration (m/s/s)
CC	car (rated) capacity (persons)
CF	capacity factor (%)
d_f	average inter-floor height (m)
df_n	height floor n (m)
d_H	distance to reach reversal floor H excluding express zone (m)
d_X	total height of un-served floors in express zone (m)
H	average highest reversal floor
j	jerk (m/s/s/s)
L	number of lifts
$LOSS$	round trip time losses (%)
N	number of floors above main terminal
P	average number of passengers
S	average number of stops
T	cycle time (s)
t_a	advanced door opening time (s)
t_c	door closing time (s)
$t_{fd}(d)$	flight time for travel distance d (s)
t_{f1}	single floor flight time (s)
t_l	passenger loading time per person (s)
t_o	door opening time (s)
t_p	average passenger transfer time (s)

t_u	passenger unloading time per person (s)
t_v	time to travel between two adjacent floors at rated speed (s)
t_s	time consumed when making a stop (s)
t_{start}	allowance for motor start delay (s)
P	average number of passengers in car
%POP	5 minute up-peak handling capacity (% population)
RTT	round trip time (s)
U_{eff}	effective building population (persons)
U_i	population of floor i (persons)
UPPHC	up-peak handling capacity (persons/5 min)
UPPINT	average up-peak interval (s)
v	contract (rated) speed (m/s)

4.1 INTRODUCTION

Having reviewed a probable peak traffic demand, the next lift design stage is traffic analysis. In this chapter we will look at analytical traffic analysis techniques based on Round Trip Time calculations. These techniques are currently the most popular and widely applied.

4.2 STANDARD UP-PEAK CALCULATION

4.2.1 General

Most lift designs are based on up peak calculations. As discussed in Chapter 3 of this thesis, the up peak is not always the most appropriate choice of peak period for the analysis. Nevertheless, the up peak calculation is important as an industry standard benchmark calculation, and a good starting point for assessing the handling capacity of a lift system.

The up peak lift calculation is based on estimating the time taken for a lift to make a single “round trip” of the building. The calculation assumes people load the lift at the lowest floor, and get dropped off as the lift stops off at upper floors. The lift then expresses back to the ground floor (some designers include an allowance for additional stops made by the lift on its return journey). The round trip time is calculated for a single lift, so results for two of more lifts are extrapolated accordingly.

The up peak calculation has evolved over a number of years. Jones[4.1] determined results for the probable number of stops made by the elevator during its round trip. Schroeder[4.2] determined formulae for highest reversal floor. Barney and dos Santos[4.3] formalised the method with formulae that are now generally accepted by the Lift Industry. A summary of these formulae follow.

4.2.2 Up peak formulae

The average number of passenger assumed to load into a car during up peak traffic is

$$P := \frac{CF}{100} \cdot CC \qquad (4.1)$$

The effective building population of the buildings is

$$U_{eff} := \sum_{i=1}^{N} U_i \qquad (4.2)$$

The average highest reversal floor is

$$H := N - \sum_{j=1}^{N-1} \left(\sum_{i=1}^{j} \frac{U_i}{U_{eff}} \right)^P \qquad (4.3)$$

The average number of stops made by the lift during its round trip is

$$S := N - \sum_{i=1}^{N} \left(1 - \frac{U_i}{U_{eff}} \right)^P \qquad (4.4)$$

The average time taken for a single person to load or unload the lift is

$$t_p := \frac{t_l + t_u}{2} \qquad (4.5)$$

The time taken for the lift to travel between two adjacent floors at rated speed is

$$t_v := \frac{d_f}{v} \qquad (4.6)$$

The single floor flight time, t_{f1} is taken from a table, as re-produced in Table 4.1

Contract Speed (m/s)	Acceleration (m/s^2)	Single Floor Flight Time, 3.3m floor height (s)
1.00	0.4-0.7	7.0
1.50	0.7-0.8	6.0
2.50	0.8-0.9	4.8
3.50	1.0	3.7-4.0
5.00	1.2-1.5	3.7-4.0

Table 4.1 Typical flight times

The cycle time is the time to travel a single floor, and open/close the doors

$$T := t_{f1} + t_c + t_o \qquad (4.7)$$

So the delay or "time consumed" by making a single stop is

$$t_s := T - t_v \qquad (4.8)$$

The Round Trip Time is the time taken for the travel to/from the highest reversal floor at contract speed, plus the delay for each stop, plus the time for the passengers to load/unload. Thus,

$$RTT := \left[2 \cdot H \cdot t_v + (S + 1) \cdot t_s + 2 \cdot P \cdot t_p\right] \qquad (4.9)$$

Some designers add 5-10% to the Round Trip Time for "losses" associated with controller inefficiencies, passengers holding the doors, and so on.

The up peak interval is calculated by dividing the round trip time by the number of lifts.

$$UPPINT := \frac{RTT}{L} \qquad (4.10)$$

The interval is the average time between successive lift arrivals at the main terminal floor. It is not the average waiting time, which Strakosch states is about 55 to 60% of the interval, dependant on the control system(4.4).

The up peak handling capacity is the number of passengers transported in a five minute period. This is calculated as

$$UPPHC := \frac{300 \cdot P \cdot L}{RTT} \tag{4.11}$$

The handling capacity, expressed as a percentage of the building population transported in five minutes is

$$\%POP := \frac{UPPHC \cdot 100}{U_{eff}} \tag{4.12}$$

4.3 IMPROVEMENTS TO UP-PEAK CALCULATION

4.3.1 Flight time calculation

Determining flight time from Table 4.1 is limited as the inter-floor heights are assumed to be 3.3 m, and only "standard" speeds and accelerations are considered. The author's research in ideal lift kinematics has yielded general formulae to determine flight time for any travel distance and lift dynamics.

if $d \ge \frac{a^2 \cdot v + v^2 \cdot j}{j \cdot a}$ *then* $t_{fd}(d) := \frac{d}{v} + \frac{a}{j} + \frac{v}{a} + t_{start}$ (4.13)

if $\frac{2 \cdot a^3}{j^2} \le d < \frac{a^2 \cdot v + v^2 \cdot j}{j \cdot a}$ *then* $t_{fd}(d) := \frac{a}{j} + \frac{\sqrt{a^3 + 4 \cdot d \cdot j^2}}{\sqrt{a \cdot j}} + t_{start}$ (4.14)

if $d < \frac{2 \cdot a^3}{j^2}$ *then* $t_{fd}(d) := \left(32 \cdot \frac{d}{j}\right)^{\frac{1}{3}} + t_{start}$ (4.15)

These formulae are consistent with results provided by Molz(4.5), but are in a simpler form.

Applying the $t_{fd}(d)$ function, the single floor flight time is

$$t_{f1} := t_{fd}(d_f) \tag{4.16}$$

Research in ideal lift kinematics is discussed in detail in Chapter 6 of this thesis. These travel time formulae are included in the draft revision of the new CIBSE Guide D, *Transportation Systems in Buildings*[4.6].

4.3.2 Lifts not reaching full speed in single floor jump and non-equal inter-floor heights

The conventional Round Trip Time equations assume that the lift reaches rated speed in the distance of a single floor jump; and that there are no irregularities in floor heights. This is not always the case, and the current CIBSE Guide D proposes a procedure for making "corrections" to the conventional RTT formulae. The author has formulated these corrections as follows:

Determine the distance d_H to reach reversal floor H, which can be written as

$$d_H := \left(\sum_{i=0}^{\text{floor}(H)-1} df_i \right) + (H - \text{floor}(H)) \cdot df_{\text{floor}(H)} \qquad (4.17)$$

(floor(x) is a function which returns the greatest integer less than or equal to x)

The average distance between stops is then

$$\frac{d_H}{S}$$

and the flight time to travel this distance is

$$t_{fd}\left(\frac{d_H}{S}\right)$$

The difference between this and the assumed time can be substituted into an enhanced equation for t_s which becomes

$$t_s := \left(t_{fd}\left(\frac{d_H}{S}\right) - \frac{d_H}{S \cdot v} \right) + t_c + t_o - t_a \qquad (4.18)$$

(Advanced door opening time (s) has been added to this formulae at the suggestion a member of the Guide D Revision Committee. Some designers take advanced door opening off the door opening time, but it is clearer to identify it separately.)

The $2 \cdot H \cdot t_v$ term in the RTT equation also needs to be revised to $2 \cdot \frac{d_H}{v}$ to take into account the new approach. The round trip time equation now becomes

$$RTT := \left[2 \cdot \frac{d_H}{v} + (S + 1) \cdot t_s + 2 \cdot P \cdot t_p \right] \tag{4.19}$$

Equations for UPPINT and UPPHC remain the same.

A sensitivity analysis has been carried out to establish the “correction” due to adopting these “enhanced” equations. Data and results are given in Tables 4.2 to 4.7.

a	0.8 m/s²	t_c	2.9 s
CC	16 persons	t_l	1.2 s
CF	80%	t_o	1.2 s
df_0 to df_7	3.6 m	t_u	1.2 s
j	1.6 m/s^3	t_{start}	0.5 s
L	4	U1 to U8	80 persons/floor
N	8	v	2.5 m/s²
t_a	0.5 s		

Table 4.2   Default analysis data

Speed	Acceleration	Jerk	% variation RTT
1	0.5	1	0
1.6	0.7	1.4	-0.11
2.5	0.8	1.6	0.72
3.5	1	1.6	1.01
5	1.3	1.6	1.14
6	1.5	1.6	1.15

Table 4.3 Variations in Speed

N	% variation RTT
4	0.08
6	0.36
8	0.72
10	1.08
12	1.38
14	1.6

Table 4.4 Variations in N

CC	% variation RTT
6	2.03
8	1.74
10	1.43
13	1.02
21	0.4
26	0.22
33	0.1

Table 4.5 Variations in CC

d_f	% variation RTT
3.2	0.8
3.4	0.76
3.6	0.72
3.8	0.68
4	0.64
4.2	0.6

Table 4.6 Variations in d_f

df_n	% variation RTT
all 3.6m	0.72
just df_0 5m	0.72
just df_4 5m	0.72
just df_7 5m	0.48
df_0 and df_4 5m	0.71
df_4 and df_7 5m	0.48
df_0 and df_7 5m	0.48
df_0, df_4 and df_7 5m	0.48

Table 4.7 Variations in inter-floor distances

These variations are relatively small. On balance the author, and other colleagues on the CIBSE Guide D Steering Committee are proposing to include the revised calculation for t_s and RTT, but to simplify the calculation for d_H to use simply the average inter-floor height. So, equation 4.17 becomes:

$$d_H := d_f \cdot H \tag{4.20}$$

where

$$d_f := \frac{\sum_{i=0}^{N-1} df_i}{N} \tag{4.21}$$

4.3.3 Express Zones

In high rise buildings lifts are often zoned to reduce passenger travel times and to save core space by not having all the lifts serving the upper floors of the building. An example of a zoned building is represented by the diagram in Figure 4.1.

18					●	●	●	●
17					●	●	●	●
16					●	●	●	●
15					●	●	●	●
14					●	●	●	●
13					●	●	●	●
12					●	●	●	●
11					●	●	●	●
10					●	●	●	●
9	●	●	●	●	❍	❍	❍	❍
8	●	●	●	●	❍	❍	❍	❍
7	●	●	●	●	❍	❍	❍	❍
6	●	●	●	●	❍	❍	❍	❍
5	●	●	●	●	❍	❍	❍	❍
4	●	●	●	●	❍	❍	❍	❍
3	●	●	●	●	❍	❍	❍	❍
2	●	●	●	●	❍	❍	❍	❍
1	●	●	●	●	❍	❍	❍	❍
Ground	●	●	●	●	●	●	●	●
Lift No	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
	L O W R I S E				*H I G H R I S E*			

Key ● Lift serves floor ❍ Lift expresses past floor without stopping

Figure 4.1 Zoned building

This express zone can be taken into account by revising the Round Trip Time Equation, 4.19 to

$$RTT := \left[2 \cdot \frac{d_H + d_X}{v} + (S + 1) \cdot t_s + 2 \cdot P \cdot t_p \right] \qquad (4.22)$$

where d_X is the express zone; in this example, the sum of the floor heights of Levels 1 to 9.

4.3.4 Elevate Lite

The previous edition of CIBSE Guide D made extensive use of look-up tables to simplify the calculation procedure for designers. For this next version of the guide, the author has written a computer program to implement the up peak calculations given in sections 4.3.2 and 4.3.3. The program is written using Microsoft Visual C++ and runs under 32 bit Windows ('95 and NT). It will be given away with the revised CIBSE Guide.

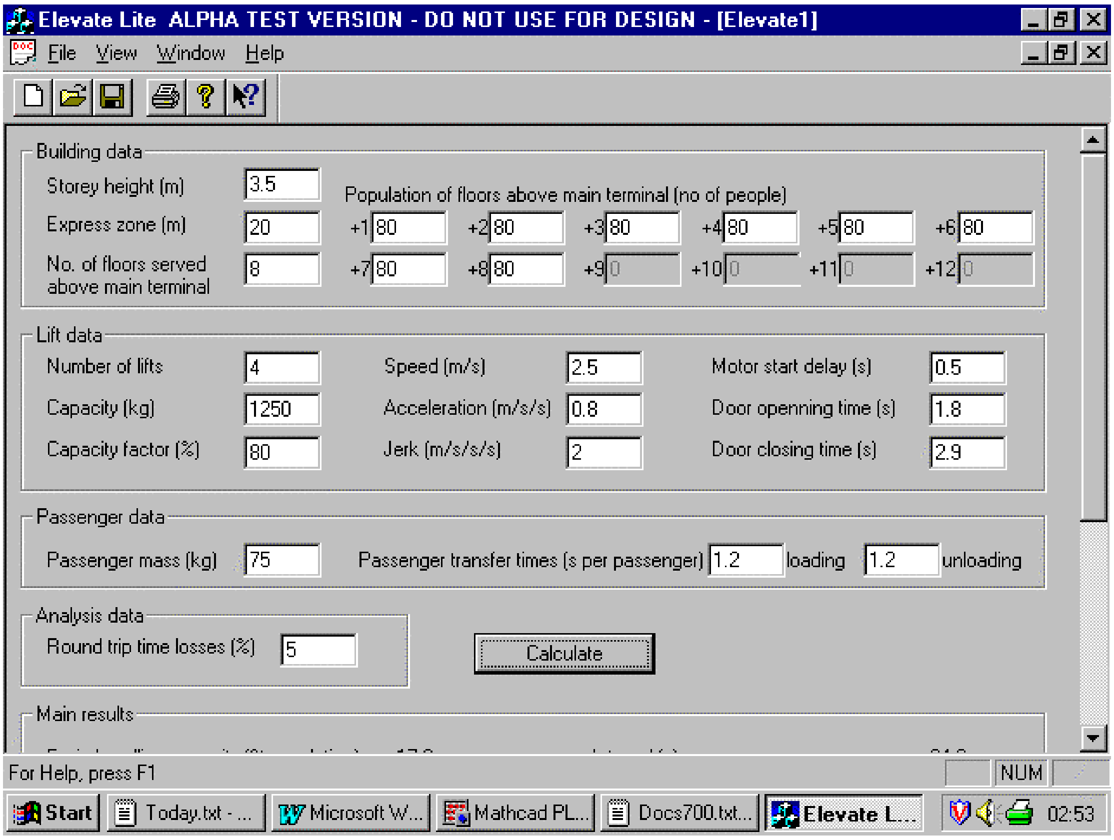

Figure 4.2 Screen shot of *Elevate Lite*

4.4 GENERAL CALCULATION

The standard up peak calculation is a valuable tool, but has a number of limitations. These include:

- the calculation only considers up peak traffic; as previously discussed, this is not believed to be the most onerous traffic flow in buildings
- in some instances up peak calculations are inappropriate, e.g. in shopping centres, car parks, airports or hospitals
- it is difficult to adjust the calculation to analyse up peaks in for buildings with basements which are occupied

Some of these limitations were overcome by Alexandris(4.7) who presented equations that allowed inter-floor traffic to be assessed. The limitation of this method is that passenger destinations are assumed to be the same from every floor, e.g. it is assumed that people travelling from floors x and y are both equally likely to want to go to floor

z. Consider the traffic in a multi-storey car park or office block with a restaurant floor to see the inconsistencies here.

Prior to joining the EngD programme, the author developed a new lift traffic analysis calculation which overcame these limitations. The *General* calculation allows us to carry out a round trip time calculation analysing any peak passenger traffic flow for any practical configuration of conventional lifts.

Details of the General calculation are widely published[(4.8)(4.9)]. The calculations have been implemented (in Fortran) by the author in the Oasys (Ove Arup Computer Systems) LIFT program. This program, issued originally in 1989, has been applied extensively through the work of the Ove Arup Partnership.

4.5 DISCUSSION

Most lift designs are based on an up-peak analysis, which is an important industry standard benchmark. The up-peak analysis has been developed over a number of years with contributions from several authors.

The author of this research project has made two contributions. Firstly, to derive formulae to determine flight times for any travel distance and lift dynamics. This extends the standard method, which uses tabulated results.

Secondly, the author has implemented in formulae, "corrections" that were recommended for lifts not reaching full speed in a single floor jump, and for non-equal inter-floor heights. A sensitivity analysis on these corrections has demonstrated that the variations between original and corrected results are relatively small (less than 2%). It can be argued that this variation is too small to warrant changes to the standard up peak calculation procedure. In itself, this is an interesting and useful result.

The up-peak calculation has been implemented in a computer program which, it is intended, will be issued with the revised version of CIBSE Guide D, *Transportation systems in buildings*.

As discussed in Chapter 3, the lunch-peak is now believed to be the busiest period in a commercial building. Prior to joining the EngD programme, the author derived the *General Analysis* calculation technique that assesses a lift system's performance given any peak passenger demand, including lunch-time traffic. This is a relatively complex technique to implement and to apply. Therefore further research to determine the equivalent lunch time handling capacity relative to a given up-peak handling capacity would be beneficial. This would allow designers to assess lunch time performance while retaining well known and understood up-peak analysis techniques.

The work presented in this chapter is a contribution to the development of green lifts in that, to avoid the inefficiencies of over-design, we need improved lift selection and analysis tools. Without these tools, it is difficult to realise the savings which it has been suggested can be achieved by improving our assessment of traffic demand.

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Chapter 5

DOUBLE DECK TRAFFIC ANALYSIS

List of Symbols

$d_{i,j}$	probability of the destination floor of a call from i being the jth floor (i and j must be both odd or both even for $d_{i,j} \neq 0$)
$DownJoin_i$	average number of passengers joining lift at ith floor on journey down
$DownLeave_i$	average number of passengers leaving lift at ith floor on journey down
FM	figure of merit for use of double deck lifts (%)
H_{rf}	average highest reversal floor of lower cab
$INT(n)$	interval (s)
INT(n)	interval, zone n (s)
JINT(i,j)	interval for journey from ith to the jth floor
L_{rf}	average lowest reversal floor of lower cab
N	number of floors ($N \geq 4$ and even)
$p_{i,j}$	probability of no calls from the ith to the jth floor in the time interval T
$pDS_{N-3} .. pDS_3$	probability that the lift will stop at intermediate floors on its journey down (subscript refers to floor lower cab stops at)
$pDSC_{N-3} .. pDSC_3$	probability that the lift will stop at intermediate floors on its journey down with stops coincident to both cabs
pH_n	probability of nth floor being the highest reversal floor (subscript refers to lower cab)
pL_n	probability of nth floor being the lowest reversal floor (subscript refers to lower cab)

$p(n)_{i,j}$	probability of n passengers travelling from the ith to the jth floor in the time interval T.
pS_1	probability that the lift will stop at the lowest floors (bottom cab floor 1, upper cab floor 2)
pS_{N-1}	probability that the lift will stop at the highest floor (bottom cab floor N-1, upper cab floor N)
pSC_1	probability that the lift will stop at the lowest floor with the stop coincident to both cabs
pSC_{N-1}	probability that the lift will stop at the highest floor with the stop coincident to both cabs
$pUS_3, pUS_5 .. pUS_{N-3}$	probability that the lift will stop at intermediate floors on its journey up (subscript refers to floor lower cab stops at)
$pUSC_3 .. pUSC_{N-3}$	probability that the lift will stop at intermediate floors on its journey up with stops coincident to both cabs
S'	probable number of stops including terminal floors
S_c	probable number of coincident stops
SPLIT(Q,i,j)	proportion of passengers travelling from the ith to the jth floor who are using lifts in zone Q
$UpJoin_i$	average number of passengers joining lift at ith floor on journey up
$UpLeave_i$	average number of passengers leaving lift at ith floor on journey up
μ_i	passenger arrival rate at floor i (persons s^{-1})

5.1 INTRODUCTION

Double deck lifts have two separate cabs built into a single unit so that the upper and lower cabs serve adjacent floors simultaneously. During peak periods maximum operating efficiency is achieved by restricting the lower cabs to serving odd numbered floors, and the upper cabs to serving even numbered floors.

Double deck lifts provide greater handling capacity per shaft than conventional lifts. This is particularly attractive for high rise buildings. The sacrifice is that double deck lifts are less convenient for passengers. Occupants of even numbered floors are required to use escalators to reach the upper lift cab on their way into the building. And again to reach the exit on their way out. Passengers have to walk one storey when an inter-floor trip from an odd to an even numbered floor, or vice-versa, is made. To alleviate this problem, double deck lift control systems can provide an odd-even floor service by operating in alternative modes out of peak times.

A more detailed discussion of the application of double deck lifts and their control systems is presented by Fortune in(5.1).

The value of double deck lifts in increasing the efficiency of lifting high rise buildings is recognised(5.1)(5.2), and calculations for their performance during the simple up peak traffic scenario have been defined(5.3). This chapter deals with the general case, allowing any practical configuration of double deck lifts and any peak traffic flow to be considered.

Similar general formulae have previously been presented by the author for conventional single deck lifts(5.4). It would be possible to extend these formulae for triple, quadruple, etc. deck lifts if required.

The calculations are based on calculating the probable number of stops and average reversal floors of a lift during its round trip. Lifts may be zoned to take into account the passenger split between different groups of lifts which may not be the same size, speed, etc., or which may not serve the same floors.

5.2 POISSON APPROXIMATION

It is generally accepted that the arrival of passengers at a lift landing station is reasonably approximated by a Poisson process. This gives the result:

$$p(n)_{i,j} := \frac{\left(\mu_i \cdot INT \cdot d_{i,j}\right)^n}{n!} \cdot \exp\left(-\mu_i \cdot INT \cdot d_{i,j}\right) \qquad (5.1)$$

When calculating probabilities, it is generally easier to calculate the probability of something not happening and then subtract this from 1 to arrive at the probability of the event happening. So, let

$$p_{i,j} := p(0)_{i,j}$$

which is the probability of no calls from the ith to the jth floor in the time interval INT. From (5.1),

$$p_{i,j} := \exp\left(-\mu_i \cdot INT \cdot d_{i,j}\right) \qquad (5.2)$$

5.3 PROBABLE NUMBER OF STOPS

When calculating the probable number of stops, it is necessary to consider both the up and the down journey of the lift, as the lift may stop at a floor twice during a single round trip.

For traffic analysis the designer is concerned with peak periods, so it is reasonable to assume that lifts are operating in their most efficient, double deck mode i.e. the lifts do not allow passengers to travel from odd to even floors or vice versa. This means that $d_{odd,even}$ and $d_{even,odd}$ must equal 0, which makes $p_{odd,even}$ and $p_{even,odd}$ equal to 1.

The probability of a lift stopping at a floor is one minus the probability that there are no calls to or from odd floors to the lower cab times the probability that there are no calls to or from the even floors to the upper cab. This gives the results:

$$pS_1 := 1 - \prod_{a=3}^{N} p_{a,1} \cdot p_{1,a} \cdot p_{a,2} \cdot p_{2,a} \tag{5.3}$$

$$pUS_j := 1 - \left(\prod_{a=1}^{j-1} p_{a,j} \cdot p_{a,j+1} \cdot \prod_{b=j+2}^{N} p_{j,b} \cdot p_{j+1,b} \right) \qquad \text{for } j := 3, 5 .. N-3 \tag{5.4}$$

$$pS_{N-1} := 1 - \prod_{a=1}^{N-2} p_{N-1,a} \cdot p_{a,N-1} \cdot p_{N,a} \cdot p_{a,N} \tag{5.5}$$

$$pDS_j := 1 - \left(\prod_{a=j+2}^{N} p_{a,j} \cdot p_{a,j+1} \cdot \prod_{b=1}^{j-1} p_{j,b} \cdot p_{j+1,b} \right) \qquad \text{for } j := 3, 5 .. N-3 \tag{5.6}$$

(Π is a mathematical symbol meaning multiply all the terms over this range.)

The total number of stops S' is calculated by adding together all the terms:

$$S' := pS_1 + \sum_{j} \left(pUS_j + pDS_j \right) + pS_{N-1} \qquad \text{for } j := 3, 5 .. N-3 \tag{5.7}$$

5.4 REVERSAL FLOORS

5.4.1 Reason for calculation

In an "average" journey, a lift may not reach the highest or lowest floor of a building. (This is less likely for double deck lifts than for conventional single deck lifts because double deck lifts carry more passengers, so are increasingly likely to have to stop at all floors.) Calculating the average highest and lowest reversal floors allows the possibility of this shortened round trip to be taken into account. In this derivation the highest and lowest reversal floors have been calculated with reference to the lower lift cab, i.e. the lowest possible floor is 1 and the highest possible floor is N-1.

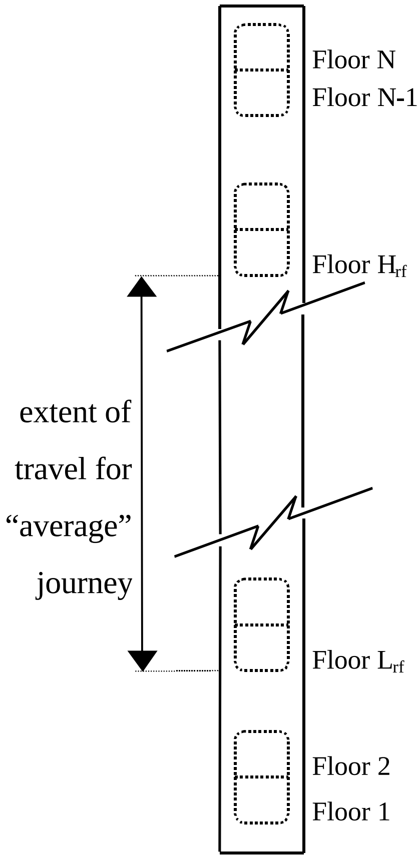

Figure 6.1 Highest and lowest reversal floors

5.4.2 Highest reversal floor

The probability of the jth floor being the highest reversal floor is the product of the probability that there is a call from a lower floor to either the jth or the (j+1)th floor and the probability that there are no calls to or from floors above j+1:

$$pH_1 := \prod_{a=1}^{N} \prod_{b=1}^{N} p_{a,b} \tag{5.8}$$

$$pH_j := \left(1 - \prod_{a=1}^{j-1} p_{a,j} \cdot p_{j,a} \cdot p_{a,j+1} \cdot p_{j+1,a}\right) \cdot \prod_{a=1}^{N} \prod_{b=j+2}^{N} p_{a,b} \cdot \prod_{a=j+2}^{N} \prod_{b=1}^{j+1} p_{a,b} \quad (5.9)$$

for $j := 3, 5 .. N - 3$

$$pH_{N-1} := 1 - \prod_{a=1}^{N-2} p_{a,N-1} \cdot p_{N-1,a} \cdot p_{a,N} \cdot p_{N,a} \quad (5.10)$$

(A good check for this is that $\sum_j pH_j = 1$)

Given the probability of each floor being the highest reversal floor, the average highest reversal floor, H_{rf} is simply:

$$H_{rf} := \sum_j j \cdot pH_j \qquad \text{for } j := 1, 3 .. N - 1 \quad (5.11)$$

5.4.3 Lowest reversal floor

Similarly, calculate the probability of the jth floor being the lowest reversal floor, which is the product of the probability that there is a call from a higher floor to or from floors j or j+1 and the probability that there are no calls to or from floors below j:

$$pL_1 := 1 - \prod_{a=3}^{N} p_{a,1} \cdot p_{1,a} \cdot p_{a,2} \cdot p_{2,a} \quad (5.12)$$

$$pL_j := \left(1 - \prod_{a=j+2}^{N} p_{a,j} \cdot p_{j,a} \cdot p_{a,j+1} \cdot p_{j+1,a}\right) \cdot \prod_{a=1}^{N} \prod_{b=1}^{j-1} p_{a,b} \cdot \prod_{a=1}^{j-1} \prod_{b=j}^{N} p_{a,b} \quad (5.13)$$

for $j := 3, 5 .. N - 3$

$$pL_{N-1} := \prod_{a=1}^{N} \prod_{b=1}^{N} p_{a,b} \tag{5.14}$$

(Again, a check for this is that $\sum_{j} pL_j = 1$)

Given the probability of each floor being the lowest reversal floor, the average lowest reversal floor, L_{rf} is simply:

$$L_{rf} := (N+1) - \sum_{j} pL_j \cdot ((N+1) - j) \qquad \text{for } j := 1, 3 .. N-1 \tag{5.15}$$

5.5 CAPACITY FACTOR

In a conventional up peak lift traffic calculation it is assumed that the lift is say 80% full at the beginning of its round trip. This approach cannot be taken for a general calculation as people may enter or leave the lift at any floor. One approach is to calculate the average number of people in the car when it leaves each floor. But first calculate the number of people entering and leaving the lift at each floor.

At the ith floor, going up, the number of passengers joining the car is

$$UpJoin_i := INT \cdot \mu_i \cdot \sum_{j=i+2}^{N} d_{i,j} \qquad \text{for } i := 1, 2 .. N-2 \tag{5.16}$$

No passengers join the lift at the top floors to go up, so $UpJoin_{N-1} := 0$ and $UpJoin_N := 0$.

At the ith floor, going up, the number of passengers leaving the car is

$$UpLeave_i := INT \cdot \sum_{j=1}^{i-2} \mu_j \cdot d_{j,i} \qquad \text{for } i := 3, 4 .. N \tag{5.17}$$

No passengers leave the lift at the bottom floors subsequent to an up journey, so $UpLeave_1 := 0$ and $UpLeave_2 := 0$.

At the ith floor, going down, the number of passengers joining the car is

$$DownJoin_i := INT \cdot \mu_i \cdot \sum_{j=1}^{i-2} d_{i,j} \qquad \text{for } i := N, N-1 .. 3 \qquad (5.18)$$

No passengers join the lift at the bottom floors to travel down so $DownJoin_1 := 0$ and $DownJoin_2 := 0$.

At the ith floor, going down, the number of passengers leaving the car is

$$DownLeave_i := INT \cdot \sum_{j=i+2}^{N} \mu_j \cdot d_{j,i} \qquad \text{for } i := N-2, N-3 .. 1 \qquad (5.19)$$

No passengers leave the lift at the top floors after a down journey so $DownLeave_N := 0$ and $DownLeave_{N-1} := 0$.

The above formulae allow you to calculated the average number of people joining and leaving the lift at each floor. From this, determine the average number of people in the car when it leaves each floor, travelling both up and down and the building. Dividing the maximum value by the lift capacity (in persons) gives the capacity factor, which is normally expressed as a percentage.

5.6 ROUND TRIP TIME

The round trip time for a single lift is the sum of the travel time from lowest to highest reversal floors, the number of stops times the delay time associated with a stop, and the time for people to load and unload the lift. An example of conventional round trip time formulae applied to double deck lift calculations can be found in [5.3]. Having calculated the round trip time for a single lift, the interval, INT may be calculated as the round trip time divided by the number of lifts.

The calculations are iterative as the result, INT is required as an input to the calculations. INT must be estimated, then the calculations repeated until the input INT is equal to the result.

5.7 FIGURE OF MERIT

The figure of merit for use of double deck lifts is defined as being the percentage of stops that are coincident to both upper and lower cabs[5.3]. A high figure of merit is preferable as it can be frustrating for passengers when the lift stops repeatedly and no one leaves or enters their lift cab.

The figure of merit is not required as an input to the iterative round trip time calculation, so only needs to be determined once a solution for INT has been found.

The probability of a stop at the jth and j+1th floors being coincident is the product of the probability of the lift needing to stop to serve a call to or from both j and j+1:

$$pSC_1 := \left(1 - \prod_{a=3}^{N} p_{a,1} \cdot p_{1,a}\right) \cdot \left(1 - \prod_{a=3}^{N} p_{a,2} \cdot p_{2,a}\right) \tag{5.20}$$

$$pUSC_j := \left[1 - \left(\prod_{a=1}^{j-1} p_{a,j} \cdot \prod_{a=j+2}^{N} p_{j,a}\right)\right] \cdot \left[1 - \left(\prod_{a=1}^{j-1} p_{a,j+1} \cdot \prod_{a=j+2}^{N} p_{j+1,a}\right)\right] \tag{5.21}$$

for $j := 3, 5 .. N - 3$

$$pSC_{N-1} := \left(1 - \prod_{a=1}^{N-2} p_{N-1,a} \cdot p_{a,N-1}\right) \cdot \left(1 - \prod_{a=1}^{N-2} p_{N,a} \cdot p_{a,N}\right) \tag{5.22}$$

$$pDSC_j := \left[1 - \left(\prod_{a=j+2}^{N} p_{a,j} \cdot \prod_{a=1}^{j-1} p_{j,a}\right)\right] \cdot \left[1 - \left(\prod_{a=j+2}^{N} p_{a,j+1} \cdot \prod_{a=1}^{j-1} p_{j+1,a}\right)\right] \qquad (5.23)$$

for $j := 3, 5 .. N - 3$

The total number of coincident stops S_c is calculated by adding together all the terms:

$$S_c := pSC_1 + \sum_j \left(pUSC_j + pDSC_j\right) + pSC_{N-1} \qquad \text{for } j := 3, 5 .. N - 3 \qquad (5.24)$$

giving figure of merit, expressed as a percentage:

$$FM := \frac{S_c}{S'} \cdot 100 \qquad (5.25)$$

5.8 OVERLAPPING ZONES

Lifts which serve the same floors and are of the same size, speed, capacity, etc. may be defined as being in a zone. If different zones do not serve the same floors, treat each as being independent, carrying out round trip time calculations for each zone separately. However, if a passenger could use lifts in either of two or more zones to make a journey, zones are “overlapping” and it is necessary to split up the passenger traffic between zones before carrying out the calculations. The results given for the single deck lifts in (5.4) also apply for double deck lifts:

$$JINT(i,j) := \sum_Z \left(\frac{1}{INT(Z)}\right)^{-1} \qquad (5.26)$$

where {Z}={all zones serving both the ith and the jth floor}

$$SPLIT(Q,i,j) := \frac{JINT(i,j)}{INT(Q)} \qquad (5.27)$$

5.9 EXAMPLES

5.9.1 Up peak analysis

Consider a 22 storey office building with 2000 m^2 net area per floor where the 5 minute up peak handling capacity required is 16%. Analyse the performance of 8 No 2.5 m/s, 1800 kg/1800 kg lifts. Assume the following additional parameters:

Population density	1 person per 15 m^2	Door operating times	1.8 s open,
Storey height	3.6 m		2.9 s close
Passenger weight	75 kg	Acceleration	0.8 m/s^2
Passenger transfer	1.2 s in, 1.2 s out	Jerk	2 m/s^3
Round Trip Time	5 % inefficiency	Motor start up delay	0.5 s

The passenger traffic can be represented as shown in Figure 5.2. Calculations are calculated according to the flow chart in Figure 5.3.

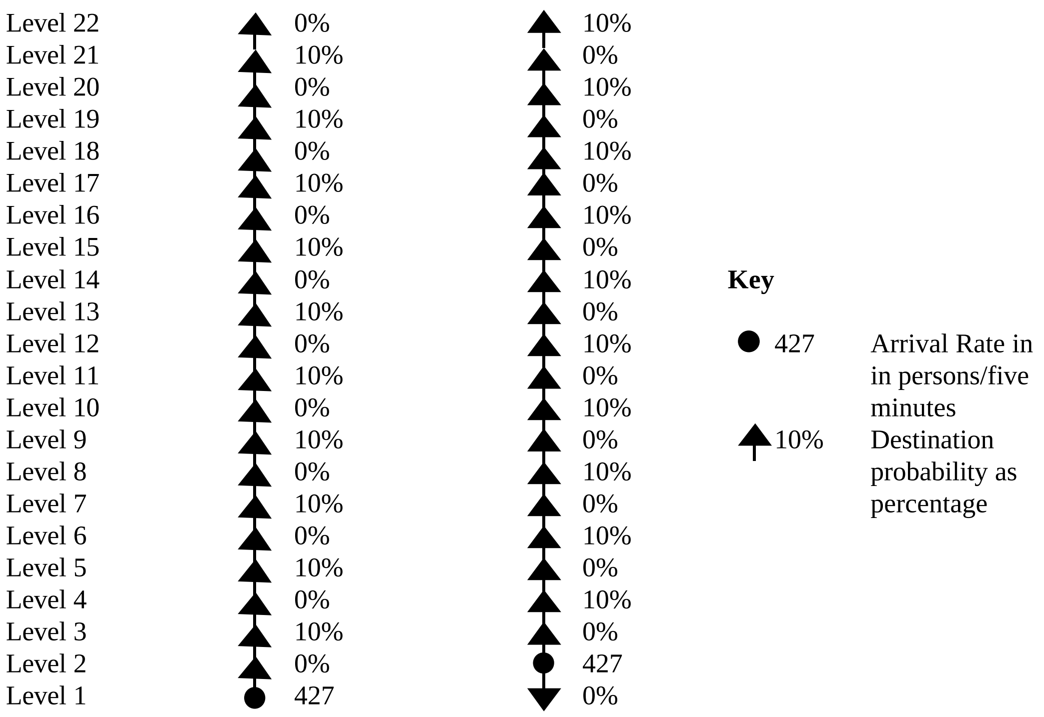

Figure 5.2 Example up peak traffic flow

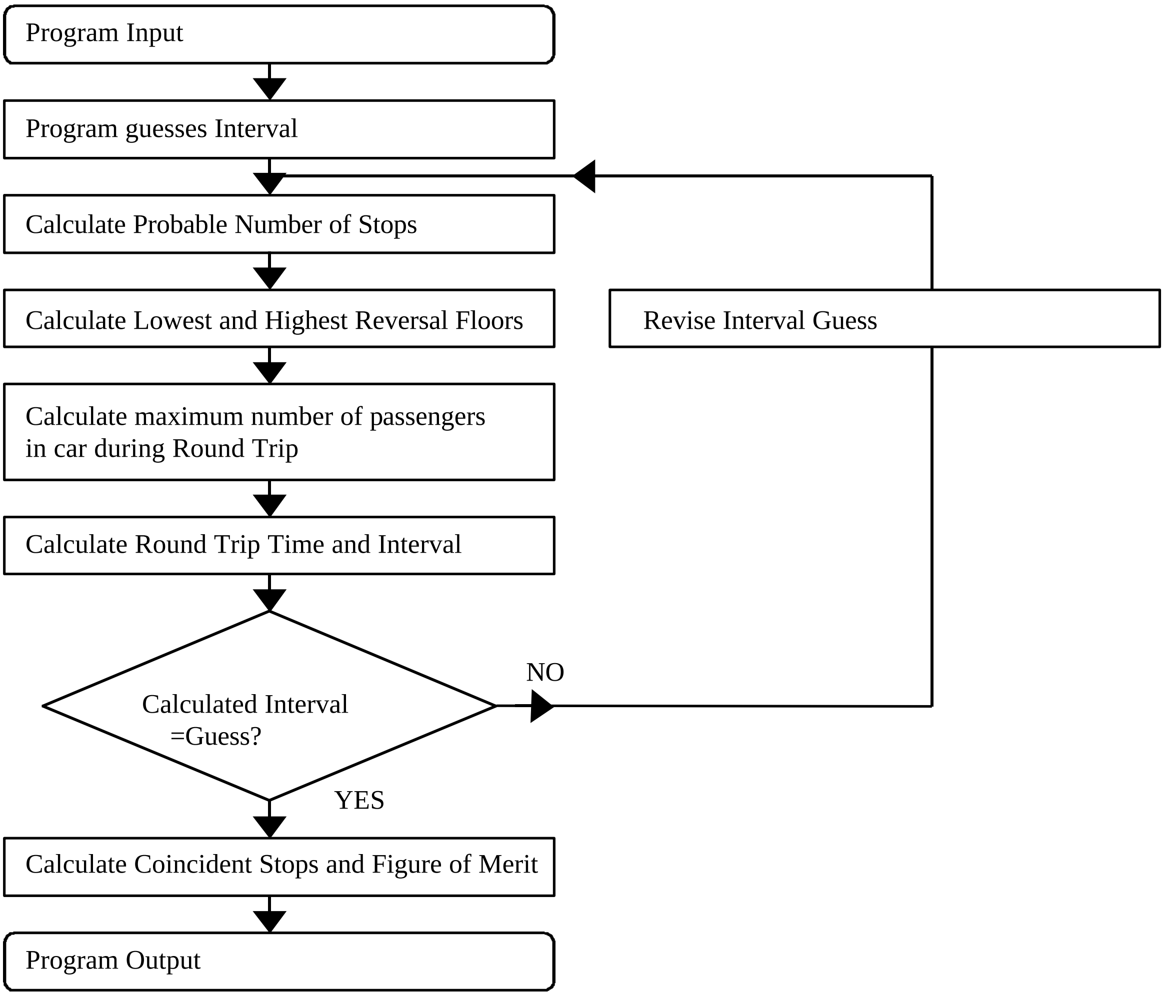

Figure 5.3 Calculation flow chart

Results from the Oasys LIFT program implementing the formulae are summarised as follows:

5 Min Handling Capacity	16%
Capacity Factor	76%
Probable Number of Stops	10.7 including main terminal
Highest Reversal Floor	Level 21 (to nearest floor lower cab reaches)
Interval	25.6 s
Figure of Merit	75 %

5.9.2 Lunch peak analysis

For a more complex example, consider the lunch peak scenario in an office building where there are double storey conference and restaurant facilities on the top two floors. Consider the scenario when a morning conference ends during the lunch time peak. Conference delegates are visitors to the building. The peak traffic is a combination of:

i. resident passengers travelling from their offices to the restaurant for lunch
ii. resident passengers travelling back to their offices after lunch
iii. resident passengers travelling to the ground floor to leave the building to buy sandwiches or eat out
iv. resident passengers returning from buying/eating lunch out

An example traffic flow is given in Figure 5.4. Assuming this traffic flow, analyse 8 No 2.5 m/s 1250 kg/1250 kg lifts and the following additional input parameters:

Storey height	3.6 m	Door operating times	1.8 s open, 2.9 s close
Acceleration	0.8 m/s^2	Passenger weight	75 kg
Jerk	2 m/s^3	Passenger transfer	1.2 s in, 1.2 s out
Motor start up delay	0.5 s	Round Trip Time	5 % inefficiency

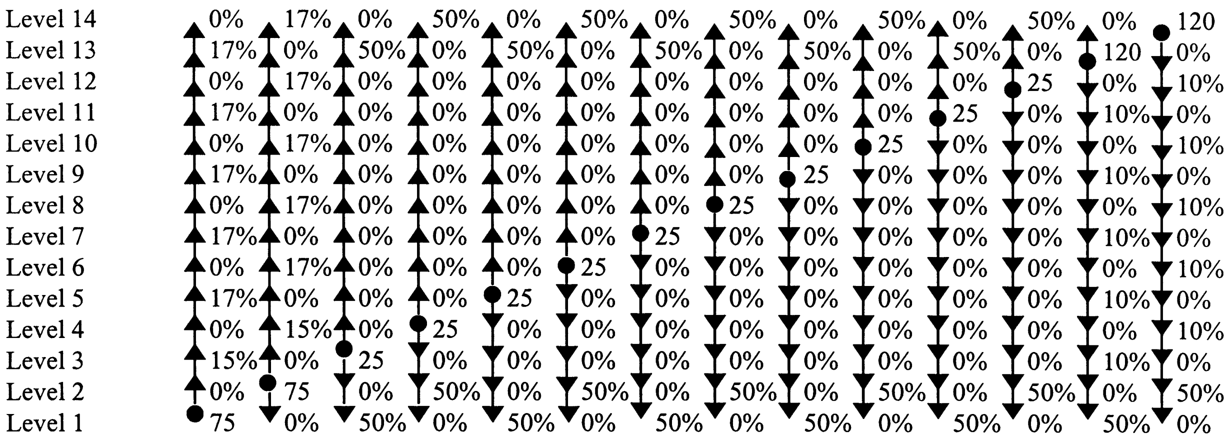

Figure 5.4 Complex traffic flow

Results from the Oasys LIFT program are summarised as follows:

Capacity Factor	68 %	Probable Number of Stops	11.9

Interval	26.7 s	Lowest Reversal Floor	1
Figure of Merit	83%	Highest Reversal Floor	13

5.10 DISCUSSION

Double deck lifts provide greater handling capacity per shaft than conventional lifts. This is particularly attractive for high rise buildings, where the core space taken by the lifts is a high percentage of the total floor area.

Kavounas[5.3] provided formulae to calculate the up-peak performance and handling capacity for double deck lifts. Formulae presented in this chapter allow analysis of any peak traffic flow for any practical configuration of double deck lifts. The approach taken for double deck lifts could be extended to cover triple and quadruple deck lifts if required.

The double deck formulae have been implemented by the author in the Oasys LIFT program, and are being used by Arup in the design of high rise developments.

This section of research has arisen primarily from commercial pressures to analyse the performance of lift systems in high rise buildings. This is a consequence of the EngD being based in industry rather than in academia. Nevertheless, it is a useful piece of research, allowing designers to consider lunch time and other peaks for double as well a single deck lifts.

It is possible to argue that double deck lifts are green; like double decker buses, they are an efficient means of transportation when fully loaded. However they are very inefficient if used for long periods while lightly loaded. A study of the relative energy consumption of double versus single deck lifts for a range of lift installations would be useful further work.

The General double deck lift traffic analysis technique was presented at the Elevator Technology Conference, ELEVCON’95[5.6]. A more detailed paper was published in the CIBSE journal, Building Services Engineering Research and Technology[5.7].

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5.4 Peters R D *Lift Traffic Analysis: Formulae for the general case* Building Serv. Res. Technol. 11(2) 65-67 (1990)

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Chapter 6

LIFT KINEMATICS

List of Symbols

a	maximum acceleration/deceleration (m/s^2)
A(t)	acceleration at time t (m/s^2)
d	lift journey distance (m)
D(t)	distance travelled at time t (m)
j	maximum jerk (m/s^3)
J(t)	jerk at time t (m/s^3)
v	maximum velocity (m/s)
V(t)	velocity at time t (m/s)

6.1 INTRODUCTION

6.1.1 Lift kinematics

Lift kinematics is the study of the motion of a lift car in a shaft without reference to mass or force. The maximum acceleration and jerk (rate of change of acceleration) which can be withstood by human beings without discomfort limits this motion. Ideal lift kinematics are the optimum velocity, acceleration and jerk profiles that can be obtained given human constraints.

Microprocessor controlled variable speed drives can be programmed to match reference speed profiles generated through the study of lift kinematics. Examples of these speed reference curves, similar to those shown in Figure 6.1, are sometimes presented in lift manufactures' sales literature as a demonstration of the fast, comfortable and efficient lift transportation available for a particular drive system.

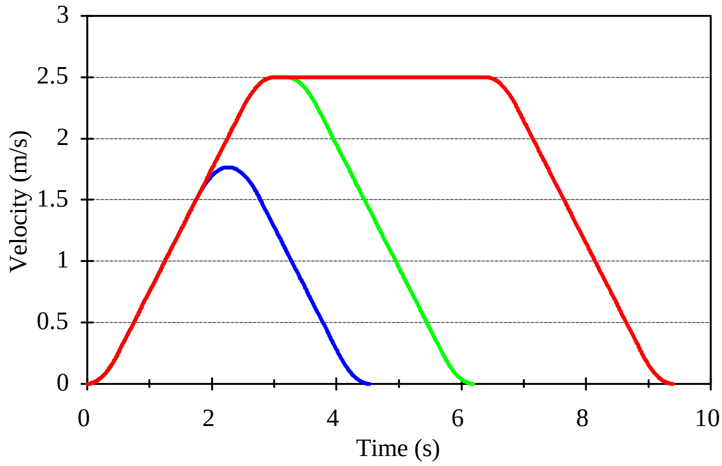

Figure 6.1 Example lift velocity-time profile for one, two and four floor runs

6.1.2 Previous work

P D Day and G C Barney provide references of previous published work in this field in section 11.4 of CIBSE Guide D, *Transportation Systems in Buildings* (6.1). In summary:

> H D Molz presented the first major work in this area in 1986. In his paper, *On the ideal kinematics of lifts* (6.2) (in German) he derives equations which enable minimum travel times to be calculated, taking to account maximum values of jerk, acceleration, and speed. If the lift trip is too short for the lift contract speed or acceleration to be obtained, the maximum speed and acceleration attained during the trip may be calculated. Some other points on the ideal kinematic curves are calculated. This paper was edited by G C Barney and re-published (6.3) by Elevatori in 1991 (in English and Italian).
>
> N R Roschier and M J Kaakinen apply Molz' formulae to provided summary tables of results for round trip time calculations (6.4).
>
> In *Elevator Trip Profiles* (6.5), J Schroeder presented a computer program that calculates the maximum speed, and minimum journey time that a lift can achieve for given flight distances if there is no speed limit. This produces interesting observations such as it would take a total trip of about 17 floors for an 8 m/s lift to reach its full speed.

In *Elevator Electric Drives* [6.6] G C Barney and A G Loher suggest a computer program based on H D Molz' equations. This is reproduced in *CIBSE Guide D, Transportation Systems in Buildings* [6.1].

6.1.3 New developments

For this research project, equations have been derived which allow ideal lift kinematics to be plotted as continuous functions for any value of journey distance, speed, acceleration and jerk. Supplementary results include journey time formulae for use in lift traffic analysis. The remainder of this chapter is a summary of this research. Some or all of the results presented in this chapter (or equivalent software routines) may have been known to individual lift manufacturers; but, to the best of the author's knowledge, they have not been published.

6.1.4 Approach to derivation

The derivation is divided into three major sections, corresponding to the journey conditions where: (A) the lift reaches full speed; (B) the lift reaches full acceleration, but not full speed; and (C) the lift does not reach full speed or acceleration. The condition where full speed is reached before full acceleration is determined and excluded as this would be an illogical design. Conditions A to C are represented graphically in Figure 6.2. Each of the three conditions is divided into time slices, beginning and ending at each change in jerk or change in sign of acceleration.

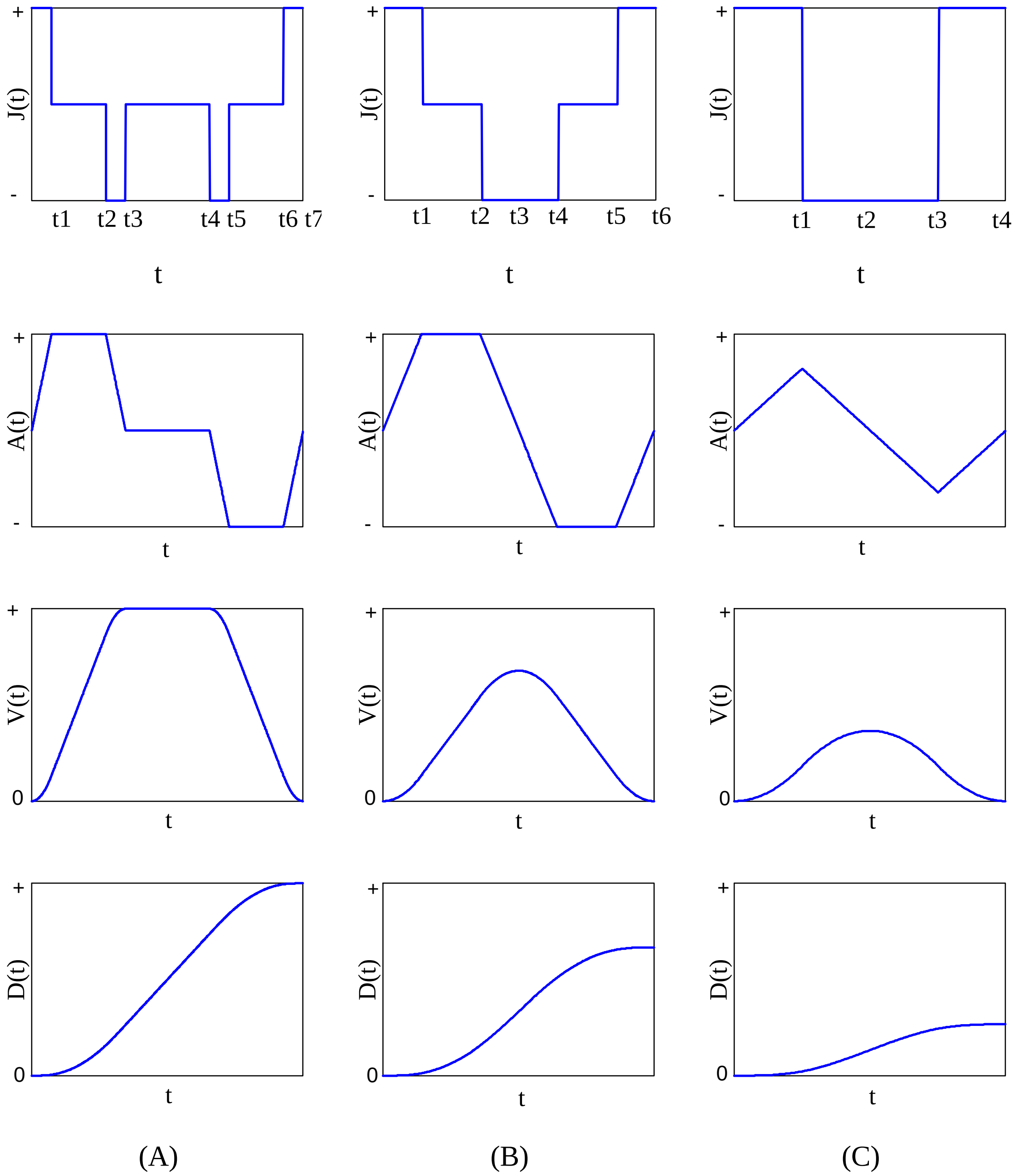

Figure 6.2 Ideal lift kinematics for: (A) lift reaches full speed; (B) lift reaches full acceleration, but not full speed; (C) lift does not reach full speed or acceleration

6.2 DERIVATION FOR CONDITION A, LIFT REACHING FULL SPEED DURING JOURNEY

6.2.1 Calculation of t_n

Referring to Figure 6.2 (A) we can write down expressions for t_n as follows:

$$t_1 := \frac{a}{j} \qquad (6.1)$$

$$\frac{a}{2}\cdot t_1 + a\cdot\left(t_2 - t_1\right) + \frac{a}{2}\cdot\left(t_3 - t_2\right) := v \qquad (6.2)$$

$$t_3 - t_2 := \frac{a}{j} \qquad (6.3)$$

$$t_5 - t_4 := \frac{a}{j} \qquad (6.4)$$

$$\frac{a}{2}\cdot\left(t_5 - t_4\right) + a\cdot\left(t_6 - t_5\right) + \frac{a}{2}\cdot\left(t_7 - t_6\right) := v \qquad (6.5)$$

$$t_7 - t_6 := \frac{a}{j} \qquad (6.6)$$

Solving for t_n gives:

$$t_1 := \frac{a}{j} \qquad (6.7)$$

$$t_2 := \frac{v}{a} \qquad (6.8)$$

$$t_3 := \frac{a}{j} + \frac{v}{a} \qquad (6.9)$$

$$t_5 := t_4 + \frac{a}{j} \qquad (6.10)$$

$$t_6 := t_4 + \frac{v}{a} \qquad (6.11)$$

$$t_7 := t_4 + \frac{a}{j} + \frac{v}{a} \qquad (6.12)$$

6.2.2 Motion during time period 0 £ t £ t_1

Referring to Figure 6.2 (A) we can write down expressions for jerk and acceleration:

$$J(t) := j \qquad (6.13)$$

$$A(t) := j\cdot t \qquad (6.14)$$

The velocity can be determined by integrating the acceleration:

$$V(t) := \int_0^t j\cdot T \, dT \quad \text{yields} \quad V(t) := \frac{j\cdot t^2}{2} \qquad (6.15)$$

The distance travelled can be determined by integrating the velocity:

$$D(t) := \int_0^t \frac{j\cdot T^2}{2} \, dT \quad \text{yields} \quad D(t) := \frac{j\cdot t^3}{6} \qquad (6.16)$$

6.2.3 Motion during time period t_1 £ t £ t_2

Referring to Figure 6.2 (A) we can write down expressions for jerk and acceleration:

$$J(t) := 0 \qquad (6.17) \qquad\qquad A(t) := a \qquad (6.18)$$

The velocity can be found by adding the velocity at the end of the previous time slice to the current acceleration, integrated:

$$V(t) := V(t_1) + \int_{t_1}^{t} a \, dT \quad \text{yields} \quad V(t) := \frac{-a^2}{2 \cdot j} + a \cdot t \qquad (6.19)$$

The distance travelled can be found by adding the distance travelled at the end of the previous time slice to the current velocity, integrated:

$$D(t) := D(t_1) + \int_{t_1}^{t} \frac{-a^2}{2 \cdot j} + a \cdot T \, dT \quad \text{yields} \quad D(t) := \frac{a^3}{6 \cdot j^2} - \frac{a^2 \cdot t}{2 \cdot j} + \frac{a \cdot t^2}{2} \qquad (6.20)$$

6.2.4 Motion during time period t_2 £ t £ t_3

Referring to Figure 6.2 (A) we can write down expressions for jerk and acceleration:

$$J(t) := -j \qquad (6.21)$$

$$A(t) := a - j \cdot (t - t_2) \quad \text{which by substitution yields} \quad A(t) := a - j \cdot t + \frac{v \cdot j}{a} \qquad (6.22)$$

The velocity can be found by adding the velocity at the end of the previous time slice to the current acceleration, integrated:

$$V(t) := V(t_2) + \int_{t_2}^{t} a - j \cdot T + \frac{v \cdot j}{a} \, dT \quad \text{yields} \quad V(t) := \frac{-a^2}{2 \cdot j} + a \cdot t - \frac{j \cdot t^2}{2} + \frac{t \cdot v \cdot j}{a} - \frac{v^2 \cdot j}{2 \cdot a^2} \qquad (6.23)$$

The distance travelled can be found by adding the distance travelled at the end of the previous time slice to the current velocity, integrated:

$$D(t) := D(t_2) + \int_{t_2}^{t} \frac{-a^2}{2 \cdot j} + a \cdot T - \frac{j \cdot T^2}{2} + \frac{T \cdot v \cdot j}{a} - \frac{v^2 \cdot j}{2 \cdot a^2} \, dT \quad \text{yields}$$

$$D(t) := \frac{a^3}{6 \cdot j^2} - \frac{t \cdot a^2}{2 \cdot j} - \frac{j \cdot t^3}{6} + \frac{a \cdot t^2}{2} + \frac{j \cdot v \cdot t^2}{2 \cdot a} - \frac{j \cdot v^2 \cdot t}{2 \cdot a^2} + \frac{v^3 \cdot j}{6 \cdot a^3} \qquad (6.24)$$

6.2.5 Motion during time period t_3 £ t £ t4

Referring to Figure 6.2 (A) we can write down expressions for jerk, acceleration and velocity:

$$J(t) := 0 \qquad (6.25) \qquad A(t) := 0 \qquad (6.26)$$

$$V(t) := v \qquad (6.27)$$

The distance travelled can be found by adding the distance travelled at the end of the previous time slice to the current velocity, integrated:

$$D(t) := D(t_3) + \int_{t_3}^{t} v \, dT \quad \text{yields} \quad D(t) := \frac{-a \cdot v}{2 \cdot j} - \frac{v^2}{2 \cdot a} + v \cdot t \qquad (6.28)$$

6.2.6 Simplification of t_4 to t_7

To complete solutions for t_n, refer to Figure 6.2 (A) to write down:

$$d := 2.D(t_3) + \int_{t_3}^{t_4} v \, dT \quad \text{yields} \quad t_4 := \frac{d}{v} \qquad (6.29)$$

By substitution, results for t_n become

$$t_1 := \frac{a}{j} \qquad (6.30) \qquad t_2 := \frac{v}{a} \qquad (6.31)$$

$$t_3 := \frac{a}{j} + \frac{v}{a} \qquad (6.32) \qquad t_4 := \frac{d}{v} \qquad (6.33)$$

$$t_5 := \frac{d}{v} + \frac{a}{j} \qquad (6.34) \qquad t_6 := \frac{d}{v} + \frac{v}{a} \qquad (6.35)$$

$$t_7 := \frac{d}{v} + \frac{a}{j} + \frac{v}{a} \qquad (6.36)$$

6.2.7 Motion during time period t_4 £ t £ t_5

Referring to Figure 6.2 (A) we can write down expressions for jerk and acceleration:

$$J(t) := -j \qquad (6.37)$$

$$A(t) := -j \cdot (t - t_4) \quad \text{yields} \quad A(t) := \frac{j \cdot d}{v} - j \cdot t \qquad (6.38)$$

The velocity can be found by adding the velocity at the end of the previous time slice to the current acceleration, integrated:

$$V(t) := V\left(t_4\right) + \int_{t_4}^{t} \frac{j\cdot d}{v} - j\cdot T \, dT \qquad \text{yields} \qquad V(t) := v - \frac{j\cdot t^2}{2} + \frac{d\cdot j\cdot t}{v} - \frac{d^2\cdot j}{v^2\cdot 2} \tag{6.39}$$

The distance travelled can be found by adding the distance travelled at the end of the previous time slice to the current velocity, integrated:

$$D(t) := D\left(t_4\right) + \int_{t_4}^{t} v - \frac{j\cdot T^2}{2} + \frac{d\cdot j\cdot T}{v} - \frac{d^2\cdot j}{v^2\cdot 2} \, dT \qquad \text{yields}$$

$$D(t) := \frac{-a\cdot v}{2\cdot j} - \frac{v^2}{2\cdot a} + v\cdot t + \frac{t^2\cdot j\cdot d}{2\cdot v} - \frac{t\cdot j\cdot d^2}{v^2\cdot 2} - \frac{t^3\cdot j}{6} + \frac{d^3\cdot j}{v^3\cdot 6} \tag{6.40}$$

6.2.8 Motion during time period t_5 £ t £ t_6

Referring to Figure 6.2 (A) we can write down expressions for jerk and acceleration:

$$J(t) := 0 \tag{6.41}$$

$$A(t) := -a \tag{6.42}$$

The velocity can be found by adding the velocity at the end of the previous time slice to the current acceleration, integrated:

$$V(t) := V\left(t_5\right) + \int_{t_5}^{t} -a \, dT \qquad \text{yields} \qquad V(t) := v + \frac{a\cdot d}{v} + \frac{a^2}{2\cdot j} - a\cdot t \tag{6.43}$$

The distance travelled can be found by adding the distance travelled at the end of the previous time slice to the current velocity, integrated:

$$D(t) := D\left(t_5\right) + \int_{t_5}^{t} v + \frac{a\cdot d}{v} + \frac{a^2}{2\cdot j} - a\cdot T \, dT \qquad \text{yields}$$

$$D(t) := \frac{-a\cdot v}{2\cdot j} - \frac{v^2}{2\cdot a} - \frac{d^2\cdot a}{v^2\cdot 2} - \frac{d\cdot a^2}{2\cdot j\cdot v} - \frac{a^3}{j^2\cdot 6} + v\cdot t + \frac{a\cdot d\cdot t}{v} + \frac{t\cdot a^2}{2\cdot j} - \frac{t^2\cdot a}{2} \tag{6.44}$$

6.2.9 Motion during time period t_6 £ t £ t_7

Referring to Figure 6.2 (A) we can write down expressions for jerk and acceleration:

$$J(t) := j \tag{6.45}$$

$$A(t) := -a + \left(t - t_6\right)\cdot j \qquad \text{yields} \qquad A(t) := -a - \frac{j\cdot d}{v} - \frac{j\cdot v}{a} + j\cdot t \tag{6.46}$$

The velocity can be found by adding the velocity at the end of the previous time slice to the current acceleration, integrated:

$$V(t) := V(t_6) + \int_{t_6}^{t} -a - \frac{j \cdot d}{v} - \frac{j \cdot v}{a} + j \cdot T \, dT \qquad \text{yields}$$

$$V(t) := v + \frac{a \cdot d}{v} + \frac{a^2}{j \cdot 2} - a \cdot t - \frac{j \cdot d \cdot t}{v} - \frac{j \cdot v \cdot t}{a} + \frac{j \cdot t^2}{2} + \frac{d^2 \cdot j}{v^2 \cdot 2} + \frac{j \cdot d}{a} + \frac{v^2 \cdot j}{a^2 \cdot 2} \qquad (6.47)$$

The distance travelled can be found by adding the distance travelled at the end of the previous time slice to the current velocity, integrated:

$$D(t) := D(t_6) + \int_{t_6}^{t} v + \frac{a \cdot d}{v} + \frac{a^2}{j \cdot 2} - a \cdot T - \frac{j \cdot d \cdot T}{v} - \frac{j \cdot v \cdot T}{a} + \frac{j \cdot T^2}{2} + \frac{d^2 \cdot j}{v^2 \cdot 2} + \frac{j \cdot d}{a} + \frac{v^2 \cdot j}{a^2 \cdot 2} \, dT \qquad \text{yields}$$

$$D(t) := \frac{-v^2}{2 \cdot a} + v \cdot t - \frac{j \cdot d \cdot v}{2 \cdot a^2} - \frac{d^2 \cdot j}{2 \cdot v \cdot a} + \frac{t^3 \cdot j}{6} - \frac{a \cdot v}{2 \cdot j} - \frac{d^3 \cdot j}{v^3 \cdot 6} - \frac{t^2 \cdot j \cdot d}{2 \cdot v} + \frac{j \cdot d^2 \cdot t}{2 \cdot v^2} + \frac{a \cdot t \cdot d}{v} \ldots \qquad (6.48)$$

$$+ \frac{t \cdot a^2}{2 \cdot j} - \frac{t^2 \cdot a}{2} - \frac{a^3}{j^2 \cdot 6} - \frac{d^2 \cdot a}{v^2 \cdot 2} - \frac{d \cdot a^2}{2 \cdot j \cdot v} + \frac{t \cdot d \cdot j}{a} + \frac{t \cdot v^2 \cdot j}{2 \cdot a^2} - \frac{t^2 \cdot v \cdot j}{2 \cdot a} - \frac{j \cdot v^3}{a^3 \cdot 6}$$

6.2.10 Verification of results at time t_7

From (6.36), we have $t_7 := \frac{d}{v} + \frac{a}{j} + \frac{v}{a}$ which by substitution into equation (6.47), yields $V(t_7) := 0$ and by substitution into equation (6.48), yields $D(t_7) := d$ which is correct.

6.2.11 Range over which results apply

Results for condition A apply if the lift reaches full speed during its trip, which occurs if:

$$\frac{d}{2} \geq D(t_3) \qquad \text{yields} \qquad \frac{a^2 \cdot v + v^2 \cdot j}{j \cdot a} \leq d \qquad (6.49)$$

6.3 CONDITION B, LIFT REACHING MAXIMUM ACCELERATION, BUT NOT FULL SPEED

The derivation for condition B is similar to that for condition A. For brevity, only results are given.

Results apply over the range $$2 \cdot \frac{a^3}{j^2} \le d < \frac{a^2 \cdot v + v^2 \cdot j}{j \cdot a} \quad (6.50)$$

6.3.1 Values of t_n

$$t_1 := \frac{a}{j} \quad (6.51)$$

$$t_2 := \frac{-a}{2 \cdot j} + \frac{\sqrt{a^3 + 4 \cdot d \cdot j^2}}{2 \cdot j \cdot \sqrt{a}} \quad (6.52)$$

$$t_3 := \frac{a}{2 \cdot j} + \frac{\sqrt{a^3 + 4 \cdot d \cdot j^2}}{2 \cdot j \cdot \sqrt{a}} \quad (6.53)$$

$$t_4 := \frac{3 \cdot a}{2 \cdot j} + \frac{\sqrt{a^3 + 4 \cdot d \cdot j^2}}{2 \cdot j \cdot \sqrt{a}} \quad (6.54)$$

$$t_5 := \frac{\sqrt{a^3 + 4 \cdot d \cdot j^2}}{\sqrt{a \cdot j}} \quad (6.55)$$

$$t_6 := \frac{a}{j} + \frac{\sqrt{a^3 + 4 \cdot d \cdot j^2}}{\sqrt{a \cdot j}} \quad (6.56)$$

6.3.2 Motion during time period 0 £ t £ t_1

$$J(t) := j \quad (6.57)$$

$$A(t) := j \cdot t \quad (6.58)$$

$$V(t) := \frac{j \cdot t^2}{2} \quad (6.59)$$

$$D(t) := \frac{j \cdot t^3}{6} \quad (6.60)$$

6.3.3 Motion during time period t_1 £ t £ t_2

$$J(t) := 0 \quad (6.61)$$

$$A(t) := a \quad (6.62)$$

$$V(t) := \frac{-a^2}{2 \cdot j} + a \cdot t \quad (6.63)$$

$$D(t) := \frac{a^3}{6 \cdot j^2} - \frac{a^2 \cdot t}{2 \cdot j} + \frac{a \cdot t^2}{2} \quad (6.64)$$

6.3.4 Motion during time period t_2 £ t £ t_3

$$J(t) := -j \quad (6.65)$$

$$A(t) := \frac{a}{2} - j \cdot t + \frac{\sqrt{a^3 + 4 \cdot d \cdot j^2}}{2 \cdot \sqrt{a}} \quad (6.66)$$

$$V(t) := \frac{-3\cdot a^2}{4\cdot j} - \frac{j\cdot t^2}{2} + \frac{a\cdot t}{2} + \frac{t\cdot\sqrt{a^3 + 4\cdot d\cdot j^2}}{\sqrt{a}\cdot 2} + \frac{\sqrt{a^3 + 4\cdot d\cdot j^2}\cdot\sqrt{a}}{4\cdot j} - \frac{j\cdot d}{2\cdot a} \quad (6.67)$$

$$D(t) := \frac{a^3}{12\cdot j^2} + \frac{a^{\frac{3}{2}}\cdot\sqrt{a^3 + 4\cdot d\cdot j^2}}{12\cdot j^2} - \frac{d}{4} - \frac{3\cdot t\cdot a^2}{4\cdot j} + \frac{t^2\cdot a}{4} + \frac{1}{4}\cdot\frac{t^2\cdot\sqrt{a^3 + 4\cdot d\cdot j^2}}{\sqrt{a}} \ldots$$
$$+ \frac{\sqrt{a^3 + 4\cdot d\cdot j^2}\cdot\sqrt{a}\cdot t}{4\cdot j} - \frac{t^3\cdot j}{6} - \frac{t\cdot j\cdot d}{a\cdot 2} + \frac{d\cdot\sqrt{a^3 + 4\cdot d\cdot j^2}}{12\cdot a^{\left(\frac{3}{2}\right)}} \quad (6.68)$$

6.3.5 Motion during time period t_3 £ t £ t_4

$$J(t) := -j \quad (6.69) \qquad A(t) := \frac{1}{2}\cdot a - j\cdot t + \frac{\sqrt{a^3 + 4\cdot d\cdot j^2}}{2\cdot\sqrt{a}} \quad (6.70)$$

$$V(t) := \frac{-3\cdot a^2}{4\cdot j} + \frac{\sqrt{a^3 + 4\cdot d\cdot j^2}\cdot\sqrt{a}}{4\cdot j} - \frac{d\cdot j}{2\cdot a} - \frac{j\cdot t^2}{2} + \frac{t\cdot a}{2} + \frac{\sqrt{a^3 + 4\cdot d\cdot j^2}\cdot t}{\sqrt{a}\cdot 2} \quad (6.71)$$

$$D(t) := \frac{-d}{4} + \frac{a\cdot t^2}{4} - \frac{a^2\cdot 3\cdot t}{4\cdot j} + \frac{\sqrt{a^3 + 4\cdot d\cdot j^2}\cdot t\cdot\sqrt{a}}{4\cdot j} - \frac{j\cdot t\cdot d}{2\cdot a} + \frac{t^2\cdot\sqrt{a^3 + 4\cdot d\cdot j^2}}{4\cdot\sqrt{a}} - \frac{j\cdot t^3}{6} \ldots$$
$$+ \frac{a^3}{j^2\cdot 12} + \frac{\sqrt{a^3 + 4\cdot d\cdot j^2}\cdot a^{\left(\frac{3}{2}\right)}}{j^2\cdot 12} + \frac{d\cdot\sqrt{a^3 + 4\cdot d\cdot j^2}}{12\cdot a^{\left(\frac{3}{2}\right)}} \quad (6.72)$$

6.3.6 Motion during time period t_4 £ t £ t_5

$$J(t) := 0 \quad (6.73) \qquad A(t) := -a \quad (6.74)$$

$$V(t) := \frac{a^2}{2\cdot j} + \frac{\sqrt{a^3 + 4\cdot d\cdot j^2}\cdot\sqrt{a}}{j} - t\cdot a \quad (6.75)$$

$$D(t) := -d - \frac{a\cdot t^2}{2} + \frac{\sqrt{a^3 + 4\cdot d\cdot j^2}\cdot t\cdot\sqrt{a}}{j} + \frac{a^2\cdot t}{2\cdot j} - \frac{a^{\frac{3}{2}}}{2}\cdot\frac{\sqrt{a^3 + 4\cdot d\cdot j^2}}{j^2} - \frac{2\cdot a^3}{3\cdot j^2} \quad (6.76)$$

6.3.7 Motion during time period t_5 £ t £ t_6

$$J(t) := j \quad (6.77) \qquad A(t) := -a + j\cdot t - \frac{\sqrt{a^3 + 4\cdot d\cdot j^2}}{\sqrt{a}} \quad (6.78)$$

$$V(t) := \frac{a^2}{j} + \frac{j \cdot t^2}{2} - t \cdot a - \frac{t \cdot \sqrt{a^3 + 4 \cdot d \cdot j^2}}{\sqrt{a}} + \frac{\sqrt{a^3 + 4 \cdot d \cdot j^2} \cdot \sqrt{a}}{j} + \frac{2 \cdot d \cdot j}{a} \qquad (6.79)$$

$$D(t) := -d - \frac{2 \cdot a^3}{3 \cdot j^2} + \frac{a^2 \cdot t}{j} - \frac{a \cdot t^2}{2} + \frac{j \cdot t^3}{6} + \frac{\sqrt{a^3 + 4 \cdot d \cdot j^2} \cdot \sqrt{a} \cdot t}{j} + \frac{2 \cdot d \cdot t \cdot j}{a} \ldots$$
$$+ \frac{\left(a^3 + 4 \cdot d \cdot j^2\right)^{\left(\frac{3}{2}\right)}}{j^2 \cdot \left[3 \cdot a^{\left(\frac{3}{2}\right)}\right]} - \frac{t^2 \cdot \sqrt{a^3 + 4 \cdot d \cdot j^2}}{\sqrt{a} \cdot 2} - \frac{\sqrt{a^3 + 4 \cdot d \cdot j^2} \cdot a^{\left(\frac{3}{2}\right)}}{j^2} - \frac{2 \cdot \sqrt{a^3 + 4 \cdot d \cdot j^2} \cdot d}{a^{\left(\frac{3}{2}\right)}} \qquad (6.80)$$

6.4 CONDITION C, LIFT NOT REACHING MAXIMUM ACCELERATION OR FULL SPEED

Results apply over the range $d < 2 \cdot \frac{a^3}{j^2}$ (6.81)

6.4.1 Values of t_n

$$t_1 := \left(\frac{1}{2} \cdot \frac{d}{j}\right)^{\frac{1}{3}} \qquad (6.82) \qquad\qquad t_2 := \left(4 \cdot \frac{d}{j}\right)^{\frac{1}{3}} \qquad (6.83)$$

$$t_3 := \left(\frac{27}{2} \cdot \frac{d}{j}\right)^{\frac{1}{3}} \qquad (6.84) \qquad\qquad t_4 := \left(32 \cdot \frac{d}{j}\right)^{\frac{1}{3}} \qquad (6.85)$$

6.4.2 Motion during time period 0 £ t £ t_1

$$J(t) := j \qquad (6.86) \qquad\qquad A(t) := j \cdot t \qquad (6.87)$$

$$V(t) := \frac{j \cdot t^2}{2} \qquad (6.88) \qquad\qquad D(t) := \frac{j \cdot t^3}{6} \qquad (6.89)$$

6.4.3 Motion during time period t_1 £ t £ t_2

$$J(t) := -j \qquad (6.90) \qquad\qquad A(t) := j^{\left(\frac{2}{3}\right)} \cdot 2^{\left(\frac{2}{3}\right)} \cdot d^{\left(\frac{1}{3}\right)} - j \cdot t \qquad (6.91)$$

$$V(t) := -\frac{1}{2} \cdot j^{\left(\frac{1}{3}\right)} \cdot 2^{\left(\frac{1}{3}\right)} \cdot d^{\left(\frac{2}{3}\right)} - \frac{j \cdot t^2}{2} + j^{\left(\frac{2}{3}\right)} \cdot 2^{\left(\frac{2}{3}\right)} \cdot d^{\left(\frac{1}{3}\right)} \cdot t \qquad (6.92)$$

$$D(t) := \frac{d}{6} + \frac{1}{2} \cdot j^{\left(\frac{2}{3}\right)} \cdot 2^{\left(\frac{2}{3}\right)} \cdot d^{\left(\frac{1}{3}\right)} \cdot t^2 - \frac{1}{2} \cdot j^{\left(\frac{1}{3}\right)} \cdot 2^{\left(\frac{1}{3}\right)} \cdot d^{\left(\frac{2}{3}\right)} \cdot t - \frac{j \cdot t^3}{6} \qquad (6.93)$$

6.4.4 Motion during time period t_2 £ t £ t_3

$$J(t) := -j \qquad (6.94)$$

$$A(t) := -j \cdot t + 2^{\left(\frac{2}{3}\right)} \cdot d^{\left(\frac{1}{3}\right)} \cdot j^{\left(\frac{2}{3}\right)} \qquad (6.95)$$

$$V(t) := \frac{-1}{2} \cdot j^{\left(\frac{1}{3}\right)} \cdot 2^{\left(\frac{1}{3}\right)} \cdot d^{\left(\frac{2}{3}\right)} - \frac{j \cdot t^2}{2} + j^{\left(\frac{2}{3}\right)} \cdot t \cdot 2^{\left(\frac{2}{3}\right)} \cdot d^{\left(\frac{1}{3}\right)} \qquad (6.96)$$

$$D(t) := \frac{d}{6} - \frac{1}{2} \cdot j^{\left(\frac{1}{3}\right)} \cdot t \cdot 2^{\left(\frac{1}{3}\right)} \cdot d^{\left(\frac{2}{3}\right)} + \frac{t^2}{2} \cdot j^{\left(\frac{2}{3}\right)} \cdot 2^{\left(\frac{2}{3}\right)} \cdot d^{\left(\frac{1}{3}\right)} - \frac{j \cdot t^3}{6} \qquad (6.97)$$

6.4.5 Motion during time period t_3 £ t £ t_4

$$J(t) := j \qquad (6.98)$$

$$A(t) := -2 \cdot 2^{\left(\frac{2}{3}\right)} \cdot d^{\left(\frac{1}{3}\right)} \cdot j^{\left(\frac{2}{3}\right)} + j \cdot t \qquad (6.99)$$

$$V(t) := 4 \cdot j^{\left(\frac{1}{3}\right)} \cdot 2^{\left(\frac{1}{3}\right)} \cdot d^{\left(\frac{2}{3}\right)} - 2 \cdot j^{\left(\frac{2}{3}\right)} \cdot t \cdot 2^{\left(\frac{2}{3}\right)} \cdot d^{\left(\frac{1}{3}\right)} + \frac{j \cdot t^2}{2} \qquad (6.100)$$

$$D(t) := \frac{-13 \cdot d}{3} - j^{\left(\frac{2}{3}\right)} \cdot t^2 \cdot 2^{\left(\frac{2}{3}\right)} \cdot d^{\left(\frac{1}{3}\right)} + 4 \cdot j^{\left(\frac{1}{3}\right)} \cdot t \cdot 2^{\left(\frac{1}{3}\right)} \cdot d^{\left(\frac{2}{3}\right)} + \frac{j \cdot t^3}{6} \qquad (6.101)$$

6.5 CONDITION TO CONFIRM MAXIMUM ACCELERATION IS REACHED BEFORE MAXIMUM SPEED

The case where the lift reaches maximum speed, but not maximum acceleration has not been considered as this would be a non-sensical design. To confirm the system does not have this anomaly, refer to Figure 6.2 (A) to write down:

$t_3 \geq 2 \cdot t_1$ which by substitution yields $a^2 \leq v \cdot j$ (6.102)

6.6 MINIMUM TRAVEL DISTANCES

During a lift journey, a new landing or car call may be introduced such that the lift needs to stop before the destination it is currently travelling to. The following results enable the lift control system to check whether the lift can stop in time for the new call. If the current D(t) is less than d_{min}, the software routines implementing the equations given in for Conditions A to C can be reset with a new value of d mid-way through a journey. The D(t), V(t), A(t) and J(t) profiles generated will remain continuous.

6.6.1 Condition A

While $0 \le t \le t_1$ refer to condition C results and set $t = t_1$

$$t := \left(\frac{d_{min}}{2 \cdot j}\right)^{\frac{1}{3}} \quad \text{yields} \quad d_{min} := 2 \cdot t^3 \cdot j \qquad (6.103)$$

While $t_1 \le t \le t_2$ refer to condition B results setting $t = t_2$

$$t := \frac{-a}{2 \cdot j} + \frac{\sqrt{a^3 + 4 \cdot d_{min} \cdot j^2}}{2 \cdot j \cdot \sqrt{a}} \quad \text{yields} \quad d_{min} := a \cdot t^2 + \frac{a^2 \cdot t}{j} \qquad (6.104)$$

If $t_2 \le t \le t_3$ the velocity profile must continue to t_3, so

$$d_{min} := 2 \cdot D(t_3) \quad \text{yields} \quad d_{min} := \frac{v \cdot a}{j} + \frac{v^2}{a} \qquad (6.105)$$

If $t_3 \le t \le t_4$ the lift commences decelerating at t_4, so set

$$t := \frac{d_{min}}{v} \quad \text{yields} \quad d_{min} := t \cdot v \qquad (6.106)$$

If $t_4 \le t$ the lift has already started decelerating, so $d_{min} := d$ (6.107)

6.6.2 Condition B

For $0 \le t \le t_1$ condition A result applies, so $d_{min} := 2 \cdot t^3 \cdot j$ (6.108)

For $t_1 \le t \le t_2$ condition A result applies, so $d_{min} := a \cdot t^2 + a^2 \cdot \frac{t}{j}$ (6.109)

When $t_2 \le t$ the lift has already begun slowing down, so $d_{min} := d$ (6.110)

6.6.3 Condition C

For $0 \le t \le t_1$ condition A result applies, so $d_{min} := 2 \cdot t^3 \cdot j$ (6.111)

When $t_1 \le t$ the lift has already begun slowing down, so $d_{min} := d$ (6.112)

6.7 APPLICATIONS

6.7.1 Motor speed reference

Motor speed reference curves are commonly held in software look up tables. It is envisaged that a software implementation of the equations presented in this paper will provide a fast, flexible and efficient way of generating optimum reference speed profiles, on line in lift system controllers. This application is modelled in the following two chapters of this thesis where the equations are applied to generate profiles for the motor model and lift simulation.

6.7.2 Lift traffic analysis

To calculate the handling capacity and performance of a lift system it is necessary to know how long it takes a lift to travel given distances. Using the appropriate formulae taken from the previous sections, the travel time of a variable speed lift (with optimum control) can be written down as follows:

if $d \geq \frac{a^2 \cdot v + v^2 \cdot j}{j \cdot a}$ then $Journey\_Time := \frac{d}{v} + \frac{a}{j} + \frac{v}{a}$ (condition A)

if $\frac{2 \cdot a^3}{j^2} \leq d < \frac{a^2 \cdot v + v^2 \cdot j}{j \cdot a}$ then $Journey\_Time := \frac{a}{j} + \frac{\sqrt{a^3 + 4 \cdot d \cdot j^2}}{\sqrt{a \cdot j}}$ (condition B)

if $d < 2 \cdot \frac{a^3}{j^2}$ then $Journey\_Time := \left(32 \cdot \frac{d}{j}\right)^{\frac{1}{3}}$ (condition C)

It is advisable to add an additional time component to allow for motor start up time and any deviations from the optimum speed profile. Depending on drive quality, Day and Barney(6.1) recommend that this component should be between 0.2 and 0.5 seconds. These equations are applied in Chapter 4 of this thesis.

6.8 DISCUSSION

Ideal lift kinematics provide the basis for optimum speed control of lifts, an essential component for fast, efficient and comfortable transportation.

Equations by Motz(6.2) give us points on these curves. The equations derived in this chapter allow continuous, optimum functions of jerk, acceleration, speed and distance travelled profiles to be plotted against time. These profiles can be generated for any journey distance given inputs for maximum jerk, acceleration, and speed.

The equations are complex, but have been implemented in software by the author.

The users of this software do not need to work through the calculations taking place, but can concentrate on entering the required inputs to generate the profiles quickly and easily.

The ability to plot profiles for any inputs gives additional flexibility in the design of lift controllers. In later chapters we will explore how building this functionality into a control system can help us save energy in a green lift system.

The results also have applications in lift traffic analysis for calculating journey time, as already discussed in Chapter 4 of this thesis.

Although there is some guidance[(6.1)] on the choice of maximum jerk and acceleration for a lift installation, there have been no major studies on the relative levels of comfort experienced by passengers given different values of these variables. Applying the work discussed in this chapter, it would be feasible to carry out such an investigation. This would yield useful results for specification and design.

The work presented in this chapter has been widely published. A summary of the research and results was presented at the Elevator Technology Conference, ELEVCON '95[(6.7)]. The written conference paper was re-published by the trade magazines, Elevator World in April 1996 and by Elevatori in May/June 1996. A more detailed paper, including details of the derivation was published in the International Journal of Elevator Engineers (IJEE)[(6.8)].

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Chapter 7

MOTOR MODELLING

List of Symbols

$a(t)$	lift acceleration at time t (m/s^2)
d_s	motor sheave diameter (m)
g	gravitational acceleration constant (m/s^2)
g_r	gear ratio (:1)
E	electromotive force (Volts)
E_t	total energy consumption of trip (Joules)
JT	lift journey time (s)
J	total moment of inertia (kgm^2)
J_b	brake moment of inertial (kgm^2)
J_g	gear moment of inertia (kgm^2)
J_m	motor moment of inertia (kgm^2)
J_p	pulleys total moment of inertia (kgm^2)
J_s	sheave moment of inertia (kgm^2)
M_c	mass of car (kg)
M_{cw}	mass of counterweight (kg)
M_p	mass of passengers in car (kg)
M_r	mass of ropes (kg)
KI_f	motor magnetising constant (amps)
$I_a(t)$	armature current at time t (ohms)
$I_{ph}(t)$	converter phase current at time t (amps)
I_n	amplitude of n^{th} harmonic current (amps)
$PF(t)$	power factor at time t
$P(t)$	power consumption at time t (Watts)

R_a	armature resistance (ohms)
r_r	roping ratio (:1)
T_L	load torque (Nm)
$T(t)$	required motor torque at time t (Nm)
$V_a(t)$	armature voltage at time t (Volts)
V_{line}	phase-phase line voltage (Volts r.m.s.)
$v(t)$	lift velocity at time t (m/s)
$\alpha(t)$	converter firing angle at time t (radians)
$\varepsilon(t)$	motor drive angular acceleration at time t (rad/s^2)
η	gear efficiency (0-1)
ω_s	supply angular frequency (rad/s)
$\omega(t)$	motor drive angular velocity at time t (rad/s)

7.1 INTRODUCTION

So[7.1] provides a comparison of the energy efficiency for a range of drives using motor models. The comparison is for a single lift trip with a fixed journey profile, load torque and inertia.

The purpose of this section of the research is to derive a motor model similar to that used by So, and to develop it to the point that it can be built into a lift simulation program. We can then calculate the total energy consumption of a lift system for a given passenger traffic profile and lift control system. This will allows us to investigate possible energy savings.

So considers AC 2 speed, AC variable voltage, AC variable voltage variable frequency, DC Ward Leonard and DC static converter drives. The AC variable voltage variable frequency and DC static converter drives are shown to be the most efficient. The drive modelled in this chapter has a separately excited DC motor, fed from a fully controlled 6 pulse converter. A diagrammatic representation of the drive is shown in Figure 7.1.

The following calculations have being prepared using Mathcad mathematical software.

The results are calculated and plotted directly from the equations entered in standard mathematical notation. To test for consistency, input parameters have been chosen to correspond with So.

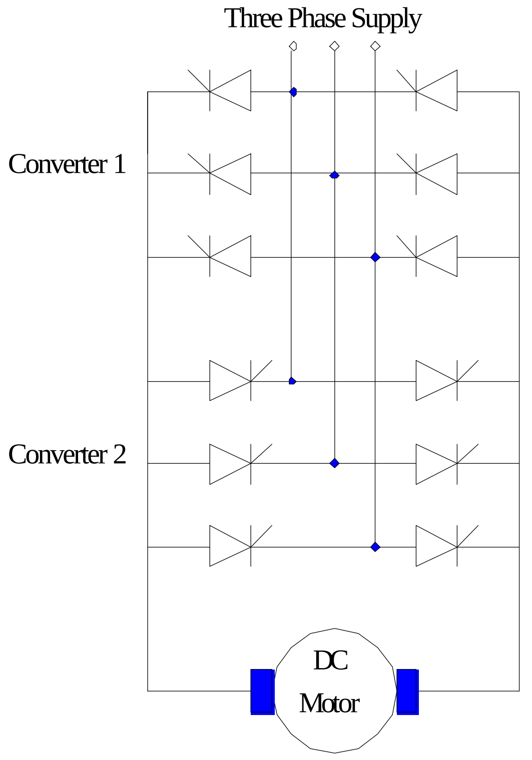


Figure 7.1   Static converter drive

7.2   LIFT MOTION

So does not consider linear motion, but takes angular velocity and acceleration as input to his model. The translation between linear and angular motion is a function of the sheave diameter, gear ratio and roping ratio, as described in equations 7.1 and 7.2.

$$\omega(t) := \frac{v(t) \cdot 2 \cdot g_r \cdot r_r}{d_s} \tag{7.1}$$

$$\varepsilon(t) := \frac{a(t) \cdot 2 \cdot g_r \cdot r_r}{d_s} \tag{7.2}$$

Applying the ideal lift kinematics equations derived in Chapter 6, we can generate suitable velocity and acceleration plots, as shown in Figure 7.2.

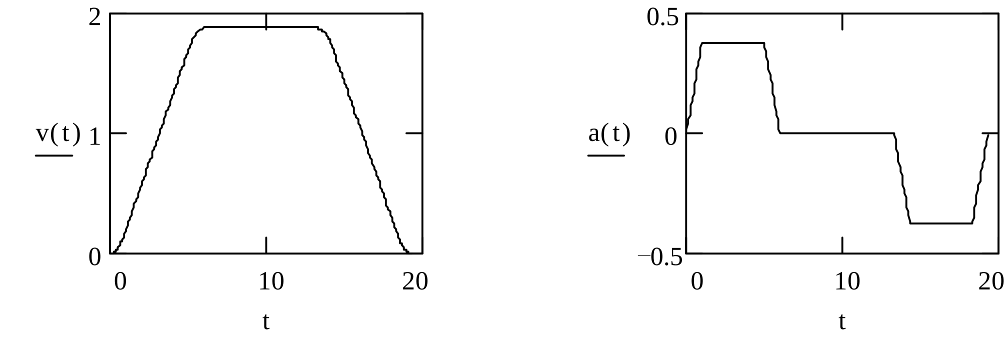


Figure 7.2 Velocity and acceleration profiles

To plot angular velocity and acceleration we apply equations 7.1 and 7.2. In this example take drive sheave diameter $d_s := 0.5$, gear ratio $g_r := 20$, and roping ratio $r_r := 1$. This gives us the profiles in Figure 7.3, which are consistent with the input to So's model.

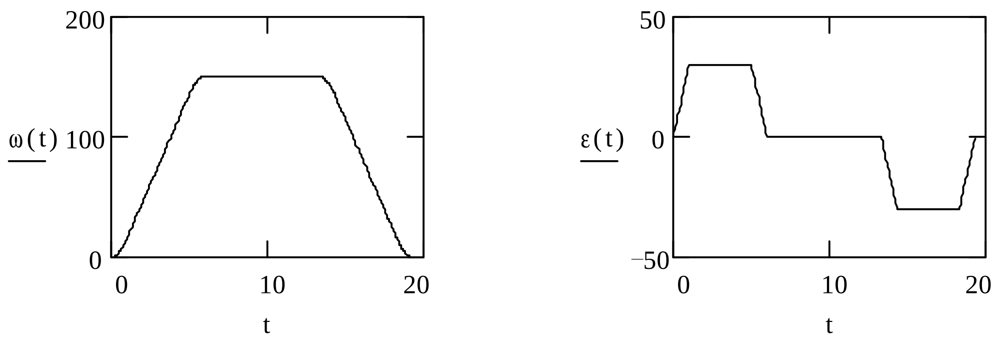


Figure 7.3 Angular velocity and acceleration profiles

7.3 LOAD TORQUE

The load torque is the result of the imbalance in static loads either side of the driving sheave as shown in Figure 7.4. Again, So does not calculate a load torque, but uses a fixed value. We need to calculate load torque if we are to apply the model in a simulation.

The torque is applied at the rim of the driving sheave, thus it is calculated as the difference in weight between the loaded car and counterweight times the radius of the driving sheave. We are interested in the load as "seen" by the motor, so must take into account the reducing effect of the roping ratio, gear ratio, and the losses caused by inefficiencies in the gear unit.

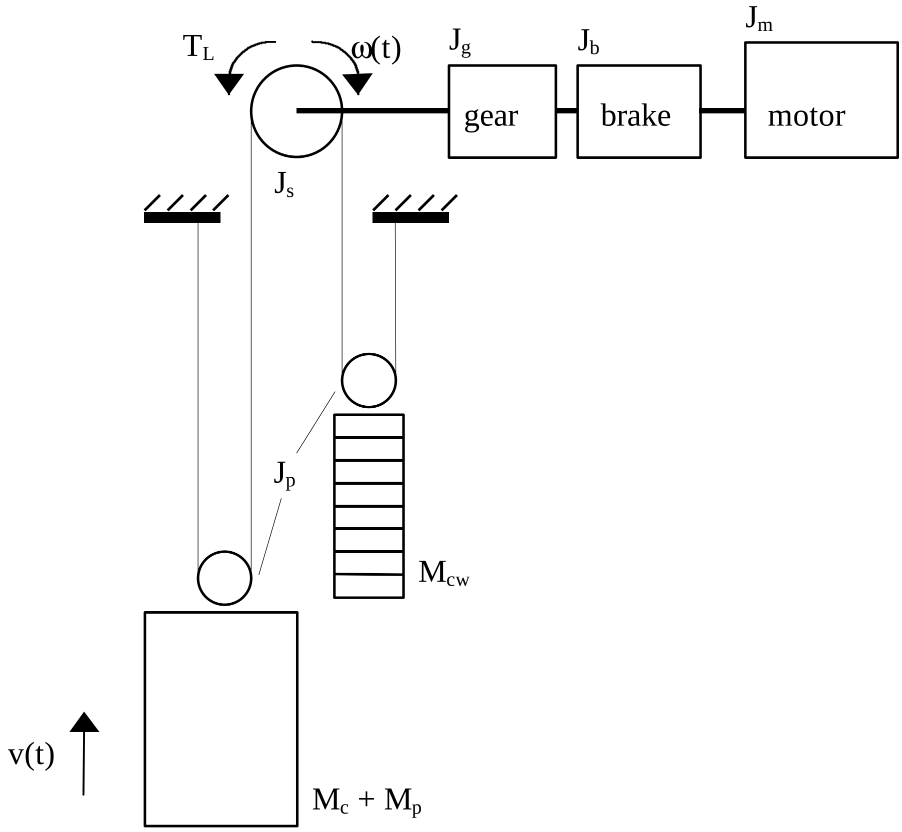


Figure 7.4 Schematic representation of traction lift
(2:1 roping ratio shown in this diagram)

Thus we can write down an expression for the load torque as follows

$$T_L := \frac{\left(M_c + M_p - M_{cw}\right)\cdot g\cdot\frac{d_s}{2}}{g_r\cdot r_r\cdot\eta} \tag{7.3}$$

Note that difference in rope weight either side of the shaft has not been included. Where there is a significant differential in rope weight, it is normal practice to include compensation roping which resolves any imbalance.

So uses the value $T_L := 60$ in his model, which we shall use for the remainder of this calculation.

7.4 LOAD INERTIA

The moment of inertia of a lift system is made up of a number of components including contributions from: motor, brake, gear, driving sheave, pulleys, ropes, lift car, counterweight, and passengers. So takes a fixed value for load inertia, but again we need to be able to calculate a value for use in a lift simulation.

Referring to Figure 7.4, the inertia of rotating components are summed, except for those rotating at a lower speed because of the gear; these must be divided by the square of the gear ratio to determine their equivalent inertia, as seen by the motor. (Note the kinetic energy of a rotating body is ½J ω^2 , hence the introduction of squared terms when considering angular velocity reductions by gear and roping ratios.)

The inertia of the car, counterweight, and ropes are seen by the motor as point masses on the edge of the driving sheave. Hence their equivalent inertia is the sum of their masses times the square of the radius of the driving sheave, divided by the appropriate gear and roping ratios.

Thus the equivalent moment of inertia that the motor sees is:

$$J := J_m + J_b + \frac{1}{g_r^2}\cdot\left(J_g + J_s + J_p\right) + \frac{d_s^2\cdot M_r}{4\cdot g_r^2} + \frac{d_s^2}{4\cdot\left(g_r\cdot r_r\right)^2}\cdot\left(M_c + M_{cw} + M_p\right) \qquad (7.4)$$

Zhou presents a similar equation in his paper on the *Analysis of Motion Equations of Elevator Drive Systems*(7.2), but does not consider a term for roping ratios. Equation 7.4 is consistent with Zhou's equations are consistent for 1:1 roping.

So uses the value $J := 10$ in his model which we shall use for the remainder of this calculation.

7.5 MOTOR TORQUE

The torque required from the motor is the load torque plus the torque required to accelerate or decelerate the lift. Thus,

$$T(t) := T_L + J \cdot \varepsilon(t) \tag{7.5}$$

which is plotted in Figure 7.5.

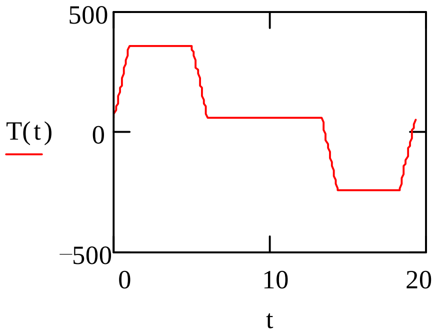


Figure 7.5 Required motor torque

7.6 MOTOR MODEL

DC Motor steady state performance equations are well known:

$$V_a := E + I_a \cdot R_a \tag{7.6}$$

where

$$E := \left(KI_f\right) \cdot \omega \tag{7.7}$$

and the torque developed is

$$T := \frac{E \cdot I_a}{\omega} \tag{7.8}$$

By substitution, the steady state equations can be rearranged to determine the required armature voltage and resultant current for the functions of torque and angular velocity which we have already determined. This approach assumes an ideal feedback control system. Thus,

$$V_a(t) := (KI_f)\cdot\omega(t) + \frac{T(t)}{KI_f}\cdot R_a \qquad (7.9)$$

$$I_a(t) := \frac{T(t)}{KI_f} \qquad (7.10)$$

For our example, let $R_a := 0.2$ and $KI_f := 1.6$. The functions of armature voltage and current in Figure 7.6 can than be plotted by applying Equations 7.9 an 7.10.

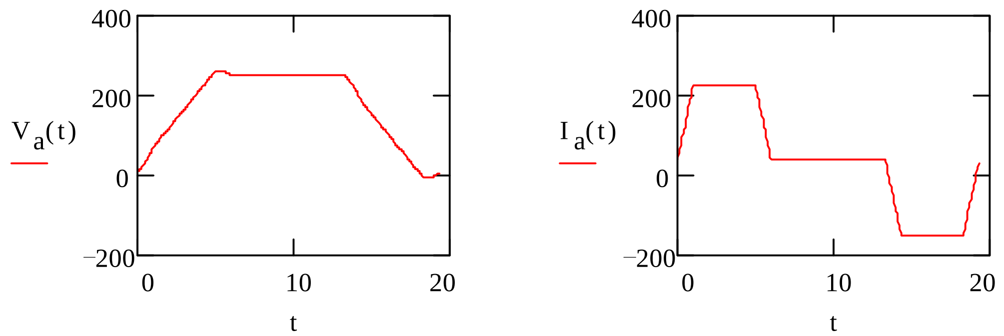


Figure 7.6 Armature voltage and current

The power consumption of the motor (ignoring field excitation) during the trip is

$$P(t) := I_a(t)\cdot V_a(t) \qquad (7.11)$$

and is plotted in Figure 7. This profile is the same as So's result.

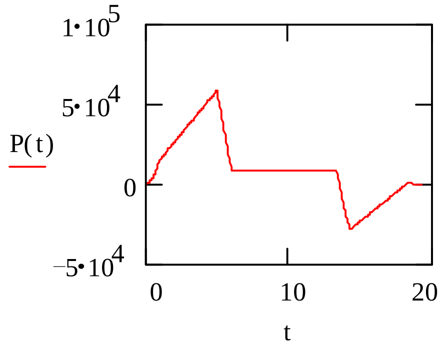


Figure 7.7 Power consumption

The total energy consumption of the DC motor during the trip is

$$E_t := \int_0^{JT} P(t)\,dt \tag{7.12}$$

which yields $E_t = 1.911 \cdot 10^5$ Joules, which again is consistent with So's results.

7.7 CONVERTER OPERATION

The voltage applied to the DC motor is controlled by the firing angle of the converter. For a fully controlled, three phase 6 pulse converter, ignoring overlap, the firing angle for the required mean dc voltage is[7.3]

$$\alpha(t) := \mathrm{acos}\left(\frac{\pi}{3} \cdot \frac{V_a(t)}{V_{line} \cdot \sqrt{2}}\right) \tag{7.13}$$

For a fully controlled converter, the firing angle is equal to the phase angle[7.3], so the power factor

$$PF(t) := \cos(\alpha(t)) \tag{7.14}$$

Taking So's value of $V_{line} := 380$ and applying equations 7.13 and 7.14 we can plot the power factor profile shown in Figure 7.8. This is consistent with So's result.

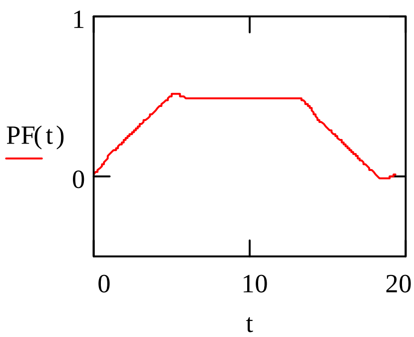


Figure 7.8 Power factor

7.8 SUPPLY SYSTEM HARMONICS

Supply system harmonics are not considered by So, but are known from the literature. By Fourier analysis, ignoring overlap, the quasi square-wave phase current of an ideal six-pulse converter can be shown to be[(7.4)]

$$I_{ph}(t) = \frac{2\cdot\sqrt{3}}{\pi}\cdot I_a(t)\cdot\left[\begin{array}{l}\cos\left(\omega_s\cdot t\right) - \frac{1}{5}\cdot\cos\left(5\cdot\omega_s\cdot t\right) + \frac{1}{7}\cdot\cos\left(7\cdot\omega_s\cdot t\right) - \frac{1}{11}\cdot\cos\left(7\cdot\omega_s\cdot t\right) \ldots \\ + \frac{1}{13}\cdot\cos\left(13\cdot\omega_s\cdot t\right) - \frac{1}{17}\cdot\cos\left(17\cdot\omega_s\cdot t\right) + \frac{1}{19}\cdot\cos\left(19\cdot\omega_s\cdot t\right)\end{array}\right]$$

- ...... + ... etc. (7.15)

Thus, the amplitudes relative to the fundamental of the 5th, 7th, 11th and 13th harmonic currents are 20%, 14.3%, 9.1% and 7.7% respectively. The total harmonic distortion of the current is defined as

$$\frac{\left(\sum_{n=2}^{\infty} {I_n}^2\right)^{0.5}}{I_1} \qquad (7.16)$$

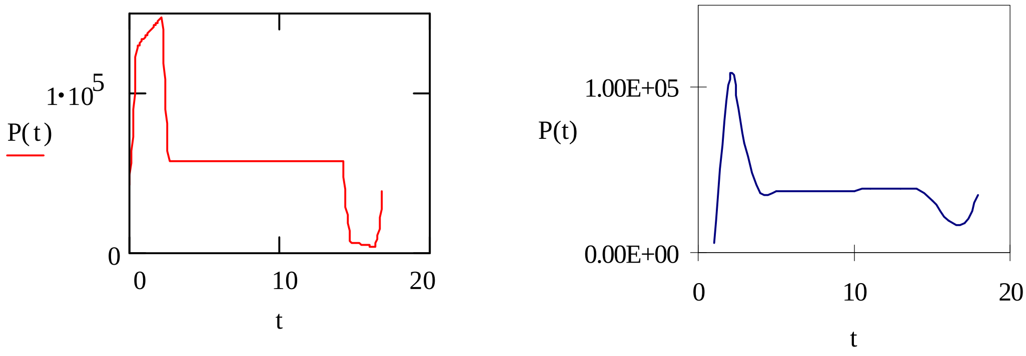
which is approximately 27% in this case.

DC system harmonics have not been considered in this research project, but are discussed and analysed by Graham A D and Schonholzer E T[(7.5)].

7.9 SITE TESTING

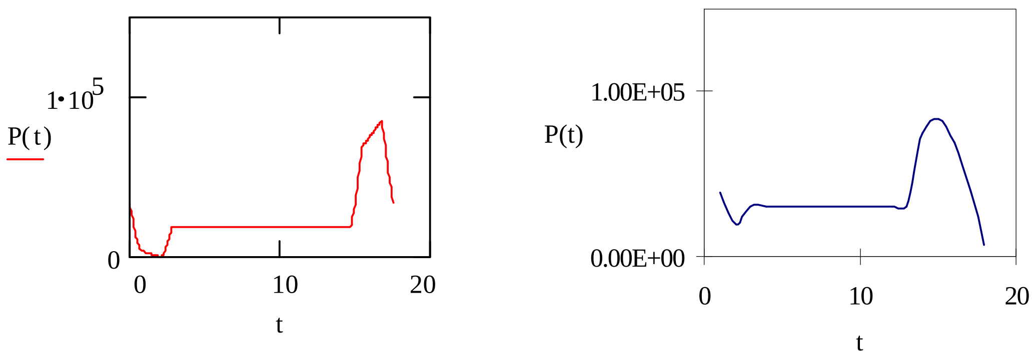
Initial site tests of the model have been undertaken on a static converter DC drive at Sheffield University Art Tower.

Restricted access to the site, and limited manufacturer's data has meant that some input variables have had to be estimated. However, the consistency between calculated and actual profiles for both up and down travel (empty car) shown in Figures 7.8 and 7.9 ascribe greater confidence to the model as a whole.



(i) (ii)

Figure 7.8 (i) Calculated and (ii) measured power consumption for up journey



(i) (ii)

Figure 7.9 (i) Calculated and (ii) measured power consumption for down journey

This drive is not regenerating. Some static converter drives do not regenerate as their braking energy is dissipated in a resistor chopper circuit rather than being returned to the mains. In this instance, there is no cut off in the profile at zero power. Thus, the absence of regeneration is believed to be due to inefficiencies in the drive, e.g. as the result of a high motor magnetising constant. The motor in question is dated (>20 years), presumably having being kept after a more recent upgrade of the drive control from motor generator set to static converter.

It should also be noted that the lift continues to take power when it is stationary (in this case approximately 5 kW). This power take will come from a combination of sources which may include brake, brake and motor fan, motor field excitation, no-load consumption of static converter.

7.10 DISCUSSION

The motor model developed by So for a DC static converter drive has been implemented and extended. The model now uses, as an input, the motion profiles generated from the kinematics research discussed in Chapter 6. Equations for load torque and load inertia have been developed as So uses fixed values.

We can now model the operation and power consumption of a lift trip for any journey, direction and loading. This motor model is included in the lift simulation program, *Liftsim*, which is discussed in Chapter 8 of this thesis. In Chapter 9 we will see how the model can be used to develop and test green lift control strategies.

Results from the model are consistent with those presented by So. Initial site tests have suggested that the model is generating consistent power consumption profiles, and can at least not be rejected. A continuous "base" load may be added to the model to account for miscellaneous small loads such as the power consumption of the brake, brake and motor fans, motor field excitation, and static converter losses. Some of these vary during the trip, but taking an average no-load value is unlikely to increase our margin of error as they are relatively insignificant during actual lift trips.

Further research into the modelling of this and other lift drives would be valuable. More comprehensive site tests would need the full co-operation of the lift manufacturer, installer and building owner. Some of the variables required are difficult to measure, and so cannot be established without full access to manufacturer's design data.

Currently designers rely on empirical methods to estimate the power consumption of a lift installation. Building motor models into simulation programs such as *Liftsim* will improve our predictions of power consumption and allow us to demonstrate the value of energy saving features.

Major elements of the research discussed in this chapter were presented at the CIBSE National Conference 1995 in the paper, *Mathematical Modelling of Lift Drive Motion and Energy Consumption*. The paper was republished by Elevator World in July 1996.

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Chapter 8

LIFT SIMULATION SOFTWARE

8.1 INTRODUCTION

The lift simulation program, *Liftsim* has been written as a development platform for “green” lift control systems. It may also be applied as an advance lift traffic analysis tool.

Development of a lift simulation program is not unique. Manufacturers(8.1), researchers(8.2) and consultants(8.3) have previously used lift simulation programs ranging from the crude to the sophisticated. The features of *Liftsim* believed to be unique are:

- it applies object oriented programming technology.

- it implements the ideal lift kinematics research discussed in Chapter 6 of this thesis allowing total control over the lift speed profiles. Often lift simulation packages use a “single floor jump time”; this ignores complexities such as lifts which do not reach full speed in a single floor jump, and calculations to determine if a travelling lift can stop in time for a new call.

- it implements a motor model, calculating the energy consumption of the lift drives during the simulation; these calculations based on research discussed in Chapter 7 of this thesis.

- it implements a passenger generator based on arrival rates and destination probabilities as discussed in Chapters 3 and 5; the use of “periods” allows sets of different arrival rates and destination probabilities to be defined such that changing levels of traffic can be modelled.

The program has been written using Microsoft Visual C++ (for Windows 95 and Windows NT). C++ is a complex object oriented language, but it produces very fast programs, and easily reusable/portable code. It is the current Arup standard for new technical software development projects.

8.2 OVERVIEW OF OBJECT ORIENTED PROGRAMMING

Traditional structural programming techniques break a program into several smaller tasks by defining a set of functions. Object oriented programming (OOP) builds on this by introducing objects. In an object, both the variables and functions are grouped together. The behaviour (i.e. the variables and functions) of an object is defined by the class to which it belongs. Each object is an “instance” of a class.

Object-oriented programming uses abstraction to allow the programmer to consider the important details of the problem in hand, and to ignore unnecessary complexities. Encapsulation is applied to hide the details of a solution so that the solution is easier to understand.

For an example of how OOP is mimicking the real world, consider *Ginger* the cat in Figure 8.1.

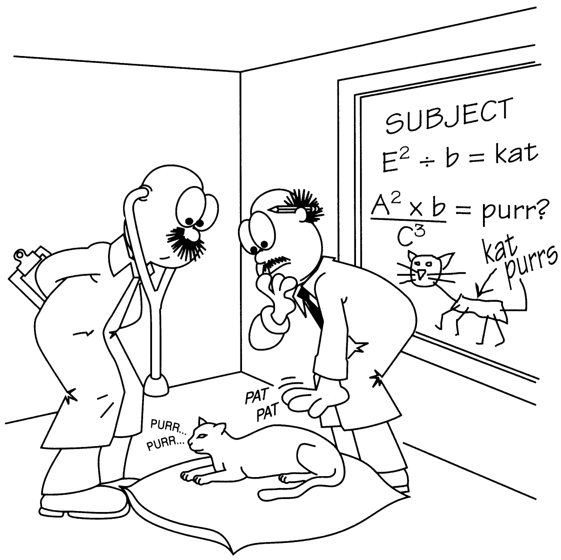


Figure 8.1 Ginger the cat [graphic from (8.4)]

The world has a class *cat*. Everything in the *cat* class has a set of the same variables (no of paws, age, sex, etc.) and a range of functions (if you chase it runs; if you pat it, it purrs). *Ginger* is an object, and an instance of the cat class. He has all the functions and variables of a cat. The *cat* class utilises abstraction and encapsulation: If we feed Ginger, he will eat without us having to understand the complexities of his digestive system; we can concentrate on the tasks in hand such as preparing his food and stroking him.

Returning to lifts, we can define the class *lift* with variables such as *capacity* and *speed*, and functions such as *StartJourney().* We can create as many lift objects as we need; each lift object is independent, but may use all the variables and functions defined by the class.

OOP helps break down complex problems into manageable parts that are easy to work with as they represent familiar ideas or components.

8.3 PROGRAM CLASSES

8.3.1 General

Liftsim has seven main simulation classes which define the behaviour of the system. These are:

8.3.2 Building class

The *building* class defines the building in terms of number of stories and story heights. Its variables and functions are summarised in Table 8.1.

Class Information	Description
member variables	
int m_NoFloors;	no of floors in building
double m_FloorPositions[MAX_FLOORS];	array of floor heights
functions	
double BuildingHeight();	calculates building height

Table 8.1 Building class variables and functions

8.3.3 Motion class

The *motion* class implements the ideal lift kinematics discussed in Chapter 6 of this thesis. Programs using the class can specify the journey distance, rated velocity, etc. and output the current distance travelled, velocity, etc. at any time, t since the journey began. Its variables and functions are defined in Table 8.2.

Class Information	Description
member variables	
double m_d;	journey distance,(+ for up travel, - for down) (m)
double m_D;	absolute value of m_d (m)
double m_v;	rated speed, (always +) (m/s)
double m_a;	rated acceleration, (always +) (m/s/s)
double m_j;	rated jerk (always +) (m/s/s/s)
double m_Tstart;	motor start up delay (s)
double m_t;	time elapsed since journey commenced (s)
double m_StartTime;	time journey commenced (s past ref.)
double m_CurrentTime;	current time (s past ref.)
double m_StartPosition;	start position (m above ref. height)
functions	
double JourneyTime();	journey time for trip (s)
char Condition();	journey condition (A, B, or C)
int Slice();	calculates which time slice journey is in
double Distance();	calculates the current distance travelled (m)
double Velocity();	calculates the current velocity (m/s)
double Acceleration();	calculates the current acceleration (m/s/s)
double Jerk();	calculates the current jerk (m/s/s/s)
double Position();	calculates current position (m above ref.)
double EndTime();	time when journey will be complete (s past ref.)
double MinDistance();	calculates minimum journey distance if lift begins slowing down immediately (m)
int ConfirmDestination();	confirmation that lift can no longer change destination, that MinDistance() is same as m_D (1- confirmed, 0 - may change)
void DataChecks();	data checks called by constructor

Table 8.2 Motion class variables and functions

8.3.4 Lift class

The *lift* class defines a lift (rated speed, capacity, floors served, etc.) and its current status (position, speed, load, etc.). The *motion* class is applied to enable the lift to move according to the selected journey profile. The *lift* class includes algorithms to allow lifts to answer landing and car calls according to the principles of directional collective control. (Most lift control systems adopt a directional collective control strategy regardless of the complexities of the dispatcher algorithms.) *lift* class variables and functions are defined in Tables 8.3 and 8.4.

Class Information	Description
about the lift	
int m_Capacity;	nominal lift capacity (kg)
double m_Velocity;	rated lift velocity (m/s)
double m_VelocityMultiply;	multiplier set by green dispatcher

double m_Acceleration;	rated lift acceleration (m/s/s)
double m_AccelerationMultiply;	multiplier set by green dispatcher
double m_Jerk;	rated lift jerk (m/s/s/s)
double m_MotorStartDelay;	motor start up delay (s)
double m_DoorPreOpen;	door pre-opening (s)
double m_DoorOpen;	door open time (s)
double m_DoorClose;	door closing time (s)
double m_DoorDwell1;	door dwell time 1 (s) (time doors will wait until closing if beam not broken)
double m_DoorDwell2;	door dwell time 2 (s) (time doors will wait until closing after beams have been broken/cleared)
int m_DoorBeams;	flag for status of door beams (corresponding to passenger transfer - 1 beams broken, 0 clear)
how the lift serves the building	
int m_NoFloors;	no of floors in building
int m_Home;	home floor/default parking position
double m_FloorPositions[MAX_FLOORS];	positions of floors in building (m above ref.)
int m_FloorsServed[MAX_FLOORS];	floors served by lift (1 yes, 0 no)
about the current status of the lift	
int m_CarCall[MAX_FLOORS];	car calls registered (1 registered, 0 not)
int m_ParkCall[MAX_FLOORS];	parking calls; lift does not open doors on arrival
int m_ParkOpenCall[MAX_FLOORS];	parking calls, lift parks with doors open
int m_UpLandingCalls[MAX_FLOORS];	up landing calls allocated to lift by dispatcher
int m_DownLandingCalls[MAX_FLOORS];	down landing calls allocated to lift by dispatcher
int m_TravelStatus;	travel status, (1 travelling, 0 at floor)
int m_Direction;	direction of travel (-1 down, 0 neither, 1 up)
double m_DestinationPosition;	current destination position (m above ref.)
double m_StartPosition;	position current journey started (m above ref.)
double m_JourneyStart;	time lift journey started (s past ref.)
int m_CurrentLoad;	current car load (kg)
int m_DoorStatus;	door status (1 fully open, 2 closing, 3 fully closed, 4 opening)
double m_DoorsStart;	time doors started opening/closing (s past ref.)
double m_TimerT1;	time timer T1 began (s past ref.),
double m_TimerT2;	time timer T2 began (s past ref.),
double m_PersonStart;	time current person began loading/unloading (s past ref.)
double m_CurrentTime;	current time (s past ref.)
double m_DestinationTime;	arrival time next planned stop (s after ref.)
double m_CurrentPosition;	current position (m above ref.)
double m_CurrentDistance;	distance travelled on current trip (m)
double m_CurrentVelocity;	current velocity (m/s)
double m_CurrentAcceleration;	current acceleration (m/s/s)
double m_CurrentJerk;	current jerk (m/s/s/s)
double m_QuickestStopPosition;	next possible stop lift can make (m above ref.)
int m_DestinationFloor;	current destination floor no.

Table 8.3 Lift class variables

Class Information	Description
void Reset(building b);	sets lift to home position, cancels all calls, etc.
int StartJourney(int floor);	start journey to destination "floor"
int ChangeJourney(int floor);	change journey, new destination, "floor"
void UpdateDestination();	check for calls allocated to lift and set destination

void SetDestination();	set destination/direction travel
void Update(double CurrentTime);	update time (s); this function updates the status of the lift (position, speed, door operation, etc.)
void RemoveLandingCall(int direction, int floor);	removes landing call - called by class when lift arrives at landing.
int LowestFloorServed();	returns number of lowest floor served by lift
int HighestFloorServed();	returns number of highest floor served by lift
int FloorAt();	return floor no if not travelling
int FloorNo(double position);	returns floor no at position
double QuickestStopPosition();	next stop lift could make (m above reference)
double QuickestStopTime();	time of next stop lift could make (s after ref.)
int QuickestFloorStopFloor();	floor of next stop lift could make
double QuickestFloorStopPosition();	position of next stop lift could make
double QuickestFloorStopTime();	time of next stop lift could make (s after ref.)

Table 8.4 Lift class functions

8.3.5 Dispatcher class

The *dispatcher* class defines rules for allocating which lift serves which calls. The default dispatcher logic has been based on conventional group control with dynamic sectoring as defined by Barney and dos Santos[8.5]. The class variables and functions are defined in Table 8.5.

Class Information	Description
member variables	
int m_Algorithm;	dispatcher algorithm no. selected
int m_NoFloors;	number of floors in building
int m_NoLifts;	number of lifts
double m_FloorPositions[MAX_FLOORS];	floor positions (m above reference)
int m_UpLandingCalls[MAX_FLOORS];	up landing calls registered with dispatcher
int m_DownLandingCalls[MAX_FLOORS];	down landing calls registered with dispatcher
member functions	
void CancelLandingCalls(lift l[MAX_LIFTS]);	cancel landing call when lift arrives at floor
void Reset(building b,int NoLifts,lift l[MAX_LIFTS]);	resets dispatcher, sets up member variables
int Update(double CurrentTime,lift l[MAX_LIFTS],motor m[MAX_LIFTS], double SimulationTimeStep);	update dispatcher; this function updates the status of the dispatcher, allocating calls, etc.

Table 8.5 Dispatch class functions and variables

8.3.6 Person class

The *person* defines a person, what time he/she arrives at the landing station, where he/she wants to go, their mass, etc. Once the journey is complete, the class provides details about passenger waiting and transit times. Waiting time *is calculated as the actual time a prospective passenger waits after registering a landing call (or entering* *the waiting queue if a call has been registered) until the responding elevator doors begin to open.* This definition has been taken from the NEI Vertical Transportation Standards[8.6]. For continuity, transit time is calculated from *the time the responding elevator doors begin to open to the time the doors begin to open again at the passenger's destination*. Variables and functions of the person class are defined in Table 8.6.

Class Information	Description
member variables	
double m_TimeArrived;	time passenger arrived at landing (s past reference) (taken to be when call button pressed).
int m_ArrivalFloor;	arrival floor
int m_Destination;	destination floor
int m_Mass;	passenger mass (kg)
int m_LoadingThreshold;	threshold determining whether passenger will get into this lift or wait for the next (%) e.g. 80% means that passenger will not load lift if the lift will then be >80% full
double m_LoadingTime;	passenger loading time (s)
double m_UnloadingTime;	passenger unloading time (s)
double m_TimeBeganTransfer;	variable used to store when passenger transfer (loading and unloading) began (s past reference)
int m_CurrentStatus;	current status of passenger's journey; 1 yet to arrive, 2 waiting, 3 loading, 4 travelling, 5 unloading, 6 journey completed
int m_LiftUsed;	lift used by passenger
double m_TimeLiftArrived;	time responding lift arrived, taken from when the doors began to open (s past reference)
double m_TimeReachedDestination;	time responding lift reached destination, taken from when the doors began to open (s past reference)
member functions	
void NewLandingCalls(double CurrentTime,dispatch& d);	registers new landing calls when passenger arrives
void Update(double CurrentTime,int NoLifts,lift l[MAX_LIFTS],dispatch& d);	update status of passengers, adjust lift load, break/clear beams, etc.
int Direction();	returns direction of call (1 up, -1 down)
double WaitingTime();	passenger waiting time (s)
double TransitTime();	passenger transit time (s)

Table 8.6 Person class functions and variables

8.3.7 Traffic class

The *traffic* class converts arrival rate and destination probability data into a corresponding set of person objects.

Class Information	Description
member variables	
int m_NoTrafficPeriods;	number of traffic periods
double m_u[MAX_TRAFFIC_PERIODS][MAX_FLOORS];	array of arrival rates (persons/s)

double m_d[MAX_TRAFFIC_PERIODS] [MAX_FLOORS][MAX_FLOORS];	array of destination probabilities (%)
double m_StartTime[MAX_TRAFFIC _PERIODS];	start times for traffic periods (s past reference)
double m_EndTime[MAX_TRAFFIC _PERIODS];	end times for traffic periods (s past reference)
int m_Mass[MAX_TRAFFIC_PERIODS];	passenger mass for each traffic period (kg)
int m_LoadingThreshold[MAX_TRAFFIC _PERIODS];	loading threshold for each traffic period (%)
double m_LoadingTime[MAX_TRAFFIC _PERIODS];	loading time for each traffic period (s)
double m_UnloadingTime[MAX_TRAFFIC _PERIODS];	unloading time for each traffic period (s)
int m_NoPassengers;	total no of passengers generated
member functions	
int MakePeople(person p[MAX_PERSONS], building b);	converts traffic flows into list of people
double AverageWaitingTime(person p[MAX_PERSONS]);	average waiting time for passengers who have completed their journey
double AverageTransitTime(person p[MAX_PERSONS]);	average journey time for passengers who have completed their journey
int AllJourniesComplete(person p[MAX_PERSONS]);	1 if all passenger journeys are complete, 0 otherwise
double CallsAnsweredInTime(double seconds, person p[MAX_PERSONS]);	Returns percentage of calls answered within specified no of seconds - use to plot waiting time
double TransitCompleteInTime(double seconds, person p[MAX_PERSONS]);	Returns percentage of transits complete within specified no of seconds - use to plot transit time
double JourneyTime(double seconds, person p[MAX_PERSONS]);	returns percentage of waiting + transit times completed with specified no of seconds - use to plot journey time distribution
double LongestWaitingTime(person p[MAX_PERSONS]);	longest passenger waiting time;
double LongestTransitTime(person p[MAX_PERSONS]);	longest passenger transit time;
double SimulationStartTime();	calculates from when first passenger could arrive

Table 8.7 Traffic class functions and variables

Different "periods" can be defined, each with separate arrival rates, designation probabilities, passenger mass, etc. The start and end time of periods may overlap if necessary. This allows the program user to generate traffic flows which vary in intensity, e.g. arrival rates at floor n starting at 5 persons per five minutes, then rising to 10 persons per five minutes, etc. And to analyse different types of loads being transported at the same time, e.g. in a hospital the traffic intensity of walking and wheelchair-bound passengers could be defined separately. Variables and functions of the traffic class are defined in Table 8.7.

8.3.8 Motor class

The *motor* class defines the characteristics of the drive. The class calculates the energy consumption and other characteristics of a DC six pulse static converter drive as discussed in Chapter 7. Motor class variables and functions are given in Table 8.8.

Class Information	Description
member variables	
double m_Acceleration;	current lift acceleration (m/s/s)
double m_ArmatureResistance;	armature resistance (ohms)
double m_GearEfficiency;	efficiency of gear (range 0 to 1)
double m_GearRatio;	gear reduction ratio (:1)
double m_Jmotor;	moment of inertia of motor (kgm^2)
double m_Jbrake;	moment of inertia of brake (kgm^2)
double m_Jgear;	moment of inertia of gear, measured from output side (kgm^2)
double m_Jpullies;	moment of inertia of diverter pulleys (kgm^2)
double m_Jsheath;	moment of inertia of drive sheath (kgm^2)
double m_LineVoltage;	phase-phase line voltage (Volts rms)
double m_MassCar;	mass of lift car including finishes (kg)
double m_MassCounterweight;	mass of counterweight (kg)
double m_MassPassengers;	mass of passengers in car (kg)
double m_MassRopes;	mass of ropes (kg)
double m_MotorMagConst;	motor magnetising constant (amps)
int m_MotorStatus;	current motor status, (1 running, 0 stopped)
double m_RealPower;	total real power consumption (kWhr)
double m_RopeRatio;	roping ratio (:1)
double m_SheathDiameter;	motor sheath diameter (m)
double m_Velocity;	current lift velocity (m/s/s)
member functions	
double AngularAcceleration();	current angular acceleration (rad/s/s)
double AngularVelocity();	current angular velocity (rad/s)
double ArmatureCurrent();	resultant armature current (amps)
double ArmatureVoltage();	armature voltage required (volts)
double FiringAngle();	firing angle of 6 pulse converter (rad)
double LoadTorque();	load torque (Nm)
double MomentInertia();	total inertia of system (kgm^2)
double MotorTorque();	required motor torque (Nm)
double Power();	current power consumption of DC motor (W)
double PowerFactor();	power factor of converter
void Reset();.	reset total power consumption, etc
void Update(lift l, double SimulationTimeStep);	updates power consumption, etc

Table 8.8 Motor class variables and functions

8.4 INTERFACE DESIGN

8.4.1 General

The interface is Windows based, and allows the user to edit all the system data in dialogue boxes containing standard Windows controls (radio buttons, drop downs, etc.), and a spreadsheet-like control for tabular data entry. The program uses a multi-document interface, so the user can be working on a number of different simulations at the same time.

In addition to the standard Windows features (save, print, etc.) there are five data entry dialogue boxes which can be accessed via the menus or button bar:

i. *building data* in which the user enters floor names and levels, as shown in Figure 8.2.

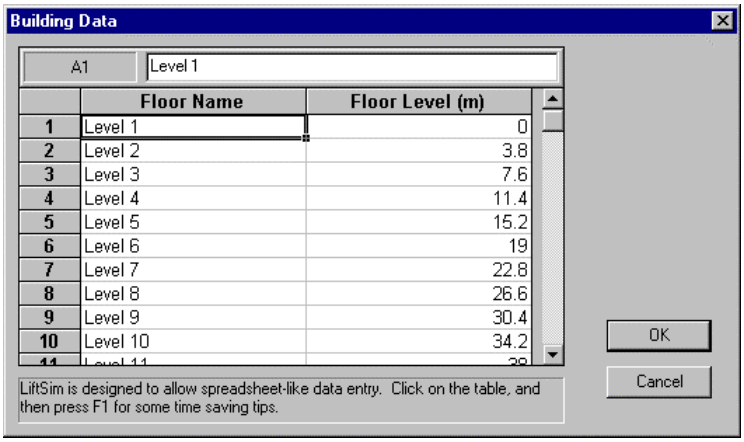


Figure 8.2 Building data dialogue box

ii. *lift data* in which the user enters details about the lifts; ranging from the number of lifts, the capacity, speed, etc. to the drive details and roping ratio, etc. The dialogue box has two modes, standard and advanced. In the standard mode, the program takes default values for all but the most basic inputs. The standard mode allows the user to cycle through a range of lift configurations with different numbers of lifts, capacities and speeds; this can be useful when searching for a solution to suit a particular traffic flow.

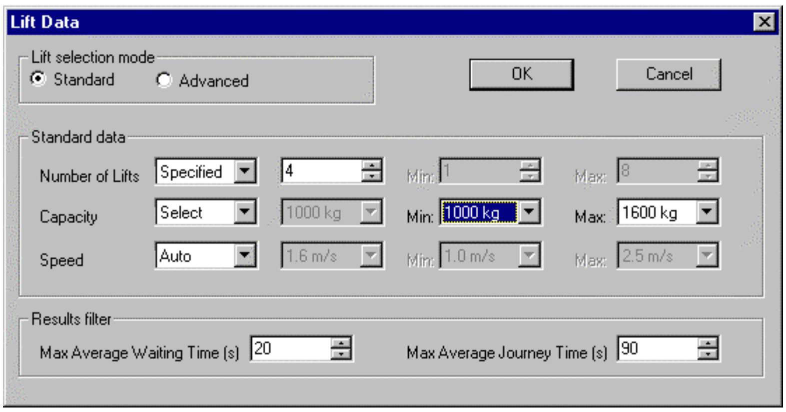


Figure 8.3 Lift data dialogue box, standard mode

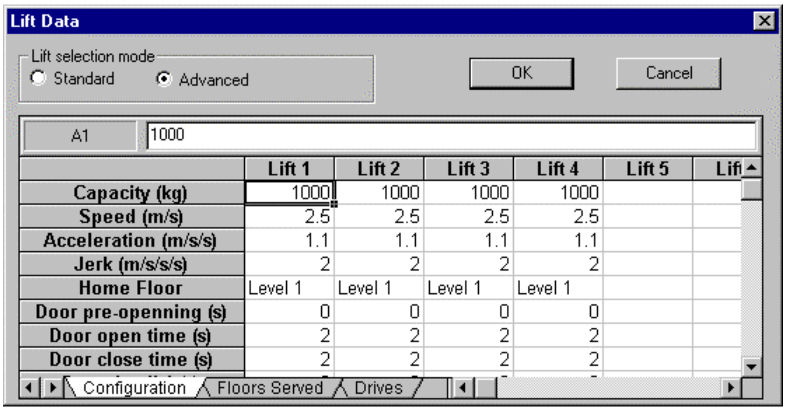


Figure 8.4 Lifts data dialogue box, advanced mode

iii. *passenger data* in which the user enters details of the estimate traffic flow in terms of arrival rates, etc. Again, there are standard and advanced modes.

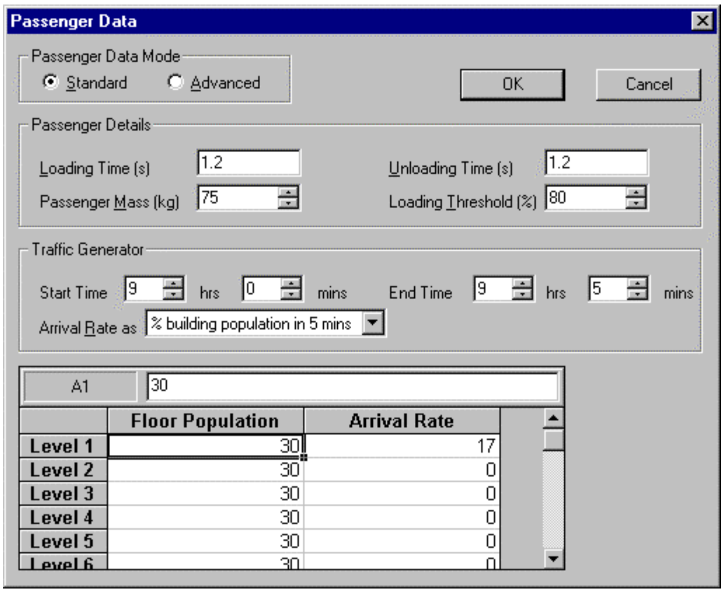
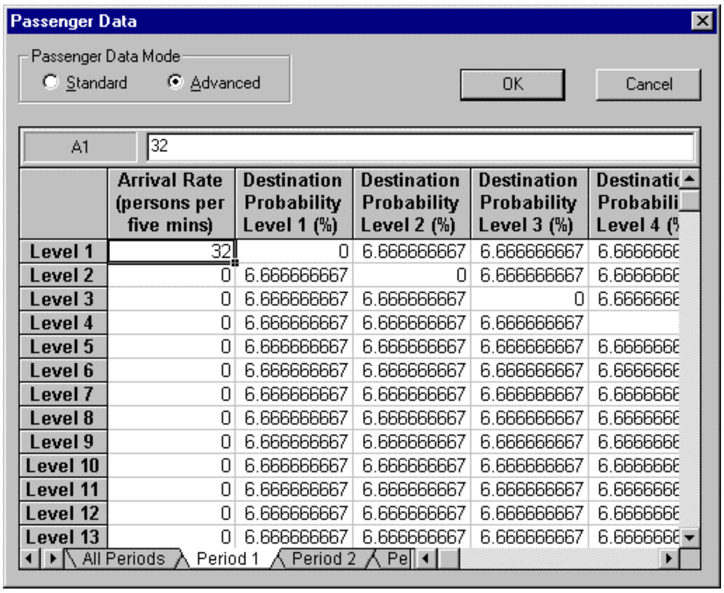


Figure 8.5 Passenger data dialogue box, standard mode



	Arrival Rate (persons per five mins)	Destination Probability Level 1 (%)	Destination Probability Level 2 (%)	Destination Probability Level 3 (%)	Destinatio Probabili Level 4 (%
Level 1	32	0	6.666666667	6.666666667	6.6666666
Level 2	0	6.666666667	0	6.666666667	6.6666666
Level 3	0	6.666666667	6.666666667	0	6.6666666
Level 4	0	6.666666667	6.666666667	6.666666667	
Level 5	0	6.666666667	6.666666667	6.666666667	6.6666666
Level 6	0	6.666666667	6.666666667	6.666666667	6.6666666
Level 7	0	6.666666667	6.666666667	6.666666667	6.6666666
Level 8	0	6.666666667	6.666666667	6.666666667	6.6666666
Level 9	0	6.666666667	6.666666667	6.666666667	6.6666666
Level 10	0	6.666666667	6.666666667	6.666666667	6.6666666
Level 11	0	6.666666667	6.666666667	6.666666667	6.6666666
Level 12	0	6.666666667	6.666666667	6.666666667	6.6666666
Level 13	0	6.666666667	6.666666667	6.666666667	6.6666666

Figure 8.6 Passenger data dialogue box, advanced mode

iv. *simulation data* in which the user can select the control algorithm, time slice, and frequency of the graphical display being updated.

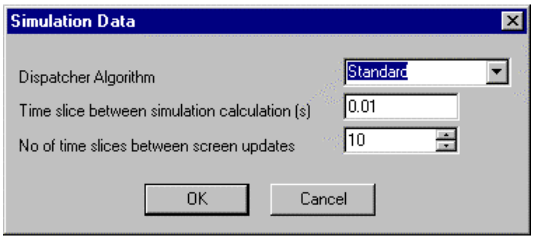


Figure 8.7 Simulation data dialogue box

v. *job data* in which the user can enter job titles, etc.

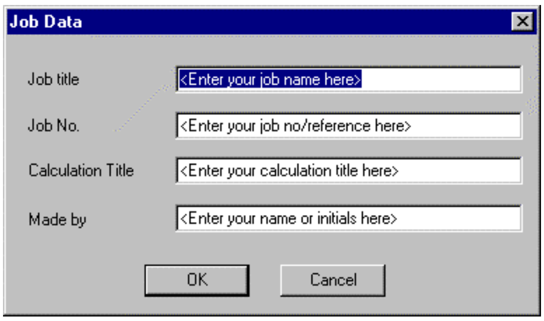


Figure 8.8 Job data dialogue box

The main area of the screen is used for the simulation display (Figure 8.9), and for a print preview of the data and results once the simulation is complete. The user can zoom in/out of these displays using the zoom buttons.

Further menu items and buttons are provided for stopping and starting the simulation; and for cycling through the results of a simulation which has looked at a range of lift configurations.

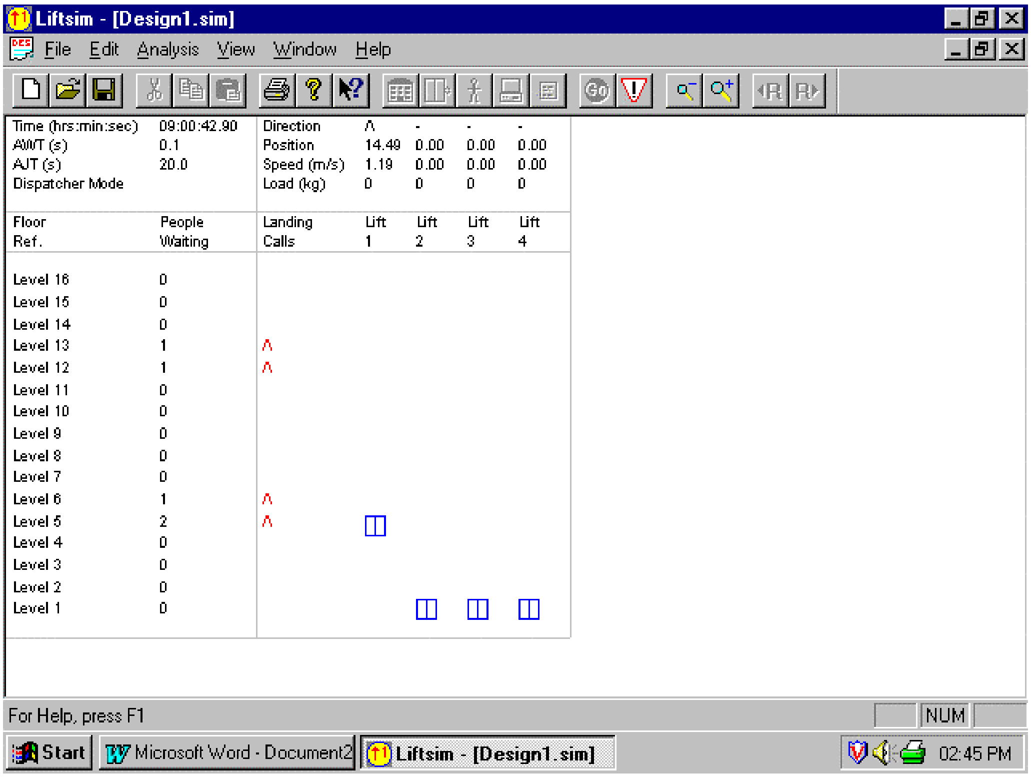


Figure 8.9 Simulation display

8.5 OPERATION OF SIMULATION

The program is a time slice simulation; it calculates the status (position, speed, etc.) of the lifts, increments the time, re-calculates status, increments time, and so on. As Windows is a multitasking operating system, the program cannot take full control of the computer's resources and run in a continuous loop. It must wait for a processing "thread" to become available, run one cycle of the simulation, then wait for the next thread to become available. Provided that there are not too many other demands on the computer's processor, the simulation will run faster than real time on a Pentium PC using a time slice of 0.01 seconds. A flow diagram of a single cycle of the simulation is given in Figure 8.10

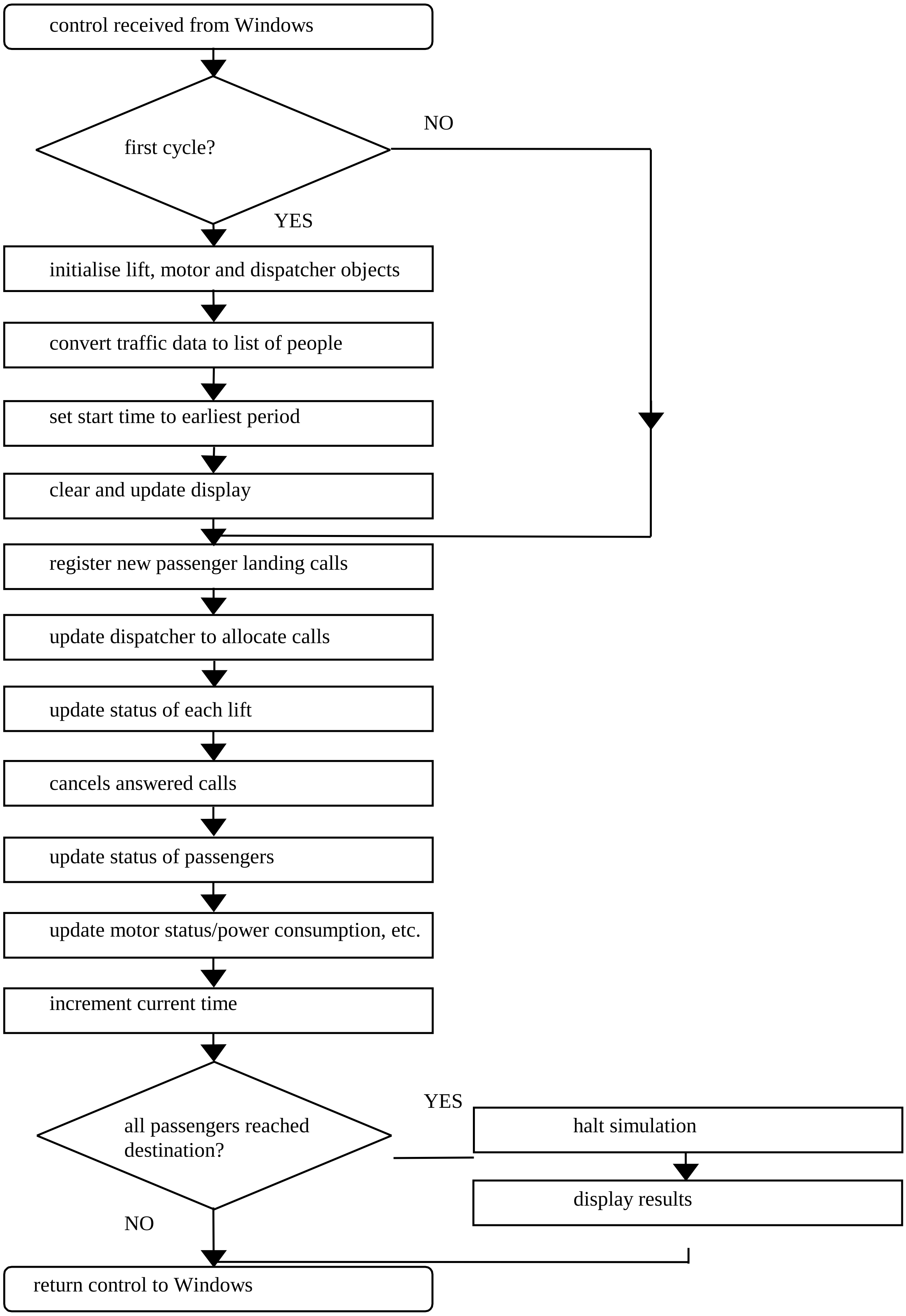


Figure 8.10 Simulation flow chart, one cycle

8.6 RESULTS

Once the simulation is complete, the results print preview includes:

- the input data
- results for average waiting time, longest waiting time, and a plot of the waiting time distribution
- results for average transit time, longest transit time, and a plot of transit time distribution
- the total power consumption for each lift, and total number of motor starts

A Comma Separated Variable (CSV) file with the input data and results is also generated. This can be imported into a spreadsheet so that the user can present the information in his/her own format. For further spreadsheet analysis, this CSV file also includes a table containing details of every passenger generated by Liftsim: what time they arrived, at which floor, what was their destination, what were their waiting and transit times, etc.

8.7 TESTING

The testing program for Liftsim has included:

- where practical, individual classes run in test programs before being added into Liftsim, e.g. a simple plotting routine was used to test the motion class.
- reviewing the graphical display of the lifts in operation; this identified most errors and omissions in the original program code.
- Mathcad was used to model individual journeys, confirming that the waiting and transit time, and energy consumption results were being calculated correctly.

A separate testing program was undertaken by others in Arup Research & Development; this confirmed Liftsim's waiting and transit time calculations for journeys for multiple passengers and trips. It also identified some minor interface bugs.

8.8 DISCUSSION

Liftsim has been written as a development platform for "green" lift control systems. The program implements the kinematics and motor model research discussed in previous chapters.

The passenger generator creates passengers in software based on arrival rate and destination probability data entered by the user. The program performs a time slice simulation, providing a graphical representation of the lifts as they serve the passengers' calls.

Liftsim is written in Microsoft Visual C++. It uses object oriented techniques, breaking down the programming tasks into classes. These classes represent objects (e.g. lift, person, building) which are straight forward to conceptualise, and therefore easier to work with. The interface is Windows based. The user enters data into dialog boxes: *building data*, *lift data*, *passenger data*, *simulation data* and *job data*.

Once the simulation is complete, *Liftsim* displays results on screen in a print preview format. These results include details of input data, waiting times, transit times, and power consumption.

The built in control system is based on conventional group control with dynamic sectoring. In Chapter 9 we discuss the application of green control strategies to this system, and make comparisons in terms of performance and energy consumption.

The program also has applications as an advanced traffic analysis tool, and is being tested on some current Arup jobs.

It is envisaged that there will be further enhancements to *Liftsim* including the development of:

(i) a fuller range of control systems
(ii) additional motor models
(iii) double deck lift version

An abstract for a paper discussing *Liftsim* has been submitted to the International Elevator Technology Conference, ELEVCON ’98.

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Chapter 9

GREEN LIFT CONTROL STRATEGIES

9.1 INTRODUCTION

Barney and dos Santos(9.1) define a group supervisory control system as *a control mechanism to command a group of interconnected lift cars with the aim of improving lift system performance*. Conventionally this system performance has concerned maximising the handling capacity of the lift system, and minimising passenger waiting and transit times. So(9.2) provides a review of the increasing advanced control strategies applied by designers in order to realise improved performance in these terms.

It would be counterproductive to ignore conventional system performance criteria as excessive waiting for lifts is very frustrating for passengers. So let us define a green lift control system as a *group control system that considers conventional measures of system performance, as well as means to reduce energy consumption*.

In this chapter we shall consider three strategies that would be appropriate to a green lift control system. The strategies have been implemented and tested using *Liftsim*.

9.2 GREEN STRATEGY NO.1 - CONTROL OF KINEMATICS

Conventionally lifts have the same maximum velocity, acceleration and jerk (rate of change of acceleration) for every trip. If the system does allow any variation, this is generally pre-set by the lift service engineer or building owner.

The ideal lift kinematics research discussed in Chapter 6 of this thesis has allowed us to generate, quickly and easily, motion profiles for any input of journey distance, velocity, acceleration and jerk. This allows us to consider control systems that vary all these parameters on line in lift system controllers.

One reason for varying the lift kinematics could be for energy saving purposes. Indeed simulation results suggest that significant savings can be achieved without a significant overall reduction in performance from the passenger's prospective. To understand how these savings can be realised, consider:

When a lift leaves the ground floor full of passengers, it is motoring, requiring predominantly positive torque in a positive direction. As passengers are dropped off up the building, the counterweight becomes heavier than the lift, so the motor is providing predominantly negative torque in a positive direction. Similarly for a journey down the building, a negative direction, the motor can be required to deliver both positive and negative torque. Thus the lift motor is said to operate in "four quadrants", as represented graphically in Figure 9.1.

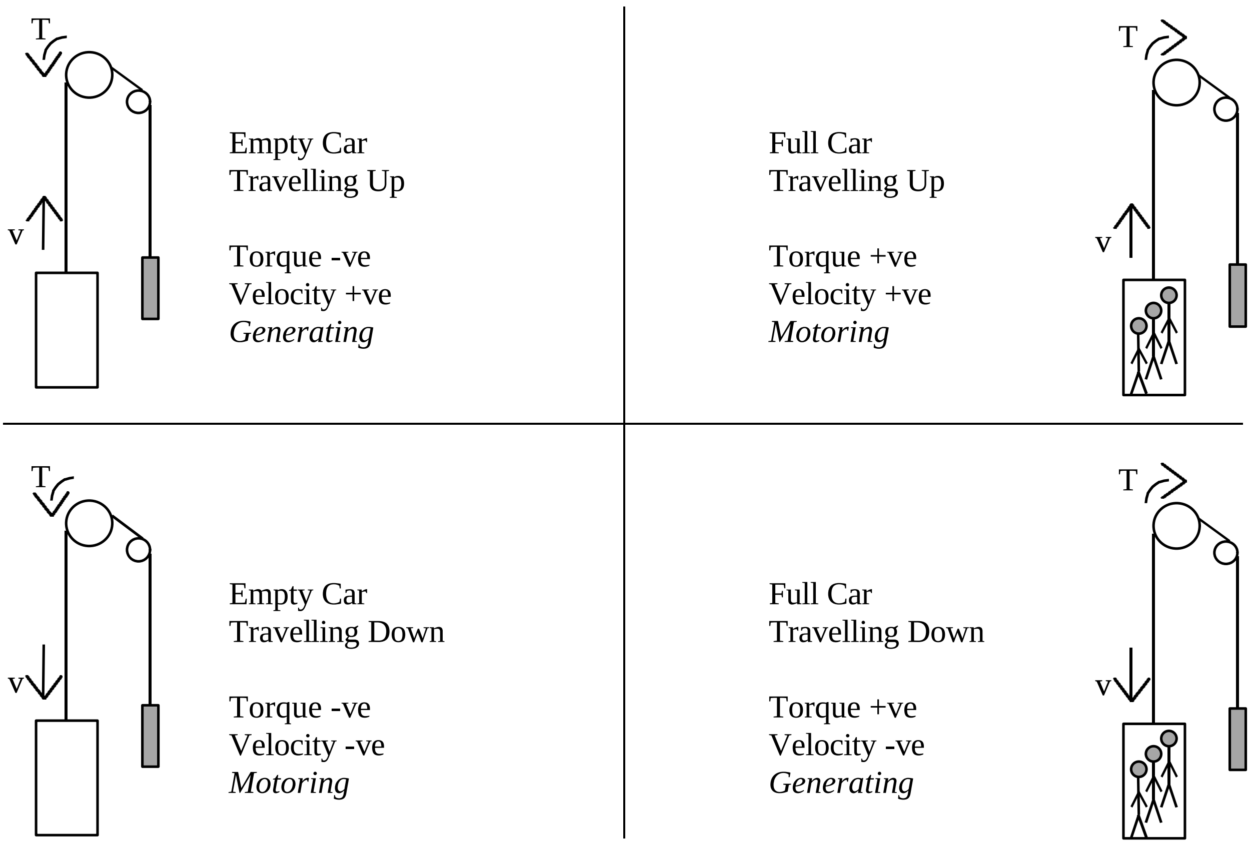

Figure 9.1 Four quadrant operation of lift drive

(This well known example of how a lift operates in four quadrants is not the whole story as the required motor torque is a function of not just the static load, but also of the angular acceleration and inertia of the system. Equations for calculating how the load torque varies over a lift trip are given in Chapter 7 of this thesis.)

In general terms, reducing the performance of the lift when it is “motoring”, and increasing it when it is “generating” can provide an energy saving in both instances, without a significant overall effect on passenger waiting and transit times.

An algorithm has been developed that tests a range of velocity and acceleration options (ranging ± 20% from rated velocity and acceleration) before the start of each trip. The algorithm then chooses the most energy efficient option. Figure 9.2 summarises the results of tests for a 10 storey building with 4 lifts. An inter-floor passenger traffic profile has been used.

In this instance a 33.4% saving in energy consumption has been achieved. The average journey time has increased by just 1.3 seconds.

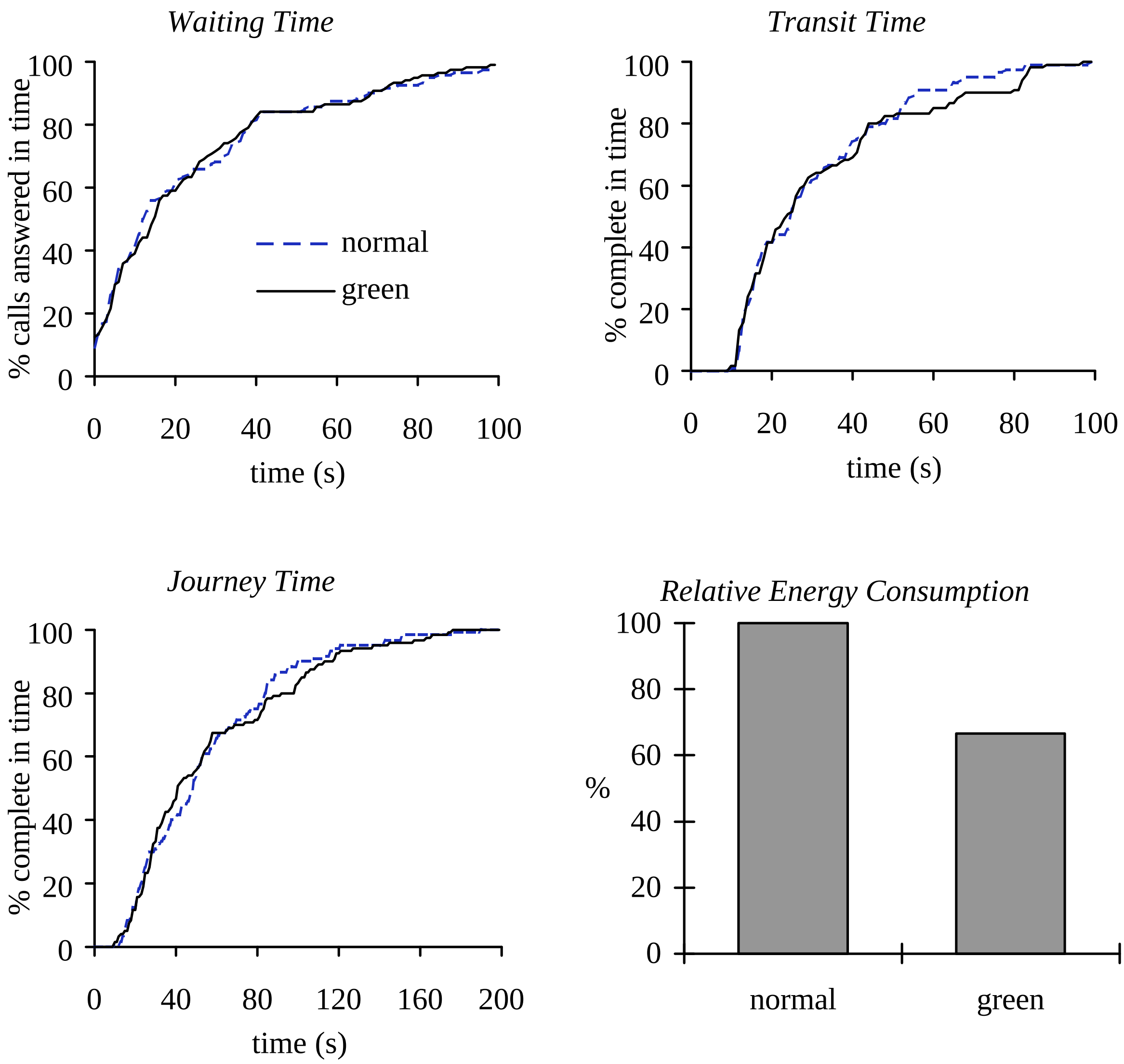

Figure 9.2 Simulation results for Green Strategy No.1 - Control of Kinematics

9.3 GREEN STRATEGY NO.2 - REDUCING THE NUMBER OF STOPS

Figure 9.3 demonstrates the energy consumed by a lift over a single trip (motoring), as presented in Chapter 7 of this thesis. The energy consumption peaks during the acceleration phase, and is relatively low once the lift reaches full speed. There is regeneration during the deceleration phase, but this is less in total than the energy expended during the acceleration phase. Thus it is reasonable to assume that there will be energy savings if we can transport the same number of passengers, with less stops, but without an increase in the overall distance travelled by the lifts.

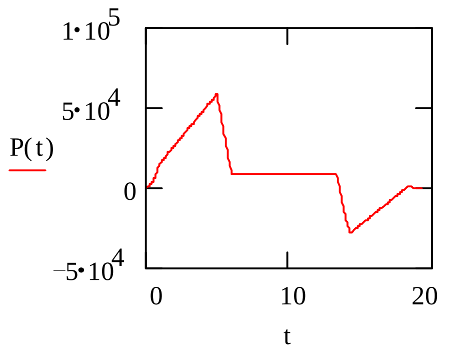

Figure 9.3 Energy consumed by a lift over a single trip (motoring)

One way to achieve this is by forcing the dispatcher to allocate a landing call to a lift when it is:

- already due to stop at that floor for a passenger's car call, and
- travelling in the right direction to serve the landing call.

This condition for a "forced" allocation may not occur for some time, e.g. it is unlikely during solely up peak traffic, or during light inter-floor traffic. But most lift systems are likely to benefit from the strategy at some time during their daily cycle.

Figure 9.4 records the results of a simulation of a 14 storey building with 6 lifts. The traffic profile is based on the beginning a the lunch period in an office building - down peak traffic to the ground floor, plus inter-floor traffic.

In this case, the "green" algorithm implementing the discussed strategy causes a 3.2% reduction in the number of motor starts, leading to a 6.2% reduction in the energy consumption. The waiting time distribution remains very similar, but there is a minor improvement in transit times. The improvement in transit time performance is explicable as the strategy will result in some passengers experiencing less intermediate stops during their journey.

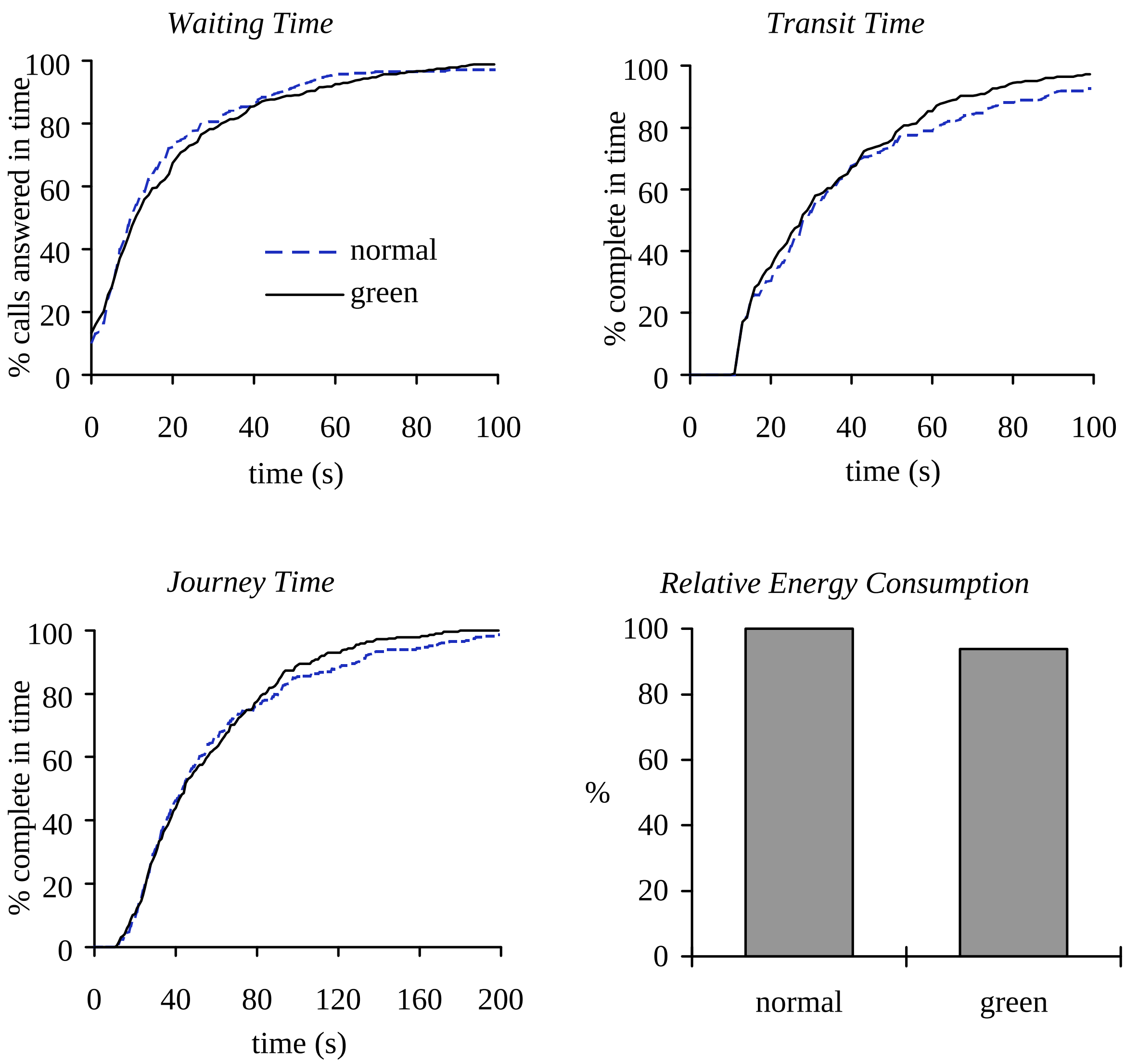

Figure 9.4 Simulation results for Green Strategy No.2 - Reducing the Number of Stops

Reducing the number of stops is not a new goal for lift control systems. This is because reducing the number of stops reduces the round trip time, increasing the passenger handling capacity of the lift system, and sometimes the lift performance. Other systems that reduce the number of stops include:

- fixed zone systems where lifts are divided into groups to serve groups of floors, e.g. 4 lifts serving ground and levels 1 to 10, 4 lifts serving ground and levels 11 to 20.

- dynamic zoning systems, where the dispatcher indicates to the waiting passengers which floors a lift will be serving every round trip, e.g. Channelling as presented by Powell[9.3].
- call allocation systems, as described by Barney and dos Santos[9.1], where passengers are required to register their destination (as opposed to direction of travel) at the landing.

While these systems do result in less stops, they do not necessarily result in an energy saving as:

- the overall distance travelled by the lifts is sometimes greater.
- the number, speed, capacity, etc. of the lifts will differ from a corresponding conventional, single zone design.

To assign credit for energy saving based on these methods, a designer would need to carry out a direct comparison of alternative schemes for the project in question.

9.4 GREEN STRATEGY NO.3 - SELECTIVE PARKING POLICIES

When a lift has answered all its calls and becomes free, it can be "parked" at the floor it last answered a call, or sent to another floor in anticipation of future calls. Barney & dos Santos[9.1] describe how re-positioning a free car to a particular floor as part of a parking strategy can improve the overall performance of a lift system.

For instance, consider the morning up peak in an office building where the main passenger traffic flow is from the ground floor to upper floors. In this scenario, the dispatcher can improve system performance by returning free cars to the ground floor, and parking them with their doors closed. When a preceding lift departs from the ground floor, and another is needed, a free lift is available immediately rather than having first to be brought to the ground floor.

Similarly during off-peak traffic, answering a series of calls may leave free lifts poorly positioned to answer future calls. Consequently, lift control systems sometimes apply parking policies to improve performance in these scenarios as well.

From the energy saving viewpoint, we should apply parking policies selectively. Figure 9.5 summarises the results of the simulation of a fifteen storey building with very light inter-floor traffic. The simulation has been run with and without a parking policy that implements a parking strategy.

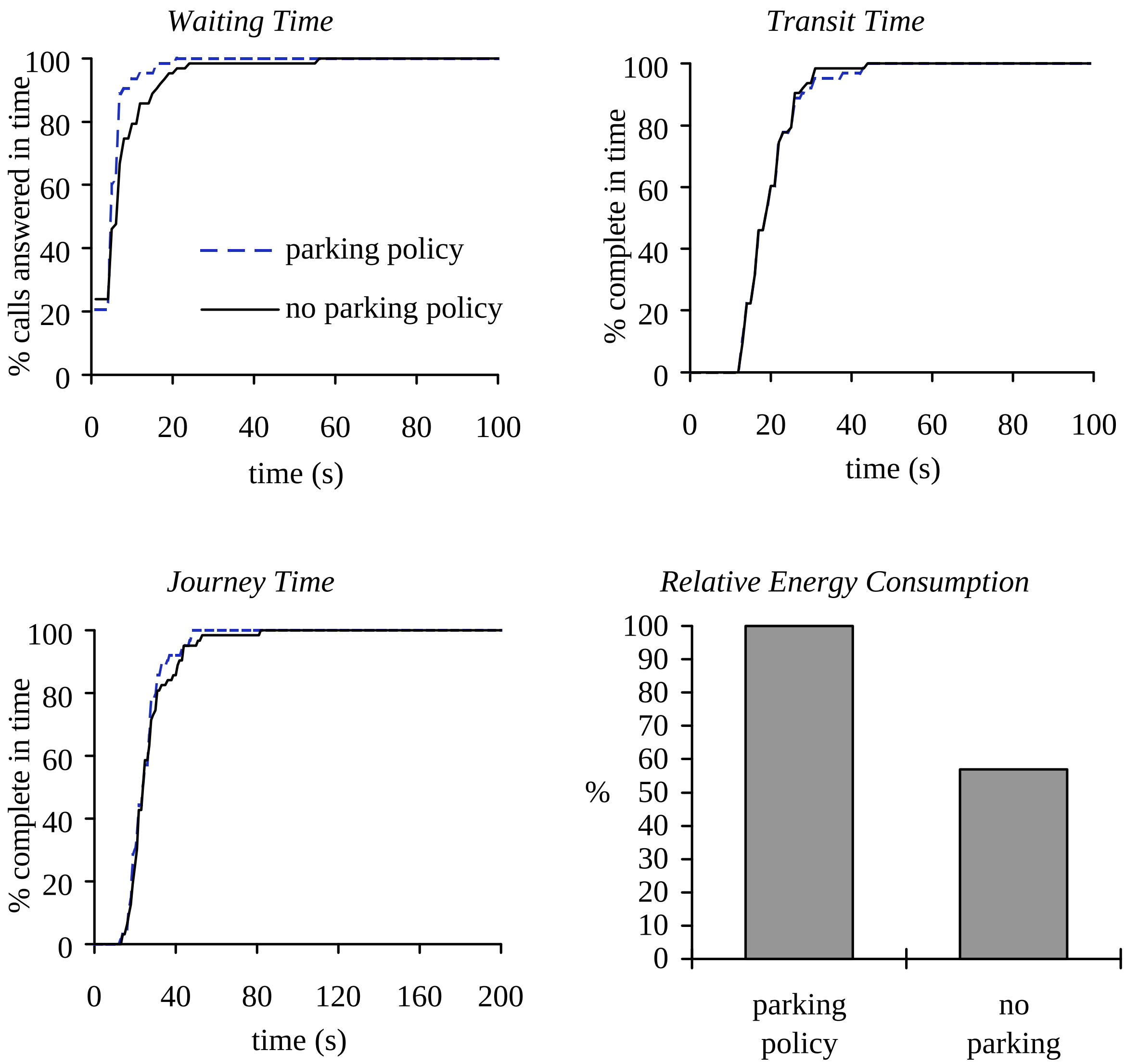

Figure 9.5 Simulation results for Green Strategy No.3 - Selective Parking Policies

The results demonstrate that the parking policy improves performance. The question is whether the improvement in performance justifies that additional energy consumed; in this instance, probably not. Other scenarios will be less clear cut.

Green control systems should place parking calls selectively. This could be achieved by the dispatcher reviewing the potential contribution to system performance of parking calls before deciding whether or not they should be made.

9.5 DISCUSSION

Applying the kinematics, motor modelling and simulation tools discussed in previous chapters, we have developed and tested three green lift control strategies:

(i) *Control of kinematics* where different values of maximum acceleration and velocity are chosen for each trip to minimise the energy consumption.

(ii) *Reducing the number of stops* where dispatcher allocations are chosen in order to reduce the total number of stops made by the lifts.

(iii) *Selective parking policies* which shows that parking policies can be applied inappropriately, yielding a marginal improvement in performance in return for a significant increase in energy consumption.

Simulation has demonstrated that each of these strategies will allow green control systems to reduce energy consumption without a significant deterioration in passenger waiting and journey times. The magnitude of energy savings is a function of the installation and traffic flow, so cannot be declared absolutely. However, simulation suggests that we can achieve an energy saving in excess of 30%.

These results are for a DC static converter drive. It is reasonable to assume that there would be similar savings in applying these strategies with other regenerative drives. The development of additional drive models, as suggested in Chapter 7, would enable us to confirm this assumption.

There is considerable scope for further development and testing of green lift control strategies using *Liftsim*. The performance of existing strategies needs to be tested across a wider range of installations and traffic flows. Other strategies are likely to arise as the simulation is applied and experimented with. It is envisaged that the research will ultimately lead to green lift control systems being implemented by control systems manufacturers.

A paper discussing this research in green lift control strategies has been accepted for publication by the International Journal of Elevator Engineers.

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Chapter 10

CONCLUSIONS AND FURTHER WORK

10.1 GREEN LIFTS

This project aims to contribute to a reduction in the environmental burdens of vertical transportation systems.

The most widely used vertical transportation system is the lift or elevator, which has been the focus of most of the research. A "green lift" can be defined as *a lift system that delivers good passenger service at an acceptable cost while incurring minimum environmental impact*.

To determine the environmental impact of a lift system, Life Cycle Analysis has been applied. This shows that energy consumption is by far the most important factor. Thus this project has focused on ways of reducing the energy consumption of lift systems. Further environmental analysis would be of academic interest only. We should apply sensible practices in the choice of lift materials, transportation, etc., but these are secondary issues, and should be regarded as such. Further work in this area should be focused on communicating these findings.

The lift system will not normally be the largest energy user in a building. Other systems have higher loads and can offer greater energy savings. Nevertheless, there is correspondingly more research in environmental friendly HVAC, lighting, etc. systems. Energy saving lifts should not be disregarded as the potential savings are still worthwhile.

A number of basic principles for green lifts have been identified. The choice of drive, position of stairs, etc. all have a major effect on the energy consumption of the vertical transportation system. As a starting point, these choices should be made with energy saving in mind. We can then go on to consider more advanced strategies.

10.2 PLANNING ISSUES

10.2.1 The need for good planning

Lift designers need to have a good understanding of passenger traffic demand, and analysis techniques to assess the performance of possible lift configurations. If both of these are not in place, then there is a high probability that installed systems will be either inadequate or over-designed. The first alternative is unacceptable to passengers. The second is unnecessarily expensive, and will consume more energy.

10.2.2 Assessing traffic demand

Designers normally assume that the up-peak is the busiest period in commercial buildings. Calculations used to select the number, size, speed, etc. of lifts required are based on this assumption.

Surveys undertaken for this research project suggest that this assumption is outdated, and need to be revised. The up-peak seen in commercial buildings is less marked than when current design criteria were formulated. The lunch time peak is now the busiest period.

Further surveys need to be carried out to confirm these results. However, they are consistent across the office buildings surveyed by the author, and with anecdotal evidence from designers to whom this work has been presented.

In carrying out further surveys, researchers should use automated people counting techniques as it is very time consuming to collect large amounts of data manually. A range of surveying techniques has been reviewed. Currently the author favours an infra-red beam system as the best available technology, although further research in passenger counting techniques would be beneficial. The author continues to collect data, and has been encouraging others to publish their results so that improved design criteria can be established.

10.2.3 Traffic calculations

Traffic analysis techniques based on Round Trip Time calculations have been developed and extended. Round Trip Time calculations are good planning tools as they give consistent results, and are not dependant on any one control system. They are likely to be our primarily design tools for some years to come.

The author of this research project has made two contributions to the up-peak analysis calculation. Firstly, to derive formulae to determine flight time for any travel distance and lift dynamics. This extends the standard method, which uses tabulated results.

Secondly, the author has implemented in formulae, "corrections" that were recommended for lifts not reaching full speed in a single floor jump, and for non-equal inter-floor heights. A sensitivity analysis on these corrections has demonstrated that the variations between original and corrected results are relatively small (less than 2%). It can be argued that this variation is too small to warrant changes to the standard up peak calculation procedure. In itself, this is an interesting and useful result.

The up-peak calculation has been implemented in a computer program which, it is intended, will be issued with the revised version of CIBSE Guide D, *Transportation systems in buildings*.

As we believe the lunch period is the most onerous time for the lifts, it is important to be able to assess this period with traffic calculations. We can do this using the General Analysis calculation technique, which the author derived prior to joining the EngD programme. The General Analysis assesses a lift system's performance given any peak passenger demand.

This General Analysis is a relatively complex technique to implement and to apply. Therefore further research to determine the equivalent lunch time handling capacity relative to a given up-peak handling capacity would be beneficial. This would allow designers to assess lunch time performance while retaining well known and understood up-peak analysis techniques.

10.2.4 Environmental benefits

The results of traffic surveys have been tested on Arup designs. Analysing the up-peak and lunch peak, it is apparent that revising our design criteria is unlikely to result in fewer lifts, but would reduce car sizes, say from 1250 kg to 1000 kg. And therefore lead to energy savings.

10.3 TRAFFIC ANALYSIS FOR DOUBLE DECK LIFTS

Double deck lifts provide greater handling capacity per shaft than conventional lifts. This is particularly attractive for high rise buildings, where the core space taken by the lifts is a high percentage of the total floor area.

Formulae have been derived and implemented that allow analysis of any peak traffic flow for any practical configuration of double deck lifts. Previously only up-peak formulae had been known. The approach taken for double deck lifts could be extended to cover triple and quadruple deck lifts if required.

This section of research has arisen primarily from commercial pressures to analyse the performance of lift systems in high rise buildings. A study of the relative energy consumption of double versus single deck lifts for a range of lift installations would be useful further work.

10.4 MATHEMATICAL MODELS OF LIFT MOTION AND DRIVES

10.4.1 The need for mathematical models

In order to develop strategies for energy saving, we need models to experiment and test our ideas. Mathematical models allow us to test a wider range of systems than it would be practical or affordable to build in real life. The motion and drive models developed for this project were implemented in the simulation program, *Liftsim*. This was used to develop energy saving control strategies.

10.4.2 Ideal lift kinematics

The equations derived allow continuous, optimum functions of jerk, acceleration, speed and distance travelled profiles to be plotted against time. These profiles can be generated for any journey distance given inputs for maximum jerk, acceleration, and speed. Previously the shapes of these curves where known, but only certain points could be plotted.

The ability to plot profiles for any inputs gives additional flexibility in the design of lift controllers. This functionality has been applied in the design of green control strategies.

The equations are complex, but have been implemented in software by the author. The users of this software do not need to work through the calculations taking place, but can concentrate on entering the required inputs to generate the profiles quickly and easily.

The flight time formulae discussed with reference to traffic calculations are a result from this section of the research.

Although there is some guidance on the choice of maximum jerk and acceleration for a lift installation, there have been no major studies on the relative levels of comfort experienced by passengers given different values of these variables. Applying the research lift kinematics, it would be feasible to carry out such an investigation. This would yield useful results for specification and design.

10.4.3 Motor model

A motor model developed by So for a DC static converter drive has been implemented and extended. The model now uses, as an input, the motion profiles generated from the kinematics research. Equations for load torque and load inertia have been developed as So uses fixed values.

We can now model the operation and power consumption of a lift trip for any journey, direction and loading. This motor model is included in the lift simulation program, *Liftsim*, which was used to develop and test green lift control strategies.

Results from the model are consistent with those presented by So. Initial site tests have suggested that the model is generating consistent power consumption profiles, and can at least not be rejected.

Further research into the modelling of this and other lift drives would be valuable. More comprehensive site tests would need the full co-operation of the lift manufacturer, installer and building owner. Some of the variables required are difficult to measure, and so cannot be established without full access to manufacturer's design data.

Currently designers rely on empirical methods to estimate the power consumption of a lift installation. Building motor models into simulation programs such as *Liftsim* will improve our predictions of power consumption and allow us to demonstrate the value of energy saving features.

10.4.4 Environmental benefits

The motion and motor models developed allow us to test the energy consumption of individual lift trips. We have full control over the inputs to the system, so can consider any lift speed, size, loading, etc. This provides us with the basis for testing energy saving ideas.

10.5 LIFTSIM AND GREEN CONTROL STRATEGIES

10.5.1 Reasons for development

The lift simulation program, *Liftsim* has been written. The program implements the kinematics and motor model research, providing a development platform for "green" lift control systems.

10.5.2 Overview of program

Liftsim is written in Microsoft Visual C++. It uses object oriented techniques, breaking down the programming tasks into classes. These classes represent objects (e.g. lift, person, building) which are straight forward to conceptualise, and therefore easier to work with. The interface is Windows based. The user enters data into dialog boxes: *building data*, *lift data*, *passenger data*, *simulation data* and *job data*.

Liftsim's passenger generator creates passengers in software based on arrival rate and destination probability data entered by the user. The program performs a time slice simulation, providing a graphical representation of the lifts as they serve the passengers' calls.

The built in control system is based on conventional group control with dynamic sectoring. Additional control systems could be added, which would be worthwhile further work.

Once the simulation is complete, *Liftsim* displays results on screen in a print preview format. These results include details of input data, waiting times, transit times, and power consumption.

Three green lift control strategies have been developed and applied to the dynamic sectoring control algorithm:

(i) *Control of kinematics* where different values of maximum acceleration and velocity are chosen for each trip to minimise the energy consumption.

(ii) *Reducing the number of stops* where dispatcher allocations are chosen in order to reduce the total number of stops made by the lifts.

(iii) *Selective parking policies* which shows that parking policies can be applied inappropriately, yielding a marginal improvement in performance in return for a significant increase in energy consumption.

Simulation has demonstrated that each of these strategies will allow green control systems to reduce energy consumption without a significant deterioration in passenger waiting and journey times. The magnitude of energy savings is a function of the installation and traffic flow, so cannot be declared absolutely. However, simulation suggests that we can achieve an energy saving in excess of 30%.

These results are for a DC static converter drive. It is reasonable to assume that there would be similar savings in applying these strategies with other regenerative drives. The development of additional drive models would enable us to confirm this assumption.

There is considerable scope for further development and testing of green lift control strategies using *Liftsim*. The performance of existing strategies needs to be tested across a wider range of installations and traffic flows. Other strategies are likely to arise as the simulation is applied and experimented with. It is envisaged that the research will ultimately lead to green lift control systems being implemented by control systems manufacturers.

The program also has applications as an advanced traffic analysis tool, and is being tested on some current Arup jobs.

10.5.3 Environmental benefits

Liftsim is a power lift simulation program. It brings together the project research in traffic modelling, kinematics, and motor modelling. The program has been applied in the development of energy saving control strategies.

It has been shown that, by the application of green control strategies, we could achieve energy savings in excess of 30%.

10.6 CONTRIBUTION TO KNOWLEDGE

The project has yielded a “contribution to knowledge” through:

- environmental assessment of vertical transportation system
- improvements in lift system models
- development of green control strategies

The research has been widely published at conferences, in journal papers, and through the national and international vertical transportation trade press. A full list of publications is included in Appendix A of this thesis.

Appendix A

LIST OF PUBLICATIONS

A1 JOURNAL PAPERS

Peters R D, Mehta P, Haddon J *Lift Traffic Analysis: General formulae for double decker lifts* Building Services Engineering Research and Technology, Volume 17 No 4 (1996)

Peters R D *Ideal Lift Kinematics: Derivation of Formulae for the Equations of Motion of a Lift* International Journal of Elevator Engineers, Volume 1 No 1 (1996)

Peters R D *Lift Traffic Analysis: Formulae for the general case* Building Services Engineering Research and Technology, Volume 11 No 2 (1990) (republished by Elevator World, December 1990) *(published before joining EngD programme)*

A2 CONFERENCE PAPERS

Peters R D *Risk and the Vertical Transportation Industry* Elevator Technology 7, Proceedings of ELEVCON'96 (The International Association of Elevator Engineers) (1996)

Peters R D, Mehta P, Haddon J *Lift Passenger Traffic Patterns: Applications, Current Knowledge, and Measurement* Elevator Technology 7, Proceedings of ELEVCON'96 (The International Association of Elevator Engineers) (1996) (also presented at IAEE London Lift Seminar May 1997)

Peters R D *Mathematical Modelling of Lift Drive Motion and Energy Consumption* Proceedings of CIBSE National Conference 1995 (The Chartered Institution of Building Services Engineers) (1995) (republished by Elevator World, July 1996)

Peters R D *Ideal Lift Kinematics: Complete Equations for Plotting Optimum Motion* Elevator Technology 6, Proceedings of ELEVCON'95 (The International Association of Elevator Engineers) (1995) (republished by Elevator World, April 1996 and by Elevatori, May/June 1996)

Peters R D *General Analysis Double Decker Lift Calculations* Elevator Technology 6, Proceedings of ELEVCON'95 (The International Association of Elevator Engineers) (1995) (republished by Elevator World, December 1996 and by Elevatori, May/June 1997)

Peters R D *Green Lifts?* Proceedings of CIBSE National Conference 1994 (The Chartered Institution of Building Services Engineers) (1994) (republished by Elevator World, June 1995 and by Elevation, Autumn 1995)

Peters R D *The Theory and Practice of General Analysis Lift Calculations* Elevator Technology 4, Proceedings of ELEVCON'92 (The International Association of Elevator Engineers) (1992) *(published before joining EngD programme)*

Appendix B

PROGRESS REPORTS

Progress reports written during of the course of the project are included in this Appendix. The reports are unedited, except for re-numbering and minor language corrections. The original report appendices are omitted for brevity.

B1 PROGRESS REPORT MAY 1994

B1.1 Introduction

This report summarises the project work I have carried out over the first six months of the Engineering Doctorate programme. The project progress was discussed with my Academic and Industrial Supervisors, Dr Pratap Mehta and John Haddon at a meeting on the 11th March 1994. A copy of the documents issued at the meeting are included in Appendix B of this report and are referred to in this text.

B1.2 Project objectives

The following project objectives were given in the original project proposal and are included for context:

Preamble

Buildings account for about a third of all the energy we consume. Lifts make up a significant proportion (5 to 10%) of the electrical load in large developments and there are potential energy savings and cost savings to be made by good planning design, control strategies and the use of high efficiency motors.

The research outlined below will provide the basis for design and specification of vertical transportation systems which are both energy efficient and provide passengers with a good service by defined standards.

Project recommendations are expected to influence lift design and specification on a national and international basis through the work of the Ove Arup Partnership, and through publications in technical journals and design guides.

Objectives

i. Measure vertical passenger traffic and lift/escalator energy consumption so as to build up pedestrian circulation and corresponding energy models for offices, residential buildings, airports, leisure complexes, etc.

ii. Compare use and performance of lifts/escalators/stairs to existing lift traffic analysis models and assumptions. Compare performance of driving motors to electrical models.

iii. Develop computer programs implementing verified analysis/simulation traffic analysis models and corresponding energy models.

iv. Use verified models to calculate: the benefits of developing and implementing energy efficient lift control algorithms, the savings achievable through the use of high efficiency motors, and the benefits of energy conscious planning strategies.

v. Establish guidelines for predicting traffic in new and refurbished buildings. Make planning and specification recommendations that reflect the need to design energy efficient buildings.

B1.3 Breakdown of time spent

In a typical week I spend two days in Arup offices, two days at Brunel University and a day working at home or on site. I log the use of my time, which has, in summary been divided as follows:

32% Pure research - literature search, background reading, developing theories, writing computer programs and drafting papers specifically for the research project

21% Arup job related - Working on Arup projects related to the research

16% EngD course work - time spend attending courses and completing course work

14% LIFT program - implementing new theories and ongoing development of Arup LIFT program which is used on Arup lift projects

10% Electrical Computing - as Chairman of the Arup Electrical Computing Working party I spend part of my time monitoring and managing Electrical Computing Development in Arup.

8% Holiday/illness

B1.4 Project research topics

Ideal lift kinematics

To model a lift system accurately, we need to consider its equations of motion or "kinematics". Some published material on this subject is given in references (1)(2) - Professor Motz is credited as having formulated equations which allow us to plot points on the corresponding time versus distance, speed, acceleration and jerk curves. I have furthered this work by deriving a set of equation that allow the equations of motion of a lift to be plotted as continuous functions for any inputs.

There appear to be errors in the original work by Motz which I have identified in reference (3). This, together with my ideal kinematics paper (4) is currently being reviewed by Dr Pratap Mehta prior to being submitted for publication in the CIBSE technical journal, Building Services Research and Technology.

The next stage in this work is to implement algorithms calculating the energy consumption associated with the various types of variable speed lift motor drives when input with the ideal journey profiles. Once tested and verified against real systems, this will provide the basis for modelling the energy consumption associated with the operation of a variable speed lift system.

Double decker lifts

Lifts are particularly critical in tall buildings where few people can be expected to walk to their destination. In tall buildings with large floor plans, double decker lifts may be used to reduce the number of lifts and core space. Double decker lift traffic analysis techniques published to date have only considered the morning up peak traffic scenario. I have derived and implemented general analysis formulae which allow any peak lift traffic to be analysed.

A draft paper summarising this technique is given in reference (5).

Oasys LIFT 6.0 Enhancements

I am the principle author of Oasys LIFT which is used internationally on Arup projects to select lift configurations for major developments. The major development for LIFT in the past six months has been the inclusion of my double decker lift traffic analysis technique. A number of minor enhancements have also been made to the user interface.

CIBSE National Conference paper

The main theme for this years Chartered Institute of Building Services Engineers National Conference in Brighton, October 1994 is environmental engineering and communications. I submitted a synopsis, reference (6), for a paper with the title "Green Lifts?" which was accepted in January. I submitted a draft of the final paper in April.

Traffic data collection

Initial site surveys collaborate the view that our standard office lift traffic design criteria are outdated due to changes in working practices and tend to result in the installation of excess lift handling capacity. Moving large, heavy lifts up and down a building when they a virtually empty at peak time is not energy efficient.

Current industry standard design criteria have been in use for many years. In order to justify proposals to change British Standard and CIBSE recommendations I will need to provide a comprehensive set of survey results.

My initial surveys have been manual counts using a notebook computer to time stamp events. This is time consuming, tedious and only provides data for one floor at any one time. I am investigating two other approaches:

- Computer video counts - using video cameras, frame grabbers and computer based (often neural network) algorithms to determine the number of people using lifts. This technology is relatively new and very expensive if purchased as a package. Colleagues at Brunel are writing a lift control algorithm which uses people counting, and the associated video based people counting methods may yield an affordable solution to my traffic data collection problem.

- Traffic analysers - some lift engineers use the data available from lift control systems (lift button presses, etc.) as a measure of lift traffic and lift system performance. But no information is known about the number of people waiting or being transported. I am currently developing a theory which applies a mathematical model to traffic analyser data in order to estimate the actual passenger traffic flow in persons per five minutes. The preliminary simplified algorithm is promising. If further testing and development is successful, this approach would allow me to collect an enormous amount of traffic data relatively simply at minimal expense.

Arup projects

I have been advising on a range of lift projects in Arup - from a single lift in a 3/4 storey building to a 50 storey building (for which a typical scheme has 36 lifts in various zoned/express lift combinations).

I have also acted as an expert witness in a Rent Review arbitration case. Included in my proof of evidence were references (7) and (8) which are a traffic survey of the building in question and an explanation of Oasys LIFT calculations.

B1.5 Comments on progress and next stage of project

I am satisfied with the progress of the first six month of my project and confident that the work carried out is in line with objectives originally agreed for the project. I am conscious of the diverse range of research topics I am investigating, but believe that the various strands should come together when I start modelling the complete lift system by simulation during the next six months. The intention is to write a lift simulation program which will:

i. use traffic data collected for the project as input
ii. implement the ideal kinematics formulae for modelling lift movement
iii. output energy consumption associated with each lift trip
iv. provide a platform for testing lift control strategies that use energy efficiency as criteria

A project programme for the second six months of the project and an overview plan for years 2 to 4 are given in Appendix A

B1.6 List of Contents for Appendices of Progress Report B1

Appendix A

Project Programme

Appendix B

i. Extract from CIBSE Guide on Ideal Lift Kinematics
ii. On the ideal kinematics of lifts by Prof Molz
iii. Commentary: On the ideal kinematics of lifts by Prof Molz
iv. Ideal lift kinematics: Formulae for the equations of motion of a lift
v. Lift traffic analysis: general formulae for double decker lifts (draft)
vi. CIBSE National Conference, "Green Lifts?" synopsis
vii. Report of Traffic Survey at 33 Wigmore Street, London on Friday 18th February 1994 (please treat as confidential)

viii. Basis of the Oasys LIFT 5.0 program implementation of general formulae for lift traffic analysis (please treat as confidential)

B2 PROGRESS REPORT MAY 1995

B2.1 Introduction

This report summarises the work I have carried out over the first 18 months of the Engineering Doctorate programme, outlines my "contribution to knowledge" in the form of published papers, and discusses future work.

B2.2 Green Lifts?

Key paper

The Environmental Technology basis for my research was demonstrated in the *Green Lifts?* paper presented at the EngD end of Year I conference. In this paper I applied Life Cycle Analysis to show that the dominant source of environmental burdens for lift systems are the non-renewable resources depleted, the waste created and the emissions generated through the production of electricity for the operation of lifts while in use.

I highlighted three areas I am working to realise a reduction in energy consumption. These are:

Modelling of lift movement and corresponding energy consumption. This provides the tools to investigate possible savings associated with varying performance, selecting different drive types, alternative lift configurations and, through the use of light modern materials.

Reviewing current traffic design criteria. I am questioning current lift design criteria which, in my opinion, are outdated due to changes in working practices and tend to result in the installation of excessive handling capacity. The goal here is to avoid excessive over sizing of lift cars. Moving large, heavy lift cars up and down buildings when they are virtually empty at peak times is not energy efficient.

Green Lift Control Algorithms. Lift control algorithms generally give consideration to optimisation of traffic flow, and minimisation of waiting and journey times. In due course I will be writing lift control algorithms that also consider energy consumption in their allocation of lifts to calls.

Paper readership/audience

The *Green Lifts?* paper was originally prepared for the Charted Institution of Building Services Engineers National Conference, for which it was refereed by two independent experts. I presented the paper at the CIBSE Conference in October 1994 to an audience of practising building services engineers.

I also presented the paper to the EngD 1994 Conference, a Brunel Research Seminar, various Arup audiences (Arup Environmental, Arup Electrical Engineers, Arup Hong Kong office), and to Hong Kong Polytechnic University Building Services students.

The paper has also been circulated to major lift manufacturers for comment (Kone, Express, Otis and Schindler).

I understand that the paper will be reported in the next edition of the CIBSE Lift Newsletter, and may be re-published in the international elevator magazine, Elevator World.

The response to the paper has been positive, affirming that the direction of the work is valid. There has been minimal previous research in this area, although it has been generally acknowledged that vertical transportation is a major building electrical load, after electric heating/air conditioning (where applicable) and lighting.

Putting the project in perspective

I am sometimes asked to discuss the significance of my research into the environmental impact of vertical transportation systems. In summary:

Buildings account for about a third of the energy we consume. The most important greenhouse gas is carbon dioxide, which is steadily increasing due to the burning of fossil fuels for energy generation and vehicles.

Where they are installed, lifts and escalators are a significant proportion of the building load - a draft CIBSE Energy Efficiency Guide suggests 4 to 7%, Kone documentation suggests 5 to 10%.

The importance of energy efficient HVAC and lighting systems is generally accepted - the wealth of related research and development in both these fields reflects this. Energy efficient vertical transportation systems are among the next in line for "greening".

I am in a excellent position to be able to encourage and guide the vertical transportation industry along the Environmental Technology route - Arup is probably one of the largest specifiers of vertical transportation systems in the world, I have supplementary sponsorship from the Chartered Institution of Building Services Engineers who publish various related journals and guides, and I am already known to the lift industry for my research publications.

B2.3 Elevcon '95

Conference visit

Elevcon is an international conference arranged by the International Association of Elevator Engineers. Elevcon '95 in Hong Kong had 145 participants from 18 countries. There were representatives from manufacturers, consultants, academics, and governmental institutions.

I presented two papers at the conference, one on ideal lift kinematics, the other on double decker lifts. The papers have been published in *Elevator Technology 6*. I also chaired a session on *Neural Network Based Traffic Control* and sat on a *Panel of Experts* answering general questions on vertical transportation.

Copies of my two papers are attached to this report in Appendix A. A brief summary of the work follows:

Ideal Lift Kinematics

Ideal lift kinematics are one element of my *Green Lifts?* research into *Modelling of lift movement and corresponding energy consumption*. They describe the optimum motion that a lift can achieve given restraints imposed by human comfort criteria. I have derived equations which enable ideal lift kinematics to be plotted as continuous functions for any values of journey distance, velocity, acceleration and jerk (rate of change of acceleration).

Ideal lift kinematics are, in themselves, an important area of lift design. For the conference I presented a paper on my work in this field. I discussed previous research, the significance of my own contribution, the mathematical derivation of ideal kinematics equations, and applications for the work.

Double Decker Lifts

Prior to joining the EngD course I derived the General Analysis technique. This allows us to analyse the performance of a lift system for a given peak passenger traffic flow. I implemented the technique in the Oasys LIFT Program, which has been used throughout the international Arup Partnerships for analysis/selection of lift systems since 1989.

More recently, I have extended the technique so that it can be used to analyse double decker lifts. Double decker lifts have two separate cabs built into a single unit so that upper and lower cabs serve adjacent floors simultaneously. They provide greater handling capacity per shaft than conventional lifts, making them particularly attractive for high rise buildings.

In my Elevcon paper I discussed the Double Decker General Analysis technique, its derivation and implementation. I gave an example comparing the results with a more simple analysis technique, before looking at a scenario that only the General Analysis technique can consider.

Double decker lifts are reported to be more energy efficient than single decker lifts - as they serve two floors simultaneously, they have less starts and stops per round trip. This is easy to see for peak traffic. But what is the position for non-peak traffic, when the (large and heavy) double decker lifts are only transporting a few people at a time? I shall be investigating this in more detail when I commence simulation modelling.

Other activities

I took the opportunity while in Hong Kong to visit Arup's offices where I gave an extended lunchtime presentation of my work. I was also invited to, and gave a two hour lecture to Hong Kong Polytechnic University students.

B2.4 Traffic Surveys

I have now carried out four major traffic surveys:

Offices at 33 Wigmore Street
The Ritz Hotel
Arup head office in Fitzroy Street
British Standards Institution head office, Chiswick

Analysis of results from traffic surveys is ongoing, and will form the basis for recommendations for revised traffic design criteria towards the end of my project.

Surveys to date have been carried out by manual count. I had hoped to test the automatic people counting theory I am developing at the BSI office, but the controller manufacturer was unable to down load the data I required from the lift system. I am exploring other contacts to find a site where I can test this work.

B2.5 Motor Modelling

My Academic Supervisor, Dr Pratap Mehta has an undergraduate student working on an actual scale model of a lift. It is intended that this will give me a lab based testing facility for mathematical motor models. I have been developing a DC drive motor model to tie up with the installed system.

B2.6 Lift Simulation

I have started learning C++ which I will use to program the proposed lift simulation program. The lift simulation program will be used to bring together my work on ideal lift kinematics, motor modelling and lift traffic surveys. With these implemented, I can then design and test my "green lift control algorithms".

B2.7 Arup Projects

I continue to give general advise on vertical transportation issues from my base in Arup Research & Development. This involves me, to various degrees, in several different projects most weeks.

In my role as Chairman of the Electrical Computing Working Party, I have co-ordinated Arup Electrical Computing Development Fund Applications for the year April 1995/96, and been involved in discussions concerning the strategy of Arup program development.

B2.8 Programme

A copy of my current programme is enclosed in Appendix B. There has been some slippage, particularly in the Poisson people counting algorithms, and motor modelling. This is mainly due to EngD course work taking longer than planned for.

B2.9 List of Contents for Appendices of Progress Report B1

Appendix A

B3 END OF YEAR II DISSERTATION OCTOBER 1995

B3.1 Summary

This dissertation summarises project progress over the first two years. The environmental basis of the research has been defined in the paper "Green Lifts?". Life Cycle analysis demonstrates that the dominant source of environmental burdens for lift systems are the non-renewable resources depleted, the waste created and the emissions generated through the production of electricity for the operation of lifts while in use. Several areas of research are being considered in order to realise a reduction in energy consumption; progress in each of these areas is reviewed. A summary of Arup project work, and development to the Oasys LIFT program is presented. Masters level modules completed as required by the EngD programme, are listed. An outline programme for the remaining two years of the project is given.

B3.2 Introduction

This project is based at Brunel University and sponsored by Ove Arup and Partners. Supplementary sponsorship is received from the Chartered Institution of Building Services Engineers. Richard joined Arup as a graduate electrical engineer in 1987. His special interest in vertical transportation led to the publication of a number of research papers, prior to joining the EngD programme in 1993.

In this dissertation we will review the project objectives, the environmental basis of the research, and the work carried out in each of the areas defined. Associated work, the EngD taught modules and Arup project work will also be discussed. A plan for the next two years work is proposed.

Some of the contents of the EngD Portfolio and previous progress reports are repeated to allow a complete overview of the work to date in a single document.

B3.3 Project Objectives

The original project objectives were set out in the project proposal 6 June 1993. These were:

i. Measure vertical passenger traffic and lift/escalator energy consumption so as to build up pedestrian circulation and corresponding energy models for offices, residential buildings, airports, leisure complexes, etc.

ii. Compare use and performance of lifts/escalators/stairs to existing lift traffic analysis models and assumptions. Compare performance of driving motors to electrical models.

iii. Develop computer programs implementing verified analysis/simulation traffic analysis models and corresponding energy models.

iv. Use verified models to calculate: the benefits of developing and implementing energy efficient lift control algorithms, the savings achievable through the use of high efficiency motors, and the benefits of energy conscious planning strategies.

v. Establish guidelines for predicting traffic in new and refurbished buildings. Make planning and specification recommendations that reflect the need to design energy efficient buildings.

These objectives remain an integral part of the research. However, the environmental basis and focus of the project has become more clearly defined, as discussed in the following section.

B3.4 Establishing the Environmental Basis of the Project

The environmental basis for the project was set out in the paper "Green Lifts?", which was presented at the EngD Conference (September 1994) and the Chartered Institution of Building Services Engineers (CIBSE) National Conference (October 1994). Most recently, this paper was reproduced in the international trade magazine, Elevator World; a copy is included in Appendix A. By applying Life Cycle Analysis, it has been demonstrated that the dominant source of environmental burdens for lift systems are the non-renewable resources depleted, the waste created and the emissions generated through the production of electricity for the operation of lifts while in use.

Putting this finding into prospective, it is worth considering that buildings account for about a third of the energy we consume. The most important greenhouse gas is carbon dioxide, which is steadily increasing due to the burning of fossil fuels for energy generation and vehicles. Where they are installed, lifts and escalators are a significant proportion of the building load - a draft Chartered Institution of Building Services Engineers (CIBSE) Energy Efficiency Guide suggests 4 to 7%. Kone Lifts Ltd documentation suggests 5 to 10%.

The importance of energy efficient HVAC and lighting systems is generally accepted - the wealth of related research and development in both these fields reflects this. Vertical transportation systems are among the next in line for "greening".

Three areas of research are being considered in order to realise a reduction in energy consumption. These are:

i. *Modelling of lift movement and corresponding energy consumption* Providing the tools to investigate possible savings associated with varying performance, selecting different drive types, alternative lift configurations and, through the use of light modern materials.

ii. *Reviewing current traffic design criteria* Questioning current lift design criteria which, we believe, are outdated due to changes in working practices and tend to result in the installation of excessive handling capacity. The goal here is to avoid excessive over sizing of lift cars. Moving large, heavy lift cars up and down buildings when they are virtually empty at peak times is not energy efficient.

iii. *Green Lift Control Algorithms* Lift control algorithms generally give consideration to optimisation of traffic flow, and to the minimisation of waiting and journey times. Lift control algorithms that also consider energy consumption in their allocation of lifts to calls are being considered.

B3.5 Modelling of Lift Movement and Corresponding Energy Consumption

Ideal Lift Kinematics

Ideal lift kinematics describe the optimum motion that a lift can achieve given restraints imposed by human comfort criteria. Previous research by others gave us points on time versus distance, velocity, acceleration and jerk (rate of change of acceleration) curves. The author derived equations allowing ideal lift kinematics to be plotted as continuous functions for any value of journey distance, speed, acceleration and jerk.

Ideal lift kinematics are, in themselves an important area of lift design. A paper on this element of the work was presented at the Elevcon conference in March 1995, which is discussed in a following section. A copy of the paper is included in Appendix B.

This research in ideal lift kinematics provides us with the full control over the reference speed, acceleration, etc. input to lift drives so that we can investigate energy savings associated with varying the lift performance.

Motor Modelling

Electric lift drives, and their relative energy consumption are discussed in the paper prepared for the EngD Conference September 1995. A copy of this paper is included in Appendix C. The paper was subsequently presented at the CIBSE National Conference (October 1995). A mathematical model of a separately excited DC motor, fed from a fully controlled 6 pulse convertor is presented. Kinematics are input into this model to plot the required torque, armature voltage/current, and power factor. The total energy consumption over the whole trip is determined, and an assessment of the supply system harmonics is given.

This model is used to demonstrate that, by reducing the maximum accelerating by 50%, an energy saving of 16% is achieved. The increased journey time of 23%, would not be prohibitive if introduced during periods of light traffic.

This, and other motor models will be implemented in a lift system simulation to aid development and testing of "green" control strategies.

B3.6 Reviewing Current Traffic Design Criteria

General

The need for reviewing current lift traffic design criteria was discussed in section 3.

Traffic surveys can be carried out in a number of ways. Manual surveys are time consuming and tedious to carry out, so the main focus has been on developing automatic counting techniques. If successful, this will allow large amounts of, and therefore more representative, traffic data to be obtained for a wide range of building types.

Manual counts

Manual lift traffic surveys have been carried out at:

i. Offices at 33 Wigmore Street
ii. The Ritz Hotel
iii. British Standards Institution head office, Chiswick
iv. Arup head offices in Fitzroy Street

Surveys (i) to (iii) are documented in reports prepared for Arup clients. Survey (iv) is currently being documented. A summary report of the manual surveys will be prepared.

Poisson Counting

In the “Green Lifts?” paper the author discussed applying a mathematical model to traffic analyser (or lift control system) data in order to estimate actual passenger traffic flow in persons per five minutes.

To date, the main difficulty has been collecting the data required for analysis (time of lift button presses, etc.). This data is sometimes collected by traffic analysers which you hard wire into the lift system. The proprietary traffic analysers reviewed process and analyse the data themselves before giving the user an analysis. The “raw” data we require is not available.

Now that lift manufactures use microprocessors in their lift controllers, it should be possible to interface and download the data we require directly. Through the CIBSE Lift Committee the author has approached the major lift manufacturers (Otis, etc.) to establish if their microprocessor based lift controllers can download the appropriate data. To date, the answer has been no, although Thyssen are currently investigating adding a serial port to one of their lift controllers. However, many manufacturers can remotely monitor their sites and current lift operation, so are effectively broadcasting the data required for the analysis.

One such manufacturer, The Thames Valley Lift Company, has provided a copy of their software which allows us to monitor their sites remotely by modem. As they are unwilling to provide the program source code so that modifications can be made to log the incoming data to disk, we need to use a second program to monitor and time stamp data for analysis. Because communications software uses “handshaking” there are difficulties in two programs monitoring the data simultaneously. We hope to overcome this difficulty shortly.

Video Counting

Three of the four manual surveys carried out have used video cameras to record passenger movements. This allows us the possibility of using computer programs to count the traffic. These programs are a relatively new development. A Brunel people counting program is currently being tested on the Arup head office traffic survey videos.

B3.7 Lift Simulation Program

The purpose of the lift simulation program is to:

- implement the research in ideal lift kinematics, motor modelling for power consumption and traffic survey data.
- Provide a test tool for lift control algorithms
- provide and advanced traffic/lift performance analysis tool

A draft outline specification for the development is included in Appendix D.

We are currently negotiating with a lift Thames Valley on possible co-operation, in particular including their lift control algorithm in the simulation. The benefits of this co-operation would be:

- we would have a benchmark “modern” lift control system against which to test development control algorithms
- development algorithms would be developed in a similar format, making them more straight forward to implement on real systems

B3.8 Oasys LIFT Program

Prior to joining the EngD, the author derived the General Analysis technique. This allows us to analyse the performance of a lift system for any given peak passenger traffic flow. The technique is implemented in the Oasys Lift Program and has been used throughout the international Arup Partnerships for analysis/selection of lift systems since 1989.

The technique has now been extended so that it can be used to analyse double decker lifts. Double decker lifts have two separate cabs built into a single unit so that upper and lower cabs serve adjacent floors simultaneously. They provide greater handling capacity per shaft than conventional lifts, making them particularly attractive for high rise buildings.

A paper discussing the Double Decker General Analysis technique, its derivation and implementation was presented at Elevcon ‘95, and is included in Appendix E.

Double decker lifts are reported to be more energy efficient than single decker lifts - as they serve two floors simultaneously, they have less starts and stops per round trip. This is easy to see for peak traffic. But what is the position for non-peak traffic, when the (large and heavy) double decker lifts are only transporting a few people at a time? This will be investigate in more detail using the simulation model.

B3.9 EngD Modules and Electives

As part of the EngD programme, Research Engineers are required to complete a number of Masters modules (or equivalent). To date the following core modules have been completed:

- Leadership and LCA 1
- LCA 2 and Research Training Programme
- Global Monitoring
- Risk Perception 1
- Introduction to Sociology
- Hands on Audit and Introduction to Legislation
- Environmental Measurement
- Risk Communication and Project Management
- Environmental Law
- Sociology of the Environment
- Advanced Leadership

And the following elective modules:

- Neural Networks
- Project Management of EngD Conference 1995

Copies of module assignments are kept in the EngD Portfolio.

B3.10 Arup Project and Related Work

General

As an engineer in Arup Research and Development, I am regularly called upon to advise line group engineers on all aspects of vertical transportation engineering. Queries range from the simple, "what size lift shaft do I require?" to the more interesting "can we have a 13 person lift which travels on a curved incline to follow the building structure?".

I also advise on some of the more complex traffic analysis problems. These range from high rise buildings with express lifts and sky lobbies, to unusual traffic flow scenarios such as back stage in a theatre.

I acted as an expert witness for a rent review arbitration case concerning the office building, 33 Wigmore Street in London. The quality of lift service was in question, and I presented, and was cross examined on evidence relating to the lift traffic analysis and the performance of the lift installation in question.

Electrical Computing Working Party

As chairman of the Arup Electrical Computing Working Party, I oversee the development and application of computer programs for Electrical Engineering in Arup. Arup have historically developed most of their own programs, many of which remain technically superior to other, commercially available programs. The building services software market is now developing fast, and we are having to review the strategy of developing our own programs. We are currently reviewing "cable" distribution software to determine whether the building services software companies can provide us with a program of high enough quality, and at a cost that makes it no longer worthwhile for us to continue to develop our own program.

CIBSE Guide

Prior to joining the EngD programme, I contributed to the computer programs section of CIBSE Guide D, *Transportation systems in buildings*. This guide has been a success, and a second, revised edition is being planned. I have been asked to look at three sections in particular relating to planning of installations, lift monitoring, and computer programs. This is an excellent opportunity to establish elements of "green" research into common design practice.

B3.11 Elevcon '95 Conference Report

Elevcon '95 was the 6th international conference on Elevator Technology, held on 13-16 March 1995 at the Riverside Regal Hotel in Sha-Tin, Hong Kong. The conference had 145 participants from 18 countries. There were representatives from manufacturers, consultants, academics, and governmental institutions. Subjects discussed included components, traffic, control, monitoring, education and training, escalators and drive systems.

Elevcon is the only international conference in this field, and a valuable opportunity for lift engineers and researchers to learn about and to discuss new technologies. Some particularly interesting papers were:

- *Elevator Group Control System with Fuzzy Neural Network Model* - just one of several papers describing how the latest in artificial intelligence thinking can be applied to lift control systems.

- *Active Noise Control of Elevator Noise From Ventilator* - describing how noise can be reduced by emitting sounds that are anti-phase to noise sources.

- *Marketing Strategy of Lifts and Escalators in the Far East* - an outline of the development and analysis of market demand in Far East Asia, reporting on economic growth and identifying opportunities for foreign investment.

- *A Super High-Rise Escalator with a Horizontal Mid-Section* - describing an escalator with a horizontal mid section in the middle of its 42 m rise.

- *The User's Ideal Lift* - an interesting survey of Italian lift users, and a reminder that the user's main concern is safety.

- *The Latest Drive Technology for Elevators* - discussing inverter control of electric and hydraulic lifts.

The author presented two papers at the conference, *Ideal Lift Kinematics*, and *General Analysis Double Decker Lift Calculations*. The author also chaired the session on *Neural Network Based Traffic Control* and sat on a *Panel of Experts.* The panel answered general questions on vertical transportation issues ranging from the ownership of data collected by remote monitoring (does it belong to the client or lift supplier?) through to a questioning of our current reliance on mechanical (as opposed to electronic) safety devices.

All the papers have been published *Elevator Technology 6.*

Besides the main sessions, there were workshops, tutorials and seminars. The author participated in two seminars, one on remote monitoring and data logging, another on lift traffic design and control.

B3.12 Future Programme

An outline programme for the remaining two years of the project is included in Appendix F. The main work will be development of the simulation program, which is in the early stages of coding. As discussed in previous sections, the simulation program brings together the main elements of the research - kinematics, motor modelling, traffic data, and green lift control algorithms. A period has been set aside for testing the simulation models against real systems, and making modifications as necessary.

B3.13 Conclusions

The environmental basis of the work has been established and widely reviewed within the building and vertical transportation industry through the paper “Green Lifts?”. Several key areas of work have been defined, and significant progress has been made in developing these areas.

The doctorate requirements of "contribution to knowledge" have been demonstrated through the publication of refereed conference papers.

The remaining project programme outlines plans for the next two years. The remaining work is primarily focused on the development of a lift simulation program, various "green" control algorithms, and the testing of these models against real systems.

B3.14 Acknowledgements

The author would like to thank his supervisors, lecturers and colleagues at Brunel University, Ove Arup & Partners and the CIBSE Lift Group for sharing their knowledge and experience which are providing an excellent basis for his research. The author acknowledges, with gratitude, financial support from the Engineering and Physical Sciences Research Council, The Ove Arup Partnership, and the Chartered Institution of Building Services Engineers.

B3.15 List of Contents for Appendices of Progress Report B3

Appendix A

Peters R D *Green Lifts?* Proceedings of CIBSE National Conference 1994 (The Chartered Institution of Building Services Engineers) (1994)

Appendix B

Peters R D *Ideal Lift Kinematics: Complete Equations for Plotting Optimum Motion* Elevator Technology 6, Proceedings of ELEVCON'95 (The International Association of Elevator Engineers) (1995)

Appendix C

Peters R D *Mathematical Modelling of Lift Drive Motion and Energy Consumption* Proceedings of CIBSE National Conference 1995 (The Chartered Institution of

Building Services Engineers) (1995)

Appendix D

Outline Specification for Lift Simulation Program

Appendix E

Peters R D *General Analysis Double Decker Lift Calculations* Elevator Technology 6, Proceedings of ELEVCON'95 (The International Association of Elevator Engineers) (1995)

Appendix F

Project Programme

B4 PROGRESS REPORT APRIL 1996

B4.1 Introduction

This project is addressing the finding that the dominant source of environmental burdens for lift systems are the non-renewable resources depleted, the waste created and the emissions generated through the production of electricity for the operation of lifts while in use.

A comprehensive background to the project, and progress in the two years to October 1995 is given in the end of Year II dissertation, a copy of which is kept in the project portfolio. This report assumes the reader has reviewed this dissertation.

B4.2 Simulation Development

The main focus of the work is now the development of a simulation program which brings together the main elements of research carried out to date. This includes the work on ideal lift kinematics, motor modelling and traffic survey data.

The simulation will enable development of green lift control algorithms. And enable users to test the performance of lift systems, both in terms of energy consumption and passenger service. A specification for the program was included in the appendices of the End of Year II Dissertation.

I have previous programming experience in Fortran, Basic and Pascal. But C++ has been chosen as the language for this program due to its speed, portability, functionality, code re-usability, and industrial acceptance as *the* professional programming language. Arup Computing have also moved to C++ in recent years, so support and development of the program after the end of the project will be viable.

C++ is a complex language, and getting to a stage where useful code can be written has taken considerable effort. But having got to this stage, its advantages are proving very valuable. Key concepts such as "object-orientation" and "encapsulation" play a major part in breaking down and simplifying programming.

At this stage I have developed two major C++ "classes", a motion class and a lift class. The motion class implements all the work on ideal lift kinematics for use in the simulation. The lift class represents a lift - each instance of the class (i.e. an "object") represents a lift in the simulation - it has a nominal capacity, speed, door times, etc. And functions that allow you to move it up and down, make it answer calls, etc. The most recent header files for these classes are included in Appendix A. Header files are the programmer's interface to the coding of a class, showing its functionality and how to access it without needing to see its implementation (i.e. the detailed C++ coding). The variables and functions are commented in detail, and most should be self-explanatory to readers with an elementary knowledge of computer programming.

Next stages in developing the simulation include writing classes to represent the motor power consumption, people, and "green" dispatcher control algorithms. Time has been put aside towards the end of the project for testing and verification of the simulation model against real systems.

B4.3 EngD Course Work Activities

An optional elective module on Clean Technology was attended the week commencing 30 October 1995. This proved to be very thought provoking; we were challenged to consider our own environmental "paradigm shift".

An EngD core module on Risk Assessment took place on the week commencing 8 January 1996.

A Life Cycle Analysis Workshop was held 8 February 1996 at Surrey University, attended by EngD RE's together with staff and students of Surrey's Universities' Centre for Environmental Strategy. This was a good opportunity to present the Life Cycle (inventory) Analysis prepared for the *Green Lifts?* paper. A useful discussion reached a consensus view that the basis of my claims were well founded i.e. that the dominant source of environmental burdens for lift systems are the non-renewable resources depleted, the waste created and the emissions generated through the production of electricity for the operation of lifts while in use. A more detailed Life Cycle Analysis of lift systems could be carried out; in fact it could be a four year project in itself. But for the purposes of demonstrating that energy consumption was the key issue for vertical transportation, the assessment is quite adequate.

B4.4 Papers, Seminars and Publications

Elevcon '95 papers on ideal lift kinematics and double decker lifts have been developed further, and offered for publication in professional journals. The paper, *Ideal Lift Kinematics: Derivation of Formulae for the Equations of Motion of a Lift* has been accepted for publication in the International Journal of Elevator Engineers. This includes new results which allow calculation of minimum stopping distances once a lift journey has commenced (found to be useful in the lift simulation when new calls are registered after a trip has commenced). A copy of the final submission incorporating referees comments is included in Appendix B. The paper, *Lift Traffic Analysis: General formulae for double decker lifts* has been submitted, and is currently being reviewed by the CIBSE Journal, Building Services Engineering Research and Technology (BSERT).

A seminar titled, *Lift Controls for the Future* was given for a CIBSE Regional meeting at Reading University on 7 November 1995. And repeated as a Brunel Research Seminar 15 November 1995. Some of the ideas discussed in this seminar are being developed by a group of Arup colleagues to contribute towards an article for the CIBSE Building Services Journal (a trade magazine).

Abstracts for two papers have been accepted for Elevcon '96 in Barcelona, October 1996. The first, *Lift Passenger Traffic Patters: applications, current knowledge and measurement* is intended to bring together my research in this area. The second, *Risk and the Vertical Transportation Industry* is intended to bring together, and apply to the lift industry, the lessons learnt from the three EngD risk modules. (This paper is being accepted by our tutor as an alternative to the module assignment.) Abstracts for both these papers are included in Appendix C.

I have been using the Internet occasionally for work purposes, and in my own time to develop a home page for the IEE South Bucks Younger Member Section (of which I am a committee member). I wrote an article about my experiences for feedback to Arup, which is at the early stages of exploring this medium. The article was published in our in-house *Computer News*, and is included in Appendix D.

B4.5 Arup Project and Related Work

The Oasys LIFT program has been extended to allow imperial calculations, as requested by the Arup USA office.

As chair of the Electrical Computing Working Party, I have overseen the preparation of computer development fund applications for the year 1996/97, totalling approximately 31 man weeks work. These include applications relating to lift, lighting, cable sizing, power systems analysis and CAD software.

I continue to advise line group engineers on vertical transportation issues. Recent projects of interest include a prospective high rise complex in USA (example design options given in Appendix E). And a survey of Charring Cross Hospital, which has a severely overloaded passenger lift systems; we have proposed a major modernisation of the systems (including specification of energy efficient drives), and a re-think of transportation strategy. Estimates for the proposed work suggest a budget of £3.2 million.

B4.6 CIBSE Lift Group

I am pursuing a more active involvement in the CIBSE Lift Group, and attend meetings as a member of the group. We are currently awaiting formal approval of outline proposals to revise CIBSE Guide D *Transportation Systems in Buildings*, for which I am nominated as a principle author for three sections. As discussed in the End of Year II dissertation, this will provide an excellent opportunity to establish elements of "green" design into common practice.

I am currently investigating setting up a CIBSE Open Forum on Remote Monitoring of Lifts. As noted in Guide D, and experienced in my own research, it is very difficult to obtain lift controller data. We are hoping this open forum will be one step forward to achieving (more) open systems - which would allow building owners to monitor lifts from different manufactures using the same software (possibly integrated into BMS software). And allow lift researchers/consultants to download and analyse data without being restricted by the limitations of any one manufacture's monitoring package.

The CIBSE Lift Group would like to set up Lift Training courses - from general short courses to post graduate degrees. I have initiated a training questionnaire to establish demand for various types of courses; this is being circulated by CIBSE and by the vertical transportation industry press.

B4.7 Project Programme

An updated project programme is included in Appendix F.

B4.8 Conclusions

The environmental basis of the research has been demonstrated, and doctoral requirements of "contribution to knowledge" continue to be added to through conference and journal paper publications. The main elements of the research are now coming together in the lift simulation program, the development, testing and verification (against real systems) of which is the main focus for the remainder of the project.

B4.9 List of Contents for Appendices of Progress Report B4

Appendix A

Header Files for motion and lift Classes

Appendix B

Peters R D *Ideal Lift Kinematics: Derivation of Formulae for the Equations of Motion of a Lift* International Journal of Elevator Engineers, Volume 1 No 1 (1996)

Appendix C

Abstracts for Elevcon '96:

i. "Lift Passenger Traffic Patterns: Applications, Current Knowledge, And Measurement"

ii. “Risk And The Vertical Transportation Industry”

Appendix D

Arup Computer News Article: “Surfing on the Crest of an Internet Wave”

Appendix E

High Rise Design options for prospective Arup project in USA

Appendix F

Project Programme

B5 PROGRESS REPORT OCTOBER 1996

B5.1 Introduction

The main focus of this project is energy efficient lifts. This progress report covers the period April to September 1996 (second half of Year 3). Background to the project, and progress in the preceding two and a half years can be found in:

- End of Year II Dissertation
- Progress Report April 1996

Copies of these reports are kept in the project portfolio. This report assumes that the reader has reviewed these documents.

B5.2 Simulation Development

The simulation program brings together the main elements of research carried out for the project, including ideal lift kinematics, motor modelling and traffic survey data.

The program was outlined in the 1996 EngD Conference Paper, *Green Lift Control Strategies* (a copy of this paper is held in the portfolio).

In summary, this object oriented program has six main classes:

> *building* - defines the building in terms of number of stories and story heights.
>
> *motion* - implements research in ideal lift kinematics.
>
> *lift* - defines a lift (rated speed, capacity, floors served, etc.) and its current status (position, speed, load, etc.). The motion class is applied to enable the lift to move according to the selected journey profile.
>
> *dispatcher* - defines rules for allocating which lift serves which calls. For fair comparison of the green control strategies, the default dispatcher logic has been

based on conventional group control with dynamic sectoring.

person - defines a person, what time they arrive at the landing station, where they want to go, their mass, etc. Once the journey is complete, the class provides details about passenger waiting and journey times.

motor - defines the characteristics of the drive. Calculates the energy consumption and other characteristics as per research in motor modelling.

Within the limitations of computer memory, the program will allow any number of lifts, floors, and persons. Lifts are individually defined, so if necessary can serve different floors, be different sizes, speeds, etc.

As discussed in *Green Lift Control Strategies*, the program is being used to develop "green" dispatcher control algorithms. Initial simulation results suggest that installations with regenerative drives could achieve additional savings in excess of 30% without reduction in the overall system performance. Further savings could be achieved with marginal reductions in system performance.

The next development stages for the lift simulation are:

- test the simulation against real systems
- write a user interface
- enhance, de-bug as necessary

It is envisaged that the final program will be used in Arup for lift system selection/analysis.

B5.3 EngD Course Work Activities

I presented *Green Lift Control Strategies* as a five minute talk, and as a poster-board at the EngD Conference 10-11 September 1996. The written paper was included in the conference proceedings.

I have completed the EngD distance learning Finance and Marketing module and am currently finalising the assignment.

In June 1996 I attended a four day *C Programming for Interfacing and Signal Processing* course run by the Brunel M&ES department. Parts of this work are being applied to interface with people counting devices (for lift and escalator traffic surveys).

B5.4 Publications

The paper, *Lift Traffic Analysis: General formulae for double decker lifts*, has been accepted for publication by the CIBSE Journal, *Building Services Engineering Research and Technology* (BSERT). This paper provides a more detailed review of the double decker lift research presented in a previous conference paper. A copy of the journal paper is in Appendix A of this report.

The following two papers have been accepted for the International Elevator Technology Conference, ELEVCON '96 in Barcelona, 23-25 October 1996.

- Peters R D Risk and the Vertical Transportation Industry. This paper applies EngD course material on Risk to my industry sector.
- Peters R D, Mehta P, Haddon J Lift Passenger Traffic Patterns: Applications, Current Knowledge, and Measurement. This paper summarises the lift traffic research that has been carried out for the project to date.

Copies of these papers are in Appendix B of this report.

Further past conference papers have been republished by trade magazines:

- Mathematical Modelling of Lift Drive Motion and Energy Consumption was republished by Elevator World in July 1996
- Ideal Lift Kinematics: Complete Equations for Plotting Optimum Motion was republished by Elevator World in April 1996 and by Elevatori in May/June 1996

A full list of publications is given in Appendix C of this report.

B5.5 Arup Project and Related Work

I have been appointed Convenor of a new Arup Research & Development *Look Forward Group (7-10 years)*, reviewing medium to long term business development opportunities for our department. This group will meet about three/four times a year - we had our first meeting in July 1996, which was used mainly to brainstorm possible ideas/issues for the group to address.

I have been designing lifts for an increasing number of high rise and high volume projects, the largest of which is Togok, which has six interconnecting towers, two of which are inclined. This Korean development, currently at pre-feasibility stage, will have in the region of 27,000 occupants. An extract from the design report concerning the "occupant transport systems" (which I wrote) is included in Appendix D. This project is currently confidential.

In September 1996 my colleague, Roger Howkins and I presented a day course on Vertical Transportation to Arup graduates. I covered Lift Basics, Calculating Quantity and Quality, Lift Operation, Lift Layouts, and Escalator Basics. Roger covered Specification, Codes and Standards, Commissioning, Modernisation, Building Interface, and Maintenance.

B5.6 IEE, IAEE and CIBSE

I applied for transfer to Institution of Electrical Engineers Membership in April this year and, following an interview, was accepted in September 1996 as a Corporate Member of the Institution, and as a Chartered Electrical Engineer.

The International Association of Elevator Engineers is setting up a distance learning college offering modules in Elevator Engineering. The IAEE will award postgraduate Certificates/Diplomas to successful students. And work with collaborating universities to complete associated project work/additional modules leading to a MSc. I have been invited to serve on the "academic board" of the college. The time commitment is minimal at this stage (i.e. few hours reviewing course material, opinions on students, etc.), but could develop if appropriate to my position/other commitments in future years. On this basis, I have accepted the position.

As discussed in previous reports, it has proved difficult to obtain lift controller data for my research. I agreed with CIBSE that it would be worthwhile arranging an Open Forum on the *Remote Monitoring of Lifts*, to attempt to address and progress the status of lift communications. I organised this as a joint event with the IAEE, co-ordinating arrangements with the IAEE Chairman, Dr George Barney. The event took place at CIBSE in Balham on the 13th May 1996. It was well attended and received, though the goal of "open systems" still seems a long way off. Promotional material and press cuttings are included in Appendix E. The Elevator World re-prints include the written version of my talk in their *Consultant's Forum* column.

The CIBSE Lift Group has now received formal approval to commence revising CIBSE Guide D *Transportation Systems in Buildings*. I am one of the principle authors for the new version, and will be contributing to various sections. I have also been investigating lift training on behalf of the CIBSE Lift Group. As a consequence of my findings, the Group has decided to concentrate on CPD (Continuing Professional Development) courses, and to seek to use its influence (via CIBSE course accreditation) to encourage Building Services undergraduate courses to cover vertical transportation in more depth.

B5.7 Project Programme

An updated project programme is included in Appendix F.

B5.8 Conclusions

The main elements of the research have been brought together in the lift simulation program, which is being applied as a basis for designing "green" lift systems. Further development, testing, and verification against real systems are planned. To date the project has yielded two journal papers and six conference papers, demonstrating the doctoral requirements of "contribution to knowledge". Several of these papers have been republished in lift industry trade journals, reaching a large and influential audience. I continue to broaden my experience with new roles in Arup, contributions to major construction projects, and associations with IEE, IAEE and CIBSE.

B5.9 List of Contents for Appendices of Progress Report B5

Appendix A

Peters R D, Mehta P, Haddon J *Lift Traffic Analysis: General formulae for double decker lifts* Building Services Engineering Research and Technology, Volume 17 No 4 (1996)

Appendix B

ELEVCON'96 Papers:

i. Peters R D *Risk and the Vertical Transportation Industry* Elevator Technology 7, Proceedings of ELEVCON'96 (The International Association of Elevator Engineers) (1996)

ii. Peters R D, Mehta P, Haddon J *Lift Passenger Traffic Patterns: Applications, Current Knowledge, and Measurement* Elevator Technology 7, Proceedings of ELEVCON'96 (The International Association of Elevator Engineers) (1996)

Appendix C

List of Journal and Conference Publications

Appendix D

Extract from Togok Pre-Feasibility Study

Appendix E

Remote Monitoring of Lifts Open Forum

Appendix F

Project Programme

B6 PROGRESS REPORT APRIL 1997

B6.1 Introduction

The main focus of this project is energy efficient lifts. This progress report covers the period October 1996 to March 1997 (first half of Year 4). Background to the project, and progress in the preceding three years can be found in:

- End of Year II Dissertation
- Progress Report April 1996
- Progress Report October 1996

Copies of these reports are kept in the project portfolio. This report assumes that the reader has reviewed these documents.

B6.2 Simulation Development

A lift simulation program is the main deliverable of the project. The program, Liftsim, brings together and implements the main elements of research carried out; this includes work in ideal lift kinematics, motor modelling, green control algorithms and results from traffic survey data.

Liftsim has been written using Microsoft Visual C++ and runs under 32 bit Windows (95 and NT).

My experience with Arup software has taught me that however clever a program's algorithms, it will be unpopular with users if it has a poor user-interface. Thus, in the last six months, considerable effort has been put into writing a Windows interface that is friendly and easy to use. In addition to the standard Microsoft data entry controls, I have purchased and implemented the "Formula One" software component that allows spreadsheet-like entry of data tables.

In *Passenger Data* and *Lift Data* I have allowed the user to select between *Standard* and *Advanced* modes. Again this feature is something that has arisen from my experience in software development and support. Some users want a quick analysis and expect a program to automatically (but intelligently) select inputs to all but the key variables. Programs insisting on a complete data set are deemed too complex for the task. Other users need and want full control over all analysis variables, and are prepared to put in the time and effort required to compile and enter the full data set.

In most instances designers are looking for the minimum installation specification (number of lifts, speed, capacity) that meets their design criteria. Liftsim allows a range of configurations to be analysed with a single run of the simulation, which speeds up the design process.

The program is now ready for Alpha testing, which is due to commence in April 1997. Testing will be carried out under my direction by graduates seconded to ARD as part of their training. Liftsim will be put on general release to Arup before the conclusion of my EngD.

Liftsim is likely to become the primary Arup lift design tool for the foreseeable future, with developments continuing beyond the conclusion of my EngD project. Budgets for maintenance and support of the program have been included in the Arup 1997/98 Electrical Computing Development Fund Applications (for my time post 1st October 1997).

Screen shots of the program, and example output are given in Appendix A of this report.

The remaining tasks for the lift simulation are:

- de-bugging and testing, including against real systems
- manual/on line help authoring
- further enhancements as time allows

B6.3 EngD Course Work Activities

I have completed and submitted the *Finance and Marketing* assignment.

I attended the *Talking to the Media* module and contributed to the group assignment which was to produce a 5-10 minute promotional video about the EngD program aimed at prospective sponsors.

B6.4 BSc Project Supervision

I have taken the lead role in supervising a final year engineering BSc project student, Shirley Yeung. The project is to implement and to apply my single deck *general* lift traffic analysis technique. The engineering and computing concepts are complex, but Shirley has worked hard to understand the mathematics, and to expand her BASIC computing knowledge to write C++ code.

B6.5 Arup Project and Related Work

As discussed in my last progress report, I have been appointed Convenor of a new ARD *Look Forward Group (7-10 years)*. This group meets to discuss prospective business opportunities for ARD. As an indication of our discussions, minutes of our second meeting 10 January 1997 are included in Appendix B of this report. Further to this meeting I gave a progress report to the ARD management meeting (EXCO).

Vertical Transportation (elevators and escalators) design is a successful and profitable part of ARD, and it is envisaged that our activities will be broadened and expanded into “Arup Lift”. In the past few months we have had a number of discussions about developing new business areas, parts of which arise from expertise developed through the EngD programme. In particular the simulation program, Liftsim, is likely to be an important design and sales tool.

In Arup we bid annually for computing development fund resources. As Chairman of the Electrical Computing Working Party, I co-ordinate the electrical engineering applications. This involves taking submissions from various electrical working groups, chairing discussions about the proposals, and obtaining backing for the work from the Arup Electrical Co-ordination Committee. A summary of the 1997/98 applications that we have submitted is included in Appendix C of this report.

I continue to give general advice on Vertical Transportation for various projects in Arup. I was pleased to be given a copy of a client's letter which showed that I had made a positive impression (see Appendix D). I was the Electrical and Vertical Transportation Project Engineer for this 1,000,000 ft^2 commercial and residential development in Egypt in 1992/93. I continue to be consulted, particularly on vertical transportation issues.

B6.6 Elevcon '96

I attended the IAEE International Elevator Technology Conference, ELEVCON '96 in Barcelona, 23-25 October 1996, presenting papers on *Risk and the Vertical Transportation Industry,* and *Lift Passenger Traffic Patterns: Applications, Current Knowledge, and Measurement.* Copies of the written papers were included in my October 1996 progress report.

I also presented the paper, *Time, Distance, Speed, Acceleration and Jerk in Elevator Starting and Stopping* by Dr. Kepa Zubia. Dr Zubia was expected to present his own paper, but was delayed on his way to the conference. As the subject was within my area of expertise, I was asked to present the work instead. Presenting someone else's conference paper at an hour's notice, with just the conference proceedings and hastily prepared acetates was a challenging, but valuable experience.

A number of papers at Elevcon '96 were directly related to my research, and I was able to discuss this work directly with the authors, both during and following the conference.

The Elevcon conferences are the only truly international forum at which to present vertical transportation research. I have been very fortunate in being able to participate in two of these conference during my EngD.

B6.7 Institutional Activities

In November 1996 I was elected as Secretary of the CIBSE Lifts Group. As an indication of the Group's activities, I have included in Appendix E a copy of the 1996 progress report, prepared for *Building Services, The CIBSE Journal* by Dr G Barney.

The revision of CIBSE Guide D, *Transportation Systems in Buildings* is progressing. At the last Guide D meeting my proposed synopses for *Planning and selection of equipment and performance of transportation systems,* and *Remote monitoring and interfacing with BEMS* were accepted. I will be writing the first drafts of these sections (with input from other contributors) in the next six months. Copies of the my synopses are included in Appendix F of this report.

As discussed in my last progress report, I have accepted an invitation to serve on the academic board of the International Association of Elevator Engineers distance learning college. I attended the first meeting at Elevcon '96.

B6.8 Publications

The paper, *Lift Traffic Analysis: General formulae for double decker lifts,* was published in the CIBSE Journal, *Building Services Engineering Research and Technology* (BSERT), Volume 17 No 4 1996. A copy of final submission of this paper was included in my October 1996 progress report.

Ideal Lift Kinematics: Derivations of Formulae for the Equations of Motion of a Lift, was published in *The International Journal of Elevator Engineering*, Volume 1 1996. A copy of the final submission of this paper was included in my April 1996 progress report.

My Elevcon '95 paper, General Analysis Double Decker Lift Calculations was republished by Elevator World in December 1996.

My article, *Surfing the Internet on the Crest of an Internet Wave*, written originally for the Arup in-house *Computer News*, was adapted and published in the Autumn 1996 edition of *Elevation*. (The original version is included in my April 1996 progress report.)

Following an approach by the publishers E & FN Spoon, I am acting as a referee for the second edition of the *Elevator & Escalator Micropedia* by Dr G Barney, D Cooper and J Inglis.

An updated list of journal and conference publications is given in Appendix G of this report.

B6.9 Project Programme

An updated project programme in included in Appendix H.

B6.10 Conclusions

The main element of work in this past six months has been developing Liftsim from a research tool into a program that can be used by others to apply my work in their design of vertical transportation systems. Liftsim has been very well received in the initial demonstrations that I have carried out, and I am confident it will be applied for many years to come.

My academic and industrial experience continues to develop through various roles and responsibilities at Brunel, Arup, and in Institutional business.

I believe that I am in a good position now to finalise the research and writing up in time to submit a completed portfolio in October 1997.

B6.11 List of Contents for Appendices of Progress Report B6

Appendix A

Liftsim Screen Shots & Example Printed Output

Appendix B

Sample Minutes of "ARD Look Forward Group (7-10 years)"

Appendix C

1997/98 Electrical Computing Development Fund Applications

Appendix D

Client commendation

Appendix E

CIBSE Lifts Group Progress Report 1996

Appendix F

CIBSE Guide D Synopsis for sections

i. Planning and selection of equipment and performance of transportation systems

ii. Remote monitoring and interfacing with BEMS

Appendix G

List of Journal and Conference Publications

Appendix H

Project Programme