1.0 INTRODUCTION
Elevators have always been critical to the successful operation of any building and have become especially critical in the case of high rise buildings. Elevator traffic engineering involves the analysis and design of elevator systems in order to deal with the passenger traffic flow in buildings.

This series of articles will attempt to present the principles of elevator traffic engineering, as well as placing it in a modern context and discussing the latest developments in the field.

2.0 TRAFFIC DESIGN VS. ENGINEERING DESIGN
When discussing the term design in the context of elevator systems, it is important to distinguish between two main areas of elevator design: engineering design and traffic design. Engineering design involves the electrical and mechanical design of the various components and systems in the elevator. Traffic design involves the design of the elevator system such that it can transport the required number of passengers in a specified period of time under the stipulated performance conditions.

This series of articles is only concerned with the traffic design of elevator systems, rather than the engineering design. However, it is necessary in certain cases to deal with certain engineering design topics due to the fact that they are closely linked with traffic design aspects and have a significant impact on decisions made within the traffic design process. An example is the effect of shaft space on the selection of the rated speed of the elevator, where the selection of the rated speed of the elevator requires minimum clearances in the pit and the head of the shaft, referred to as pit depth and headroom respectively.

3.0 THE VERTICAL TRANSPORTATION PROBLEM
In any engineering design, it is vital to clearly formulate the problem prior to attempting to solve it. This is no different to the case of the vertical transportation problem.

The vertical transportation problem can be summarised as the requirement to move a specific number of passengers from their origin floors to their respective destination floors with the minimum amount of waiting and travelling time, using the minimum number of elevators, core space, cost and using the smallest amount of energy.
The aim of elevator traffic engineering is to achieve a compromise between cost and performance. A number of parameters have to be optimised such as the average passenger waiting time, the average passenger travelling time and the energy consumed by the elevators. The used core space must also be minimised in the building, in order not to take up valuable net usable area. The solution of the vertical transportation problem identifies the number of the elevators to be used (as well as their rated speed and rated capacity) in the building in order to achieve the required performance. In effect, the vertical transportation problem is a multiple-constraint-multiple-objective problem that aims to produce a solution that is:

1. Functional.
2. Safe.
3. Reliable.
4. Cost effective.
5. Meets the passenger performance requirements (waiting time and travelling time).
6. Uses the smallest possible core space of the building.
7. Energy efficient.

In order to solve the problem, it is necessary to identify demand and supply. Demand is represented by the arrival of passengers for service. Supply is represented by the number of elevators, their rated speed and rated capacity.

4.0 THE CORE SPACE AND THE LOSS OF NET AREA
The elevator shaft is a vertical space within the core of the building that contains the cars and the counterweights of the elevator cars, as well as the landing doors and any ancillary equipment. In addition to the core space that each elevator takes up, the elevator system requires lobby space to provide an area for passengers to wait for the next elevator and to access the elevator when it arrives.

This core space (shaft space and lobby space) is a cost to the building developer, due to the loss of net-useable area. This loss in net area is repeated on every floor. One of the main aims of elevator system design is to minimise this space by finding the optimum number of elevators required for an optimum design.

5.0 PEAKS IN DEMAND FOR SERVICES AND PRODUCTS
As is the case with many other services, demand for elevator service is usually irregular, peaky, random and time dependent. This presents a problem for the designer of the elevator system.

There are examples of peaks in the demand from other industries.

1. Fireworks: The demand for fireworks varies annually and peaks in the United Kingdom in November every year (bonfire night).

2. Electrical Supply: The demand for electricity follows a daily cycle, and usually peaks in the evenings just after sunset (especially in the winter) when people get back to their homes and turn the lighting and the electrical heating on. This represents a challenge for the electricity generating companies who have to meet the heavy demand during the peak, with other times during the day experiencing much lower demand (e.g., 3 a.m.). The cost of meeting this
peak is very high as it requires extra generation capacity, which is not fully utilised during non-peak times.

3. **Public Transportation**: The demand for public transportation systems also peaks in the morning rush hour (07:30-09:30) and the evening rush hour (16:30-18:30) where large numbers of passengers require the use of the trains, metros and buses.

A similar pattern of variable demand with peaks and troughs can be seen in many other service industries (e.g., call centres; post offices; restaurants, telephone services). The cycles can be daily, monthly or yearly.

The peaks in demand are a major challenge for the service providers, as they would have to provide extra capacity (and the associated infrastructure) in order to meet the peak in demand, which is very costly.

One possible strategy is to try to manage demand by removing the peaks. Suppliers try to find ways of levelling the demand (i.e., move some of the demand from the peaks to the troughs). This can be done for example by providing financial incentives for users to use the service during the troughs in demand. For example, electricity providers design tariff structures that offer electricity at lower prices during low demand periods and at higher prices during peak demand periods. Another example is where public transportation providers offer cheaper off-peak train fares, or even different fares for different times of the day or the year.

Another possible strategy to meet the peaks in demand is to employ extra capacity during the peaks, such as bringing in extra part time staff during the peaks for a restaurant.

Nevertheless, there will remain peaks in the demand and suppliers have to be able to meet this demand. Designers have to design systems that can meet these expected peaks in demand.

Elevator systems are designed based on the peak of the demand. The demand for the elevator service is a daily cycle. For office buildings, it usually peaks at the start of working day (for example, 08:00) when workers arrive for work. A significant peak in demand usually takes place in buildings that have a fixed starting time, and is less dominant in buildings that have a flexible starting time.

In the following sections, the method of assessing the passenger demand in a building will be introduced. This will form the basis for the elevator traffic design process.

### 6.0 ASSESSING THE DEMAND

Prior to designing the elevator system, it is necessary to assess the demand. Passenger demand is driven by four elements:

1. **Building Population**: This is the total number of persons in the building, denoted as $U$.

2. **Arrival rate**: This is represented by the peak in the arrival rate of passengers, denoted as $AR\%$.

3. **Traffic-Mix**: This is the traffic-mix that exists in the building at any one point in time. In general, the traffic could comprise a mix of incoming, outgoing and inter-floor traffic.
4. The stochastic passenger arrival model: This is the process by which passengers arrive for service. It can be either assumed to be a constant arrival process or a random arrival process. The randomness in the passenger arrival places extra demand on the elevator system.

These four drivers are discussed in more detail in the next four sub-sections.

6.1 The Arrival Rate (AR%)
The demand is driven by the passenger arrival process. The peak passenger arrival is used as the basis for quantifying the demand.

6.1.1 The Five Minute Basis for the Arrival Rate
The demand for any service can be based on the peak arrival rate during the busiest one minute in the day, the peak five minutes during the day or the peak 15 minutes during the day. Using the one minute as a time base is the most onerous; using the 15 minute time base is the least onerous.

Using the 15 minute arrival rate as the basis will reduce the demand on the system and hence allow a cheaper system. However, the quality of service will suffer (e.g., the average waiting time that the passengers experience will increase unacceptably). Using the one minute equivalent arrival rate as a basis will increase the cost of the elevator system unnecessarily. The convention in elevator system traffic design has been to use five minutes as the time base.

6.1.2 Normalisation
Thus the demand is measured in unit of passengers arriving in the busiest 5 minutes (300 second) period. In order to normalise this figure, it is usual to divide it by the total building population and express it as a percentage. This is called the arrival rate and is denoted as AR%. It is the percentage of the building population arriving in the lobby for elevator service during the busiest five minutes during the day. It is used as an indicator for the quantity of service.

This concept of normalisation is used in other disciplines. For example the per capita income is an indicator of the standard of living in a country and is evaluated by dividing the Gross Domestic Product (GDP) by the population. The per capita income can be used to compare the standard of living between different countries.

6.1.3 Dependence of the Arrival Rate on the Building Function
The advantage of normalising the arrival rate by dividing the number of passenger arrivals in five minutes by the building population is that it allows the use of general rules of thumb regarding the expected arrival rate in a building by the function of the building. These suggested function based arrival rates have been based on years of experience. The following is a list of different functions for buildings:

1. Offices.
2. Residential.
3. Hotels.
4. Hospitals.
5. Shopping centres and malls.
6. Car parks.
7. Theatres.
8. Stadia.
9. Educational buildings (e.g., university lecture room buildings).
10. Railway stations and airport (referred to using the generic terms: public transport terminals).
13. Factories.

For each of these types of buildings, there are typical arrival rate percentages. For example, a typical arrival rate for office buildings is between 12% to 17% depending on whether the building is a multiple tenancy building (the lower end of the range of $AR\%$) or a single tenancy building (the upper end of the range of the $AR\%$). The actual value also depends on whether starting times are fixed or flexible and the presence of a significant number of hot desks.

Typical values for residential buildings range from 5% to 7%. The arrival rate for hotels ranges from 10% to 15%, where the peak usually takes place during the morning period around breakfast time (when some passengers are heading for breakfast and others are checking out). More details about suggested values for arrival rates for different types of building can be found in CIBSE Guide D, section 3 [2].

Some buildings will exhibit very strong peaks, such as educational buildings (between lectures), stadia (at the end of the game) and theatres (during the interval break). Other buildings have complex and different modes of traffic, such as hospitals and hotels. Viewing towers are very peculiar in that they only have two stops and thus act as shuttles for visitors from the ground floor to the top of the tower.

6.1.4 Finding the Arrival Rate from Surveys
The previous section provided a methodology for assessing the demand for a future building. However, for an existing building, is it also possible to assess the passenger demand, by carrying out a survey to measure the arrival rate. This is sometimes necessary in order to understand the reasons for inadequate elevator traffic service performance.

A chart showing typical passenger arrivals in a lobby is shown in Figure 1. It shows a minute-based-survey of passengers arriving in the lobby. The $x$-axis (abscissa) has units of time, gradated in minutes. The $y$-axis (ordinate) is the number of passenger arrivals. Each bar represents the number of the passengers arriving in each minute. In order to find the peak arrival in five minutes, a 5 minute wide window is slid horizontally. The window is stopped at the position that produces the maximum total number of passengers in five minutes. The window is shown in Figure 1 placed in the position that produces the largest number of passengers arriving in five-minutes.
Based on the survey results, it is possible to quantify the arrival rate ($AR\%$). Once the maximum number of passengers arriving in five minutes has been found using the sliding window tool, this yields the number of passengers per five minutes. In order to normalise it, this number must be divided by the total building population, $U$.

$$AR\% = \frac{P_{5\min}}{U}$$

Where:
- $AR\%$ is the arrival rate expressed as a percentage of the building population arriving in the busiest five minutes
- $P_{5\min}$ is the number passengers arriving in the busiest five minutes expressed in units of passengers per five minutes
- $U$ is the total building population in persons

**Demand can be assessed independently of supply**

It is important to note that the passenger arrivals are independent of the elevator system. Passenger demand can be assessed and quantified regardless of the presence or otherwise of an elevator system that is capable of serving it.

The following two examples reinforce the concept of finding the arrival rate from the one minute survey.

**Example 1**
The results from an arrival survey carried out at the reception entrance of an office building are shown below. Assuming that the total building population is 500 persons, assess the passenger demand by evaluating the arrival rate ($AR\%$).
Using a five-minute wide sliding window and moving it over the data in the table above, it can be found that the maximum number of passengers arriving in a consecutive five-minute period occurs between 08:05 and 08:09, with a total number of passengers arriving totalling 78 passengers (10+14+24+18+12).

Dividing this number by the total building population of 500 persons, gives an arrival rate ($AR\%$) of 15.6%.

**Example 2**

Results from an arrival survey in an office building are shown below. If the total population of the building is 1500 persons, find the peak arrival rate in percentage population per 5 minutes (i.e., $AR\%$).

The arrivals per minute have been plotted in the form of a bar chart in Figure 2 below. It can be seen that using a sliding window shows that the peak five-minute demand occurs between 07:37 and 07:41. The total number of passengers arriving during this five-minute period is 183 passengers per five minutes. Dividing this
number by the total building population of 1500 persons gives an arrival rate \( AR\% \) of 12.2%.

\[
\lambda = \frac{AR\% \cdot U}{300}
\]  

Where:
- \( U \) is the total building population in persons
- \( AR\% \) is the arrival rate in five minutes expressed as a percentage of the building population
- 300 represents 300 seconds per five-minutes and is used to convert the units
- \( \lambda \) is the passenger arrival rates in units of passengers per second

**6.2 The building population, \( U \)**

Another driver of the passenger demand is the building population. The assessment of the potential building population (denoted as \( U \)) is based on the net floor area for office buildings.

Net area is the area that the building owner can let to the user and represents useful space to the tenant. It usually includes spaces such as closed offices, open plan offices, meeting rooms, meeting areas as well as restaurants and cafeterias. It excludes core areas such as those used for elevators and stairs, plant areas

**Figure 2:** A bar chart plot of the passenger arrivals for example 2.
(machine room areas for electromechanical services) and toilets. As a general rule of thumb net area to gross area ratio can vary from 85% for a low rise building down to 65% for a tall slender building.

In residential buildings and hotels, the building population is usually based on the number of rooms (bedrooms in the case of residential buildings).

More details about assessing the building population can be found in chapter 3 of CIBSE Guide D [2].

6.3 Traffic Mix
The third driver of passenger demand is the type of traffic. In order to define the mix of traffic in a building, it is first necessary to classify the types of floors.

6.3.1 Types of floors
It is necessary at this point to set the convention for the different types of floors. There are two types of floors in any building: occupant floors and entrance/exit floors. It is assumed that the building is sub-divided into groups of floors: exit/entrance floors and occupant floors.

An exit/entrance floor is a floor that allows passengers to enter or exit the building. Most buildings have one exit/entrance floor, but other buildings might have multiple entrances. Some reasons for having multiple entrances are the presence of underground car parks, entrances at different street levels due to sloping ground landscape, adjacent buildings or railway stations. It usually assumed that no population exists on the entrance/exit floors.

An occupant floor is a floor where passengers spend their time within the building, such as office floors in an office building. Passengers are not able to leave or enter the building via an occupant floor.

Figure 3 shows an overview of a building that has a single entrance/exit floor and seven occupant floors.
Figure 3: Overview of a building, showing entrance/exit floors and occupant floors.

Figure 4 and Figure 5 show examples of two buildings that have multiple entrances, namely two entrances from two different levels caused by sloping landscape, or underground car parks (respectively).

Figure 4: Overview of a building showing entrance/exit floors and occupant floors.
Figure 5: Overview of a building with multiple entrances from an underground car park.

Figure 6 shows an overview of a building that has a restaurant floor on the top floor. Strictly speaking, and in accordance with the definitions of the types of floors presented earlier, this is an occupant floor as passengers do not leave the building when they go to the restaurant. However, some designers treat such a floor as an entrance/exit floor.
6.3.2 Types of Traffic
Having defined the types of floors, it is possible now to define the different types of possible journeys in a building.

Passenger journeys that start at an exit/entrance floor and terminate at an occupant floor are classified as incoming traffic. Passenger journeys that start at an occupant floor and terminate at an exit/entrance floor are classified as out-going traffic. Passenger journeys that start and terminate at occupant floors are classified as inter-floor traffic. Passenger journeys that start and terminate at entrance/exit floors are illogical/irrational journeys and are thus effectively disallowed and will not be considered any further.

The four types of traffic are further clarified in the 2 by 2 array shown in Table 1 and in Figure 7.

Table 1: Definition of the types of journeys based on the type of origin and destination floors.

<table>
<thead>
<tr>
<th>Start/Origin of the passenger journey</th>
<th>End/Destination of the Passenger Journey</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Occupant Floor</td>
</tr>
<tr>
<td>Occupant Floor</td>
<td>Inter-floor Traffic</td>
</tr>
<tr>
<td>Exit/Entrance Floor</td>
<td>Incoming Traffic</td>
</tr>
</tbody>
</table>
Surveys have shown that the prevailing traffic during different times of the day in an office building comprises a specific mix of the modes of traffic. Examples of traffic mix conditions include: 40%:40%:20% [1]; 45%:45%:10% [2]; 42%, 42%, 16% [3]; incoming, outgoing and inter-floor traffic, respectively. Such traffic mix ratios are believed to be representative of the lunch-time peak traffic conditions in many modern office buildings. Surveys have been carried out in buildings in order to further quantify the current trend in prevailing traffic mixes during the day [5].

6.4 Stochastic Passenger Arrival Process
The fourth driving factor to consider when assessing demand is the nature of the passenger arrival model. It is well known that the passenger arrival process is a random process. However, simplifications are often made in the design process. This section outlines the three most widely used models in the elevator traffic design process.

1. Constant inter-arrival time: This is a simplification of the passenger arrival process. It is assumed that the time between the arrivals of consecutive passengers is constant (i.e., deterministic rather than random). The inter-arrival time (i.e., the time between the arrivals of consecutive passengers) can be calculated using the equation shown below:

\[ \Delta t = \frac{1}{\lambda} \]  

..........(3)

Where:
\( \Delta t \) is the inter-arrival time between two consecutive passengers in s

\( \lambda \) the passenger arrival rate in passengers per second

A diagrammatic representation of passenger arrivals against time under a constant inter-arrival time process is shown in Figure 8. As the arrival rate is 0.2 passengers per second, then the inter-arrival time is 5 seconds (i.e., reciprocal of the passenger arrival rate).

2. Random Inter-arrival time with a uniform probability density function: This is another simplification of the passenger arrival process, but assumes that the inter-arrival time is random. It assumes that the inter-arrival time follows a uniform distribution (rectangular probability density function, pdf). The value of the inter-arrival time has an average value of \( \frac{1}{\lambda} \) and varies between 0 seconds and the twice the average value \( \frac{2}{\lambda} \). The Uniform probability density function for a passenger arrival rate of 0.2 passengers per second is shown in Figure 9. It is worth nothing that the height of the rectangle is 0.1, so that the total area under the curve is 1.
The value of an inter-arrival sample time can be evaluated using the equation below.

$$\Delta t = \frac{2 \cdot \text{Rand()} }{\lambda} \quad ........(4)$$

Where:
- $\Delta t$ is the inter-arrival time between two consecutive passengers in seconds
- $\lambda$ the passenger arrival rate in passengers per second
- $\text{Rand()}$ is a function that generates a uniformly distributed random number between 0 and 1

An example of a number of passenger arrivals generated using a uniform pdf with an average of 5 seconds ($\frac{1}{\lambda}$) is shown in Figure 8.
3. **Random Inter-arrival time with an exponential probability density function**: The most widely accepted passenger arrival model is the Poisson process [4]. This assumes that the number of passengers arriving in a period of time follows a Poisson distribution. This is equivalent to saying that the inter-arrival time between consecutive passengers follows an exponential distribution.

The exponential probability density function for the inter-arrival time is shown in Figure 11.
Figure 11: Exponential pdf for the inter-arrival time (for a Poisson passenger arrival process).

The inter-arrival time can be generated using the equation shown below:

\[
\Delta t = \frac{-\ln(1 - Rand(\ ))}{\lambda}
\] ...........(5)

Where:
\( \Delta t \) is the inter-arrival time between two consecutive passengers in s
\( \ln \) is the natural logarithm (base e logarithm)
\( \lambda \) the passenger arrival rate in passengers per second
\( Rand() \) is a random number between 0 and 1

An example of a number of passenger arrivals generated using an exponential probability density function for the inter-arrival time with an average of 5 seconds \((1/0.2)\) is shown in Figure 8.
Demand vs Supply

This article has outlined the driving factors for assessing demand. This has been done independently from the selected elevator system use to meet such demand. The next article will start considering the system that can meet such demand.

REFERENCES


