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Capacity Analysis of Escalators Installed At Metro Rail Stations in India

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Abstract

Cities in developing countries like India are evolving, where emphasis in transport sector is on provision of public transport systems. Associated feature to such provision is the provision of stations and terminals. One of the mechanism of crowd (here pedestrians) management is through properly located pedestrian facilities having adequate capacity. In and out movement of pedestrians at such locations is through stairs, ramps and escalators. This paper presents the academic research work that is taken up in Delhi, India with respect to the analysis of capacity of escalators installed at Delhi Metro Rail stations. All such analysis need flow characteristics data which is extracted from the video recorded at the site. Pedestrian flow data (peak and average) is extracted for 10s, 30s and 1 min time interval. Escalator flow capacity analysis is carried out regarding theoretical, operational and actual capacity. Analysis indicated that HCM concept can be discarded for developing countries on account of lesser gaps being maintained by the pedestrians while moving. Fruin's and Indo-HCM concept can be used for such analysis. The operational capacity is found to be lower than theoretical capacity, and actual capacity is found to be less than 42% of the theoretical capacity. It is suggested to study actual capacity as a part of operational capacity instead of theoretical capacity. The study provides design inputs to the practitioners working in this field.

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Keywords: pedestrian; escalator; data extraction time interval; pedestrian flow; capacity

1. Introduction

Study of pedestrian flow characteristics and capacity analysis of pedestrian facilities are the key tools in the planning and designing of pedestrian facilities. The decision on location and orientation of these facilities depends up

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on the relative pedestrian flow or demand and the capacity of the pedestrian facility. The facility requirement within a building and outside a building are totally different. Sidewalks and crosswalks are provided outside the building to connect different locations, whereas, within building these may be stairs, ramps and escalators. Escalators are mechanized systems and provide connectivity between floor levels. Escalators are roller based wherein a steel step moves up or down at a constant speed. A pedestrian has to stand on the steel step and hold the side rail carefully. Basic aim of providing such mechanized system is to reduce the pedestrian effort needed to climb the stairs, especially while carrying a baggage or a child in arms, and to increase the pedestrian handling capacity of the area. Data is needed to understand the pedestrian dynamics and facility mechanics so that these facilities are utilized in the most optimized manner. It has been observed that the literature available, in the context of developing countries, on capacity of these facilities is quite limited and insufficient. Improper planning for the provision of these facilities in a building adds to the chaotic pedestrian flows and congestion on these facilities. Design guidelines are also not available and the ones being followed are usually borrowed from the developed countries. The difference in the directional flow pattern being adopted in developing countries like India and developed countries like USA is mostly not accounted for while making provision of these facilities in the buildings. This further adds to the confusion and chaos in the approach area of the escalators. Another dimension is the way escalator is being used. Developed countries like United Kingdom (London underground) and Belgium follow escalator etiquette as “stand right” and “walk left”, whereas, countries like Australia, Japan and New Zealand follow the rule “stand left” and “walk right” (www.travelinsurancedirect.com). In developing countries like India no such rules are defined and hence the pedestrian movement on the escalators is random. Even “all standing “and “all walking” rules are also not followed. Based on the need of the hour, the pedestrians start walking on the escalators while finding path in zig-zag manner at the front. In this regard, pedestrian flow and capacity analysis on these facilities will not only help in understanding the pedestrian flow patterns and behavior but will also help in understanding its influence on the capacity of the facility, safety issues and flow regulations under emergent conditions.

Best locations to study the above-mentioned aspects on escalators are shopping malls, public transit stations, long distance railway stations and pedestrian subways or foot over bridges. At all such locations, the escalators are used by lots of pedestrians on regular basis, though the pedestrian volume varies with time in a day. The use of such mechanised systems need a bit of experience regarding how to step-in on an escalator or step-out of the escalator. In India even after decades of implementation of escalator systems at public places many people are still not familiar or confident with the use of escalators. Such pedestrian categories may be children, woman, senior citizens, and occasional visitors, persons with some particular Indian wearing, persons with disability and persons carrying baggage. These factors are not applicable in developed countries as population gets used to these facilities from an early age and provisions are made to cater to the needs of all categories of pedestrians

In the light of the above information, an academic study was carried out to understand the pedestrian flow characteristics and estimate the pedestrian handling capacity of escalators. At present insufficient information is available on these aspects in developing countries like India. There is also a need to differentiate the practical handling capacity from the theoretical capacity of the escalators. Such studies will help in providing some guidelines on the provision of escalators in buildings, their size, location and orientation. This will also ensure the safety and security of pedestrians in normal and emergent conditions at such locations along with easing out the congestion and chaotic condition in front of these facilities. This paper specifically discusses the capacity aspect of escalators.

Literature on this aspect is presented in the next section.

2. Literature Review

Few studies have been reported/are available on escalators even though Fruin (1987) introduced the concept of escalator capacity about 30 years ago. Fruin (1987) discussed the concept of human body ellipse and its relation to the human personal space. He discussed the empty steps phenomenon, according to which the escalator capacity is never higher than the theoretical capacity even in the heaviest pedestrian traffic. It is due to the agilest commuters due to which empty steps appear which reduces the overall capacity of the escalators. He also explained the pedestrians’ sub-optimizing behaviour. In system optimization, the pedestrians should stand closer to each other so that capacity is fully utilised. In user optimization, the pedestrians occupy spaces as per their comfort level. This phenomenon concludes that user optimization never leads to the system optimization. Mayo (1966) developed multiple regression equations for capacity estimation using variables like escalator speed, vertical rise and traffic flow. He developed relationships for estimating maximum capacity and mean capacity as:

$$C_{max} = 1.329s - 0.0055s^2 - 0.875h + 0.0112t + 0.0075hs - 11.20 \quad (1)$$
$$C_{mean} = 1.553s - 0.0059s^2 - 0.265h + 0.0163t + 0.032hs - 68.33 \quad (2)$$

Where, s = escalator speed (feet/m)
h = vertical rise (feet)
t = traffic flow (passenger/hr)

It is observed that pedestrians stand close together on slow-moving escalators and highest capacity is observed under unrestricted or open approaches. Al-Sharif (1996) discussed Fruin's (1987) concept of the human ellipse and found that escalator theoretical capacity is not achieved due to the human buffer zone, which is greater than the effective step dimensions. Davis and Dutta (2010) developed a model by separating the capacities of standing and walking side of the escalator. They developed multiple regression model to examine the effect of rise of the escalator on the capacity of that escalator. According to them, maximum capacity of the escalator can be estimated as:

$$C_{max} = 65.8675 + 0.2125h + 0.0112t \quad (3)$$

Where, h = vertical rise (feet)
t = traffic flow (passenger/hr)

This study is carried out on escalators moving with constant speed.

Bodendorf et *al*. (2014) conducted field studies on escalator capacity at railway station and shopping centres. They found that overall flow value of the escalator depends upon the time interval that is used for the extraction of the mean flow and suggested that the highest capacity on an escalator at a railway station occurs when data extraction time interval is taken as 10s. According to them, further field studies are required to evaluate the best time interval that can represent the capacity of the escalator at different locations. Kauffmann and Kikuchi (2013) developed a model to calculate the practical capacity of the escalators using simulation that is based on pedestrian behavioural rule. According to them, Highway Capacity Manual (2010) and the Transportation Planning Handbook (Goodman, 1992) have not provided any reference to the escalator capacity, except the basic tables which show the relationship between speed and capacity. They considered capacity, density and queue length as three parallel performance metrics which should be included in the design of an escalator. Using rule-based model and Kauffmann model (2011), they found that the practical capacity of escalators in shopping malls (commercial facility) is significantly lower than the maximum capacity of escalators in transit stations (commuter facility). The developed Kauffmann model shows that the prohibition of walking on the escalators can streamline operations under emergency conditions because it reduces variability and increases flow, particularly during peak periods. They found that upward flow on escalator operates at a lower capacity than downward flow due to the presence of facial ellipse (region in front of the pedestrian face). Li and Li (2014) found that the peak escalator passenger capacity is 87 percent of its theoretical capacity.

Table1 compiles the work done by different researchers on the capacity of the escalator.

Table 1 Capacity of the escalator reported in different studies

Researcher (Year)	Country	Escalator Data	Capacity
Oeding (1963)	Germany	Speed NA	Max: 70 to 80 persons/min
Mayo (1966)	London	1000 mm step width Speed 0.75 m/s	Max: 135 passenger/min
Fruin (1987)	United States	1016 mm step width Speed 0.61 m/s Speed 0.75 m/s	Observed Capacity: 90 persons/min 111 persons/min
Weidmann (1993)	Germany	1000 mm step width Speed 0.5 m/s	Practical: 75 persons/min; 50% of theoretical
Al-Sharif (1996)	London	30 degree up & down 1000 mm step width Speed 0.75 m/s	Max: 124 passenger/min; 55% of theoretical Actual capacity: 94 pass/min Effective capacity: 134 pass/min

Lam and Cheung (2000)	Hong Kong	up & down 1000 mm step width	MTR[1]: 120peds/esc/min (obs Max) KCR[1†]: 118peds/esc/min (obs Max)
BS 5656-2:2004 (2004)	London	1000 mm step width Speed 0.5 m/s	Practical: 75 persons/min
Schindler (2007)		1000 mm step width Speed 0.5 m/s	Practical: 75 persons/min
Xiang et *al*. (2011)	Singapore	Speed 0.75 m/s	120 pedestrians/min
Nai et *al.* (2012)	Shanghai	1000 mm step width Speed 0.61 m/s	Max: 135 pedestrian/min (both) 85 pedestrian/min (Esc & Stair)
Bodendorf et *al*. (2014)	Germany	up & down Speed 0.5 m/s	Railway station (Max): 103.77 persons/min (up) 107.72 persons/min (down) Shopping centre (Max): 91.50 persons/min (both)
Li and Li (2014)	Hohhot, Inner Mangolia	1200 mm step width Speed 0.626 m/s	Max: 136 p/min (ladder section) Max: 145 p/min (entrance section) Theoretical: 157 p/min
Sala and Ravishankar (2016)	India	1000 mm step width Speed 0.50 m/s	30 ped/m/min to 40 ped/m/min
Patra et *al*. (2017)	India	1100 mm step width Speed NA	Obs Max: 38 ped/m/min

In India, the theoretical capacity values are given by National Building Code of India (SP 7:2005). These are dependent upon the width of the step and the speed of escalators. Pedestrian density per step is taken as 1.0, 1.5 and 2.0 with respect to the varying step width respectively. As the width of the step increase from 0.6 m to 0.8 m the capacity value increases by 1.5 times for all the possible speeds of an escalator. Further change to 1.0 m increases the capacity by 2 times of basic. Similarly, an increase in the escalator speed from 0.5 m/s to 0.65 m/s increases the capacity by 1.3 times irrespective to the width of the step of escalator. Further increase in escalator speed to 0.75 m/s causes increase in capacity by 1.5 times of basic. The theoretical or operational capacity of escalator for different speed of escalators, as reported in the literature, are given in Table 2.

Table 2: Theoretical /Practical capacity of escalators operating with different speeds

Step Width (m)	Theoretical / Practical Capacity (Persons/hours)		
	u = 0.5 m/s speed	0.65 m/s speed	0.75 m/s speed
NBC, (SP 7:2005, 21)[2‡]			
0.6	4500	5850	6750
0.8	6750	8775	10125
1.0	9000	11700	13500
Schindler (2007), 16	6000	7302	-
OTIS, 22	6300	7605	8100
DIN EN 115-1:2010-06, 23	6000	7300	8200
BS 5656-2:2004, 15	4500	8778	6750

Literature indicates that the studies on escalator capacity and pedestrian flows on these facilities have been mostly reported from developed countries where the escalators have both standing and walking side. It means the pedestrians should stand on one particular side (left or right) of the escalator and leave the other side (right or left) for walking (on moving escalators). This way the escalator gets virtually separated so that half portion is reserved for standing pedestrians and half is reserved for walking pedestrians. But in the case of standing escalators, as being followed in India, no escalator etiquette is being followed. In developing countries, the escalators are by default considered as standing escalators i.e. every person should stand and not walk on the escalator. But a random movement is observed as defined before, wherein some pedestrians start walking on the escalator either initially after getting-in on the escalator or someway in between or towards the end. Some pedestrians walk continuously or start moving fast (almost

† [1] MTR: Mass transit railway, KCR: Kowloon- Canton railway
‡ [2]Theoretical Capacity; Others have given practical capacity

running). Such haphazard movements may also result in injuries which becomes significant due to mechanical system. Further, users in India are not much familiar with the use of escalators. This causes a time lag in getting-in on to the escalator or while getting-out of the escalator, which further impacts the pedestrian handling capacity of the escalators. Under such flow conditions the operation of the escalators becomes inefficient, uneconomical and underutilised.

Researchers have defined capacity of escalators in different forms. In general, the capacity is defined as the number of pedestrians who use the escalator in a unit time frame. Some researchers have discussed theoretical capacity along with highest practical capacity which has been observed on an escalator. Theoretical capacity is based on ideal assumptions like maximum occupancy of a stair, constant speed of escalator, whereas, highest practical capacity is a result of field conditions prevailing at the time of data collection and relates to time interval of data extraction. The capacity is influenced by the width of the step as it impacts occupancy. Researchers have also examined the actual flow being observed on the escalators.

In view of the above discussion following needs to be studied with respect to the use of the escalators, especially in a developing country like India:

a. Estimation of the theoretical, operational and actual pedestrian capacity of an escalator, and examining the relationship between them.
b. Examining the effect of walking pedestrians, hesitation of use and mix of pedestrian population on the actual pedestrian flow handling capacity of the escalator

The focus of this paper is on estimation of capacity of escalators. The information on effect of walking pedestrians, hesitation to use and pedestrian population mix on escalator capacity are not discussed in this paper as these are under analysis.

Next section now discusses the study locations from where the required data are collected.

3. Study Locations Selected

Stations of Delhi Metro Rail system are selected as the study locations to collect data on pedestrian flows at escalators. Delhi Metro is the world's 12^{th} longest metro rail system and 16^{th} highest in ridership. In the financial year 2016-17, Delhi Metro Rail catered to an average daily ridership of 2.76 million passengers and served 1000 million riders in total during the year. Depending upon the area restrictions, the stations have been constructed either at ground level or underground or in elevated form. The inflow and outflow of the passengers to/from station is made possible through different types of pedestrian facilities like stairs, escalators and ramps. These facilities are located either as individual entity or side by side to each other or at a distance apart. The Delhi Metro Rail network is shown in Figure 1.

Delhi metro rail caters to the population of Delhi and National Capital Region (NCR), which consist of the townships around Delhi. The whole network comprises of seven lines which are identifiable based on colour. These are – Blue, Green, Red, Orange, Violet, Yellow and Pink. Out of the seven lines, the metro rail stations on Yellow Line are selected. This line is 48.8 kilometres long and had an average daily ridership of 813,256 passengers in year 2015. This line passes through one of the most congested parts of Delhi (en.wikipedia.org). It is the second longest metro line on the Delhi Metro rail network. In general, stations on this line are considered as the crowded metro rail stations.

Three metro rail stations are selected on Yellow line. These are:

a) Rajiv Chowk (RCM) metro rail station – It caters to around 0.5 million travellers each day. It is a transfer station between yellow and blue line.
b) Kashmiri Gate metro (KGM) rail station – It is currently the largest metro rail station within the Delhi metro rail system. This station has 3 line interchange i.e. for yellow, red and pink line.
c) Central Secretariat metro (CSM) rail station - This is a terminal and transfer station. Violet and yellow line crosses each other at this station.

The access/egress condition on platforms at these stations are shown in Figure 2 and operational characteristics of these escalators are given in Table 3.

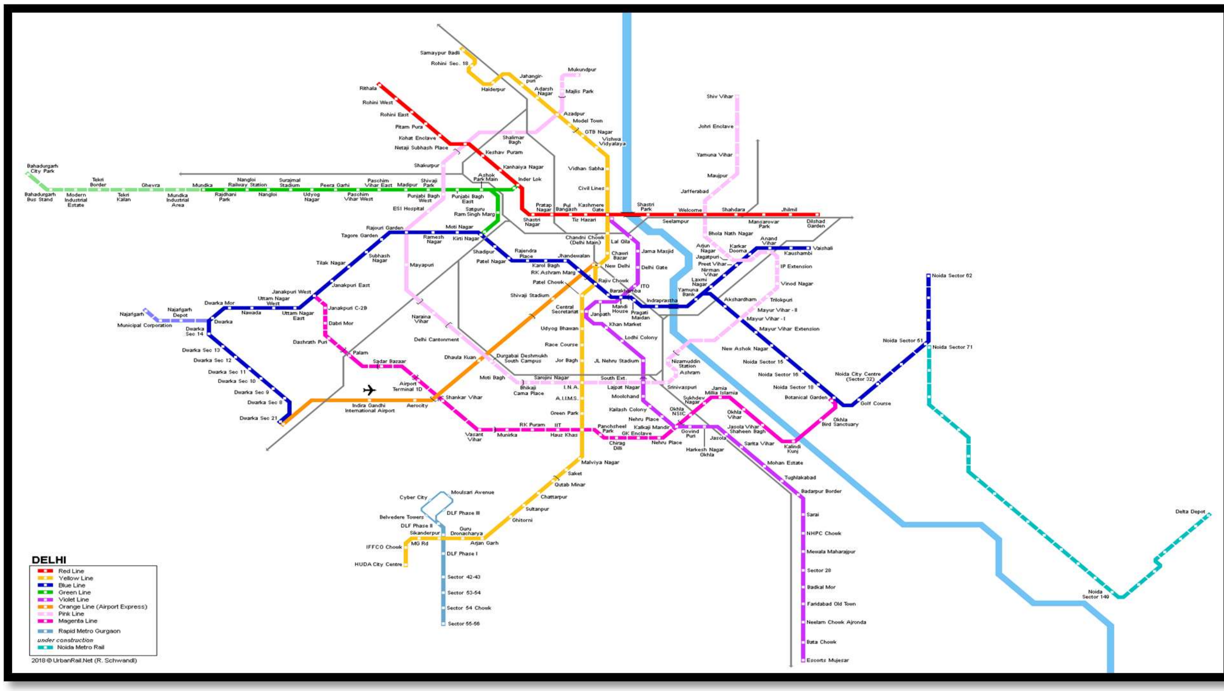

FIGURE 1 Map of Delhi metro rail network (Source: www.urbanrail.net)

(a) (b) (c) (d)

(e) (f) (g) (h)

FIGURE 2: Selected escalators at different metro stations: (a) & (b) CSM Station; (c) & (d) RCM Station; (e) to (h) KGM Station (2 escalators)

Table 3: Operational characteristics of escalators at selected metro rail stations

Sl. No.	Station Name	Escalator Operation	Presence of Stairs alongside Escalator	Station entry with respect to platform	Morning flow (ped/m/hr)	Evening flow (ped/m/hr)
1	CSM Station	One up moving	Yes	Upper level	1985	2109
2	RCM Station	Three parallel up moving	No	Upper level	11302	9340
3	KGM-1[3] Station	One up moving escalator	Yes	Upper level	1995	3654
4	KGM-2[3§] Station	One up and one down moving	Yes	Upper level	6102	7157

Certain operational characteristics of the escalators are common at all the metro rail stations in Delhi. These are:

i) Width of escalator : 1000 mm
ii) Depth of step on escalator : 400 mm
iii) Angle of escalator path : 30°
iv) Speed of movement : 0.65 m/s
v) Level difference between floors : 7200 mm

The operation of escalators in up and down direction at Delhi Metro Rail stations is found to be in a ratio of 4:1 respectively. Up moving escalators are usually provided with stairs alongside which mainly cater for downward movement. At few locations at these metro rail stations, the escalators are operated side by side for up and down movements of the pedestrians. The idea behind such an arrangement is that the platforms should get cleared in a minimum time period after the travellers alight from the arriving train or are proceeding towards the train. In most of such cases, the arrival frequency of trains is quite high or the headway is almost minimum possible. Therefore provision of escalators facilitates smooth pedestrian discharge from the platform. The up moving escalators reduces the human energy required to scale the floor level difference.

Next section now presents the data collection effort and the process adopted to extract the desired information to arrive at the pedestrian flow capacity of the escalators.

4. Data Collection and Extraction

Pedestrian flow data are collected through video graphic survey as manual method of data collection on an escalator is not easy and accurate. Before video graphic survey, permission is taken from Delhi Metro Rail Corporation (DMRC, www.delhimetrorail.com), the governing agency. Video are recorded and other required data are collected during July 2016, between 8:00 am to 10:00 am and 4:00 pm to 6:00 pm. These periods include morning and evening peak respectively. To capture the same pedestrian movement at both entry and exit on the particular escalators, two cameras are installed at the study location. One camera is fixed at upper level and other one is fixed at lower level in front of the facility to cover the required stretch. Required pedestrian flow related information are extracted manually by playing the recorded video frame by frame. A trap is marked on the escalator and flow data are calculated by counting

[§] [3] KGM-1 and KGM-2 are two escalator locations being studied at same station.

the total number of pedestrians passing that trap section during required time period. Based on the literature, the flow related information on the escalator is extracted using three time intervals as 10s, 30s and 1 min. These are expected to provide insights on impact of time interval on capacity of the escalator.

Flow values in ped/m/min are calculated using a time conversion factor related to the selected three time intervals which are used for data extraction. The width of the escalator is 1000 mm which is constant. Table 4 to 7 presents the average and peak pedestrian flows on escalators at the three metro rail stations for the three time intervals used for data extraction.

Table 4: Pedestrian flows at RCM station

Sl. No.	Data extraction time period	Average pedestrian flow		Peak pedestrian flow	
		p/m/min	p/m/hr	p/m/min	p/m/hr
Morning Data					
1	10 sec	56.10	3365	138	8280
2	30 sec	56.10	3365	132	7920
3	1 min	56.25	3375	111	6660
Evening Data					
1	10 sec	37.61	2257	156	9360
2	30 sec	37.61	2257	140	8400
3	1 min	37.67	2260	123	7380

Table 5: Pedestrian flows at CSM station

Sl. No.	Data extraction time period	Average pedestrian flow		Peak pedestrian flow	
		p/m/min	p/m/hr	p/m/min	p/m/hr
Morning Data					
1	10 sec	48.33	2900	138	8280
2	30 sec	48.33	2900	126	7560
3	1 min	48.33	2900	120	7200
Evening Data					
1	10 sec	49.12	2947	138	8280
2	30 sec	48.19	2890	128	7680
3	1 min	49.19	2950	116	6960

Table 6: Pedestrian flows at KGM station 1

Sl. No.	Data extraction time period	Average pedestrian flow		Peak pedestrian flow	
		p/m/min	p/m/hr	p/m/min	p/m/hr
Morning Data					
1	10 sec	36.31	2180	120	7200
2	30 sec	36.42	2185	104	6240
3	1 min	36.42	2185	97	5820
Evening Data					
1	10 sec	59.99	3600	132	7920
2	30 sec	60.08	3605	126	7560
3	1 min	60.08	3605	116	6960

Table 7: Pedestrian flows at KGM station 2 with respect to data extraction time periods

Sl. No.	Data extraction time period	Average pedestrian flow		Peak pedestrian flow	
		p/m/min	p/m/hr	p/m/min	p/m/hr
Morning Data					
1	10 sec	57.28	3440	150	9000
2	30 sec	57.27	3440	138	8280

3	1 min	57.27	3440	137	8220
Evening Data					
1	10 sec	74.15	4450	174	10440
2	30 sec	74.15	4450	136	8160
3	1 min	74.15	4450	128	7680

From above tables it is clear that average pedestrian flow is not getting affected by the change in data extraction time period. But the peak pedestrian flow is changing with the change in data extraction time period. In fact the peak pedestrian flow is reducing with an increase in the data extraction time period. Therefore, in this study all the three time periods of data extraction i.e. 10s, 30s and 1 min are considered to estimate the capacity of the escalator.

Next section now discusses the estimation of capacity at the escalators.

5. Capacity Analysis

Literature shows that capacity of the escalator is either calculated on the basis of peak pedestrian flow or by developing multiple regression equation wherein escalator capacity is dependent upon escalator speed, vertical rise and traffic flow.

Different code of practice indicates that the escalator speed is kept constant in a particular land use and may vary across land uses. Speed of 0.5 m/s is considered as a standard optimal speed worldwide especially in the commercial sectors. This speed is expected to provide sufficient transportation capacity, maximum safety and minimum space requirement. Speed of 0.6 or 0.65 m/s is recommended for intermittent transport requirements, trade fair centres, longer horizontal runs and larger transition curves to ensure optimal safety and loading factor. Escalator speed up to 0.75 m/s is possible and is usually used to cater for extreme transport capacity. According to standards, this speed is not recommended because of safety issues related to use by children and elderly pedestrian and the possibility of tripping or falling in the landing area. The speed of 0.65 m/s is usually used at metro rail stations and is used in India. The capacity analysis of escalators has been done with respect to the different pedestrian flows that can be observed on escalators. These are divided in three categories as defined below:

i) Theoretical capacity: This is based on ideal assumptions regarding occupancy of step of an escalator, constant escalator speed and escalator etiquette being followed by pedestrians.
ii) Operational Capacity: This is defined as the maximum field flow observed during data extraction time period. Here the escalator etiquette may or may not have been followed by the pedestrians.
iii) Actual Capacity: This is defined as the average field flow observed during the data extraction time period.

The three capacity values are now discussed in successive sections.

5.1. Theoretical Capacity

The theoretical capacity of an escalator (ped/m/min) can be calculated as:

$$C_{Th} = s * n * P \tag{4}$$

Where, C_{Th} = Theoretical capacity, ped/m
s = speed of escalator, m/min
n = number of steps in unit length, say meter
P = Pedestrian occupancy of a step of an escalator

Following are noted for the study locations selected for this work:

Speed of the escalator i.e. 's' = 0.65 m/s = 39 m/min
Depth of the stair = 400 mm
Number of steps in unit length say 1 meter = 1000 / 400 = 2.5

The pedestrian occupancy per stairs will depend on the size of the body envelope of a pedestrian. As the depth of a step of an escalator is 400 mm and width of escalator is 1000 mm, the area of one step comes out to be 0.40 m^2.

Literature or various standards provide different dimensions of a pedestrian body (top view, size of body envelop). Out of those, three standards are considered in this work. One is an oldest and most referred one as given by Fruin

(1987), other is used in US i.e. HCM (2010) and third being published in India recently as Indo-HCM (2017). The body envelop as suggested in the three standards are depicted in Figure 3.

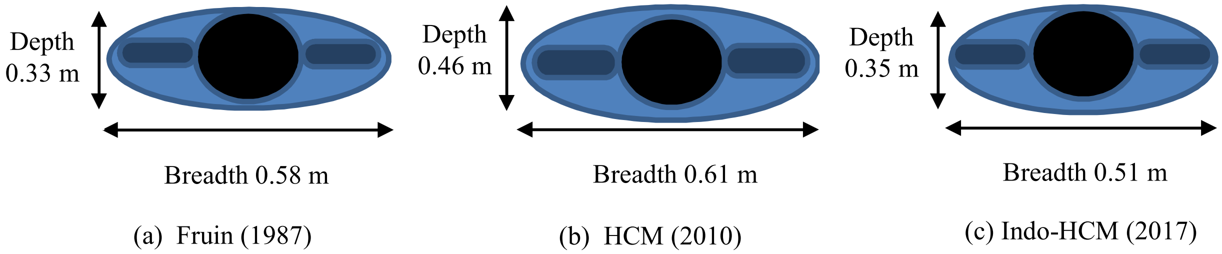

FIGURE 3: Pedestrian body ellipse according to different standards

Using the size of the body envelop given in these standards the pedestrian occupancy of the step is calculated as given in Table 8. It is assumed that the escalator is operational as a standing escalator and no pedestrian is walking on the escalator.

Table 8: Pedestrian occupancy of a step of an escalator and theoretical capacity

Reference	Size of body envelop ($\boldsymbol{m^2}$)	Occupancy of the stair (ped/step)	Theoretical Capacity ($\boldsymbol{eq^n 4}$) (ped/m/min)
Fruin (1987)	0.33m × 0.58m = 0.1914	0.4/0.1914 = 2.0	195
HCM (2010)	0.46m × 0.61m = 0.2806	0.4/0.2806 = 1.4	137
Indo-HCM (2017)	0.35m × 0.51m = 0.1785	0.4/0.1785 = 2.2	215

It can be observed that two attributes out of the three being constant in the estimation of capacity, the capacity solely depends now on size of body envelop. HCM (2010) defines the largest size and Indo-HCM (2017) defines the smallest size. Hence the theoretical capacity comes out to be highest when using the Indo-HCM standard and lowest on use of HCM standard.

Next section now discusses the operational capacity of an escalator.

5.2. Operational Capacity

Theoretical capacity of an escalator is based on certain assumptions and data which is constant. It is remote that the assumptions will be met continuously. One such assumption is number of pedestrians per step. It is based on the size of body envelop of the pedestrian. The variation in the body structure, the arrival/departure of a train at a platform, headways of operation, the arrival density of pedestrians at the facility, the experience of use of the facility etc. are some of the factors which surely impact the peak flows that may be observed on these facilities. In all such cases the theoretical capacity is not going to be met and the peak flow values will remain lower than the theoretical capacity value. Alternatively, when each step is occupied by two or more pedestrians then only the efficiency will be 100 per cent and will approach theoretical capacity of the escalator. According to Fruin's (1987) empty step phenomena, escalator's operational capacity can never be higher than the theoretical capacity even in the heaviest pedestrian traffic. It is, therefore, decided to calculate the peak flow values during the three data extraction time intervals and use the peak flow value as the operational capacity of the escalator. This value is further examined with respect to the theoretical capacity.

The percent utilization of escalator in terms of operational capacity estimated during 10s, 30s and 1 min extraction periods are given in Table 9. Only evening period data is considered here as higher variation is observed during that period.

Table 9: Operational Capacity as percentage of theoretical capacity

Observation site	Operational Capacity		Operational Capacity as Percentage of theoretical capacity		
	Ped/m/s	Ped/m/min	Fruin (1987)	HCM (2010)	Indo-HCM (2017)
Base 10s data extraction time interval					
Esc CSM	2.3	138	70.76	100.72	64.18
Esc RCM	2.5	150	76.92	109.48	69.76
Esc 1 KGM	2.2	132	67.69	96.35	61.39
Esc 2 KGM	2.9	174	89.23	127.00	80.93
Base 30s data extraction time interval					
Esc CSM	2.13	128	65.64	93.43	59.53
Esc RCM	2.33	140	71.79	102.18	61.39
Esc 1 KGM	2.10	126	64.61	91.97	58.60
Esc 2 KGM	2.27	136	69.74	99.27	63.25
Base 60s data extraction time interval					
Esc CSM	1.93	116	59.49	84.67	53.95
Esc RCM	2.05	123	63.08	89.78	57.21
Esc 1 KGM	1.93	116	59.49	84.67	53.95
Esc 2 KGM	2.13	128	65.64	93.43	59.53

According to the literature available on this aspect, operational capacity has also being defined as capacity of the escalator at peak hour or when it is fully occupied, and is reported as practical capacity. Table 9 shows that the operational capacity varies from 59% to 90% according to Fruin's concept of occupancy of step, from 85% to 127% according to the HCM concept of occupancy of step and from 54% to 81% according to Indo-HCM concept of occupancy of steps. It is already visualised that HCM (2010) marks more space per pedestrian thus indicating higher comfort level, which in general is not prevalent in the developing countries. Pedestrians in developing countries are more tolerant and move closer to each other on constrained paths like stairs and escalators. This increases the flow and has resulted in almost 100% operational capacity when calculated based on HCM (2010) concept. This does not look true in the light of body envelop size reported in India (Indo-HCM, 2017) or by Fruin (1987). Hence, HCM (2010) is not used in further analysis regarding actual capacity.

Actual capacity and its correlation with theoretical and operation capacity is discussed in the next section.

5.3. Actual Capacity

Analysis presented in previous section indicates that the working condition of the escalators during peak times is high and its efficiency is found to be as high as 89% for 10s interval, 72% for 30s interval and 66% for 1 min time interval. As highest flows are instantaneous in nature it is appropriate to look at the average flows with respect to the theoretical capacity so as to understand the level of utilisation of the facility. This provides an idea of actual working capacity of an escalator.

The actual capacity is calculated for all four study locations based on the average 10s, 30s and 1 min flows. Average capacity is very low because the flow depends upon the arrival and departure of the train on a platform. The arrival rate of the pedestrians at a facility is further dependent upon the pedestrian walking speed and the distance of escalator from the location where the pedestrian alights from the train. Based on the headway between two trains designated for same platform, the escalator is used by the pedestrians for a duration less than 3 min at a time. Intermittently, the escalator becomes vacant or caters to lower flow with low pedestrian density. The calculation of actual capacity and its measure with respect to the theoretical capacity and operational capacity are given in Table 10. It can be noted that the average flow is not changing with the change in time interval of data extraction (Refer Table 4 to 7). Hence, analysis of average flow with respect to theoretical capacity is done only once. In case of practical capacity, the values are found varying with respect to the time interval of data extraction and hence the values are calculated for three time intervals.

Table 10: Actual capacity as Percentage of theoretical and operational capacity

Observation site	Highest Average flow		Actual capacity as percentage of		
	ped/m/s	ped/m/min	Theoretical capacity		Operational Capacity for (10s / 30s / 1 min)
			Fruin (1987)	Indo-HCM (2017)	
Irrespective of the base data extraction time interval					
Esc CSM	0.82	49	25.13	22.79	35.51 / 38.28 / 42.24
Esc RCM	0.93	56[4**]	28.72	26.05	37.33 / 40.00 / 45.53
Esc 1 KGM	1	60	30.77	27.91	45.45 / 47.62 / 51.72
Esc 2 KGM	1.23	74	37.95	34.42	42.53 / 54.41 / 57.81

The average capacity of the escalator is found varying from 25% to 38% with respect to the theoretical capacity calculated based on Fruin's concept, whereas Indo-HCM concept gives this variation as 23% to 34%. According to CEN standards (1995), escalator flow handling capacity is usually 42% of its theoretical capacity. Considering that it talks about the average flow, in this study it has been found to be lower at 31% and 28% (as overall average) respectively based on Fruin (1987) and Indo-HCM (2017) concept. The discussion made in the previous section has already indicated that the peak flows on escalators under prevailing conditions (defined as operational capacity) varied from 65% to 89% of the theoretical capacity. As operational capacity is never going to be equal to theoretical capacity, it is judicious to use operational capacity as the limiting value to understand and examine the actual flows throughout the day. It can be seen from Table 10 that actual flow or capacity varies between 42% and 58% of the operational capacity when 1 min time interval is used. This clearly defines that the pedestrian flows on escalators in India are quite high even during non-peak periods as compared to other countries. This may be attributed to lower lateral and longitudinal gaps being maintained by the pedestrians with respect to each other even under normal flow conditions, thus causing increase in the flow and its proportion with respect to the operational capacity. Another reason might be the presence of stairs on the side of escalators which are used by pedestrians who are not comfortable in using the escalators or are using stairs because escalator is occupied by high pedestrian flow.

Following section now summarises the findings of this study.

6. Conclusion

This paper has discussed the escalator capacity in three forms, namely theoretical capacity, operational capacity and actual capacity. The difference between these is in the form of ideal assumptions and prevailing frictions. Theoretical capacity is dependent upon escalator speed, width of the step (both found constant in this study) and step occupancy which is controlled by the size of body envelop of the pedestrians (found varying in different standards). Analysis indicated that HCM (1987) concept is not applicable for conditions prevailing in developing countries. Fruin (1987) and Indo-HCM (2017) gave results which can be said representing the pedestrian movements in developing countries. Operational capacity, which is the field peak or highest flow under prevailing conditions, has been found quite low as compared to theoretical capacity (65% to 89%). This means that system, operational and psychological frictions will remain and influence the escalator capacity that will never reach the theoretical capacity. This is in consonance with findings of Fruin (1987), Al Sharif (1996), Li and Li (2014) and Weidman (1993). Under such circumstances it is wise to consider the operational capacity as the highest limiting value. The actual average flows (highest) are found reasonably high in a developing country context as compared to the developed countries as reported in the literature/standards when examined with respect to the operational capacity.

The variation of operational capacity with respect to the theoretical capacity (ranging between 65% and 89%) indicates towards optimal utilisation of the escalator. Ideally as soon as the operational capacity reaches 85% the planning for provision of another facility should be started. In present case only one location warrants the same. The design flow value for the provision of an escalator is suggested as 126 – 140 ped/m/min, with theoretical capacity taken as 205 ped/m/min (range 195 to 215 ped/m/min). This would be reasonable for a metro rail station, where the

[** 4] Morning data, rest are evening data

escalator is catering to the flow from a single platform.

Comparison with the peak flow values observed in different countries and as reported by researchers (Refer Table 1) indicates that the pedestrian flow values observed at the four metro rail stations in India are much higher than the reported values. Even in case of Hong Kong (Lam and Cheung, 2000), China (Li and Li, 2014) and Singapore (Xiang et *al*., 2011) the peak flow values are minimum 10% lower than those observed in India. The difference increases by minimum 24% if the values are compared with those observed in developed countries like UK, US, and Germany. This indicates that the pressure on pedestrian facilities in developing countries is much higher than that observed and reported from developed countries.

The study also directs the research to be carried in different directions. It would be reasonable to examine the capacity values when floor level change facilities are placed as an individual entity or in combination with other facilities. The reason being the presence of pedestrians in developing countries who are not comfortable in using the escalators or have to use stairs because escalator is carrying high pedestrian flow. Flow mechanics or dynamics at a platform with respect to the train arrival and departure may also provide insight on the aspect of actual usage of the escalator.

The present study has provided sufficient grounds to the practitioners for taking decisions with respect to the expected design flow and, the operational and actual capacity of the escalators. It would be helpful in taking decisions regarding the provision of escalators, their numbers and locations where to install. The information may be utilised in the formulation of design guidelines for use of escalators at public places in developing countries, specifically as a part of metro rail projects.

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