CAPACITY BASED OPERATION PLANNING OF RAIL TRANSIT SYSTEMS: A CASE STUDY FOR İZMİR LIGHT RAIL TRANSIT

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Abstract

All railway systems are more reliable than other transit modes for the operating point of view. Because most of the other transit modes are affected from random conditions of the traffic, in which demand-supply balances cannot be adjusted warrantably for the most of operating time. In this case, capacity of the transit mode may not be modulated for the transportation demand. However, especially for metros, capacity analysis is the major and most applied criterion for the operation planning of the transit system, because of the completely controlled traffic conditions. In this study, four different capacity calculation methods are discussed to obtain a suitable approach to operational purposes for rail transit systems. Some of these methods consider not only physical capacity of line and train elements of transit system, but also operational factors such as train control and signaling, station dwells, passenger loading levels and train performance. Also, operational plan of İzmir Light Rail Transit System, which has been operating for three years, is analyzed from achievable capacity point of view rather than design capacity. As a result of the study, some improvable preventions are obtained, especially for the last capacity calculation method. It is seen that, some non productive periods must be neglected for the quality of service and benefits of citizen points of view.

Keywords: Operational planning; Light rail transit; Achievable capacity; Design capacity
Topic Area: C1 Integrated Planning of Transport Systems

1. Introduction

Investigated four capacity calculation methods in these study can be considered as two main types; first three as physical (maximum) capacity based and the last as achievable capacity based. Calculated capacity values are given on the Table 1.1. The passenger area acceptance method gives the maximum value which is seem to be as not applicable for İzmir LRTS. It is found as an insensitive method which neglects quality of service. Vehicle dimensions method is seen as an applicable procedure for the determination of a reasonable vehicle capacity but it is not suitable for line capacity analysis. Because other margins than vehicle dimensions can only be attained by primitive assumptions. Levels of service method gives the most realistic results in the three physical capacity based procedures. So, it is the most useful and practical method, only if the analysis is done for obtaining the capacity value. However, the aim of this study is the use of capacity calculation as an operational planning criterion. Therefore, TCQSM method for capacity analysis is found to be the most suitable for the optimization of operational planning. Because it considers many important factors such as train control and signaling system, service speed, diversity factor etc. Besides, all these criterions are based on reasonable calculations which are dependent on some basic estimations and assumptions or neglected for the other three methods. This property of the TCQSM method gives possibility to

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planners to see which variable how affects the operation in use and to obtain optimum values for maximization of system productivity. As a result of this, the study is focused on TCQSM method and some operational regulations are proposed especially based on this method.

Table 1.1: Results of The Capacity Calculation Methods For İzmir LRTS

Capacity Calculation Method	**The Result for İzmir LRTS**
Vehicle Dimensions	15.030 pphpd
Levels of Service	11.880 pphpd
Passenger Area Acceptance	22.320 pphpd
TCQSM	11.140 pphpd

The Transit Capacity and Quality of Service Manual (TCQSM), which is a document of Transit Cooperative Research Program (TCRP) uses two definitions for transit capacity; design capacity and achievable capacity. Design capacity is the maximum number of passengers those pass a single point in an hour, in one direction on a single track. It is similar to maximum capacity, theoretical capacity or theoretical maximum capacity expressions used in other works. Design capacity makes no allowance for whether those passenger spaces going by each hour will be used; they would be fully used only if passengers uniformly filled the trains throughout the peak hour. Because of the necessity of a more realistic approach for operational purposes, design capacity cannot be enough for rail transit capacity consideration. Achievable capacity takes into account that demand fluctuates over the peak hour and that not all trains, or all cars of a train, are equally and uniformly full of passengers. The capacity type that can be used for operational purposes of the rail transit systems is achievable capacity, which means the maximum number of passengers that can be carried in an hour in one direction on a single track allowing for the diversity of demand. Achievable capacity is the product of the design (maximum) capacity and a series of reality factors, most of which downrate the ideal. These factors are not absolutes, since they reflect human perception and behavior, as well as site-specific differences. Therefore, for obtaining achievable transit capacity, addition to the technical calculation process, some experiences and social statistics are necessary. Owing to high operational expenses in Turkey, especially originating from high electricity cost, it is essential to operate the light rail transit systems via reaching to achievable capacity closely.

2. İzmir light rail transit

İzmir Light Rail Transit is a small range transit application having 11,6 km total line length, 10 stations and a feasibility capacity of 400.000 passenger per hour per direction. General map of the whole designed system is given on Figure 2.1. The Operational Plan of The İzmir Light Rail Transit is based on just some statistical data of passenger flows. It is based on continuously obtained statistics of prepaid ticket machines at the stations including time, usage and station locations. A public survey is made in 2001 for the system but it is not used directly for operational planning. It was used for the evaluation of productivity of the transit system after a short operating time. The operation plan of the system is generally organized on prepaid ticket machine statistics. The statistics are arranged and classified via an SQL type database. By using this database, passenger numbers getting into every tracks according to time and the day of week are obtained for a minimum time period of 5 minutes. In this way, assigned time intervals between tracks taking into account the effect of the day of week, are controlled for whether total passengers after each stations exceed physical capacity of the tracks or not. Thus, an optimum time interval between trains is obtained via try and error method. In this application, the physical capacity of one track is assigned as 538 passengers for 4 passengers per square meter and 3 light railway vehicles for each train. However, there is an important detail which can not be neglected for operation planning point of view that, any knowledge does not exist about how many of the passengers entered to the stations goes to which direction on the line. Because all of the entered passengers uses same prepaid ticket machines regardless of trip directions. Also, the number of passengers getting of in any station is neglected in this application. Therefore, an achievable capacity calculation process is essential to use with some other statistical data additionally.

In the study, firstly, three simple geometric capacity calculation methods are applied for İzmir Light Rail Transit System(LRTS) which are suitable for rather design capacity. Because, they are not consider lots of operating variables like loading diversity factor, train control and signaling system, service speeds etc. As the fourth method, the procedure of Transit Capacity and Quality of Service Manual(TCQSM) is analyzed for the case system. Some of the operational margins modified for the optimization of system conditions. At the end of the study, the four capacity calculation methods are discussed for the operational planning point of view and the current operation of the system is considered according to obtained results.

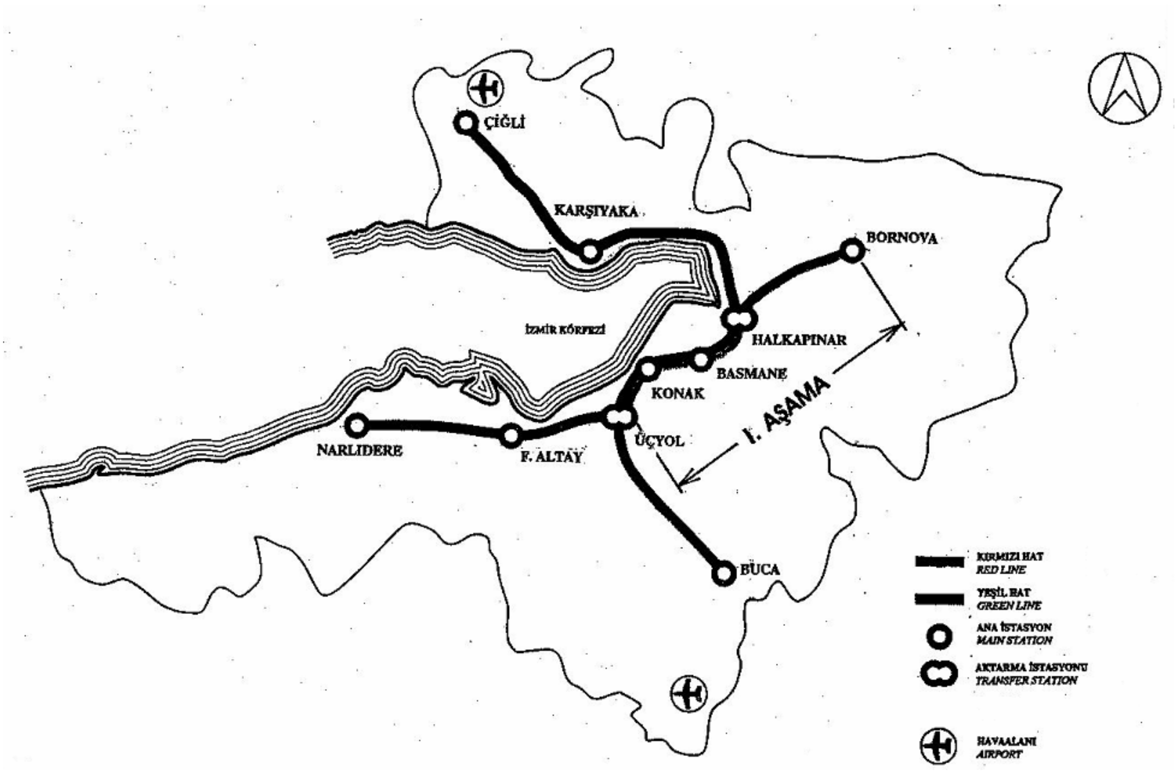

Figure 2.1: Designed İzmir Light Rail System (İzmir Metro A.Ş., 2004)

3. Capacity calculation via vehicle dimensions

The maximum capacity of a rail transit system can be calculated via characteristic vehicle dimensions. The procedure is similar to the levels of service method considered in the latter paragraph. The difference is the use of vehicle capacity instead of passengers per seat. For this purpose, Transit Research Board National Research Council defines effective dimensions of rail transit vehicles in Report 13 (1996) as given on Table 3.1. Corresponding values belonging to İzmir LRTS also can be seen in this table. Figure 3.1 represents these dimensions on a default drawing.

Table 3.1: Vehicle Dimensions Used For Capacity Calculations (TRB, 1996)

Term	**For İzmir LRTS**	**Description**
V_c	Calculated	vehicle capacity in peak 15 minutes
L_c	23,5	vehicle interior length (m)
L_a	1,05	articulation length for light rail (m)
W_s	0	stepwell width (certain light rail only) (m)
W_c	2,65	vehicle interior width (m)
S_{sp}	0,3	space per standing passenger (m^2/pas.)
N	4	seating arrangement
S_a	0,5	area of single seat (m^2)
D_n	8	number of doorways
D_w	1,4	doorway width (m)
S_b	0,13	single setback allowance (m)
S_w	0,69	seat pitch (m)

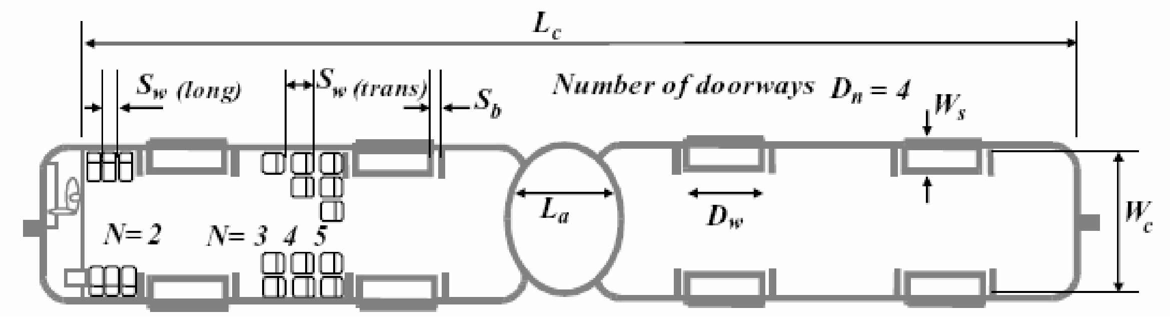

Figure 3.1: Representation of Specific Vehicle Dimensions

According to these dimensions, vehicle capacity can be calculated via the formulation developed by TRBNRC:

$$V_C = \left[\frac{(L_c - 0{,}5\,L_a)\,W_c - 0{,}5\,D_n W_s\,D_w}{S_{sp}} \right] + N\left[\left(1 - \frac{S_a}{S_{sp}} \right)\left(\frac{L_c - L_a - D_n\,(D_w + 2\,S_b)}{S_w} \right) \right]$$

$$V_C = \left[\frac{(23{,}5 - 0{,}5x1{,}05)x2{,}65 - 0{,}5x8\,x\,0\,x1{,}4}{0{,}3} \right] + 4x\left[\left(1 - \frac{0{,}5}{0{,}3} \right)\left(\frac{23{,}5 - 1{,}05 - 8\,x(1{,}4 + 2\,x0{,}13)}{0{,}69} \right) \right]$$

$$V_C = \frac{60{,}884}{0{,}3} + 4\ x\ (-0{,}667)\ x\ 13{,}290 = 202{,}947 - 35{,}458 = 167{,}489 \approx 167 \text{ pas/veh}$$

The calculation is based on to subtraction of sitting passengers according to their occupied area, from the total passengers in the net vehicle area that can stand without any seat. This calculation is made for a reasonable space per standing passenger (0,3 m^2) and it can be done for smaller spaces if quality of service factor can be neglected for the considered systems such as the one being operated close to maximum capacity. However, for İzmir LRTS, demand is nearly one quarter of the maximum capacity and, as being a new system, quality of service has considerable importance.

Capacity calculation according to vehicle capacity necessitates a train headway assumption, like which is done for levels of service method. With the same way, it is attained as 2 minutes and trips per hour obtained as 30 for İzmir LRTS. Following formulation gives the maximum capacity via a simple multiplication:

Capacity (pas./h) = [trains per hour] x [vehicles per train] x [passengers per vehicle]

$$C_{max} = 30 \times 3 \times 167 = 15.030 \text{ pphpd (passengers per hour per direction)}$$

Vehicle dimensions method is seen as an applicable procedure for the determination of a reasonable vehicle capacity but it is not suitable for line capacity analysis (Black, 1995). Because other margins than vehicle dimensions can only be attained by primitive assumptions.

4. Capacity calculation via levels of service

This method is still in use in North America rail transit systems and based on levels of services for peak hour generated from statistical data. Seven different levels of service are formed according to passengers per square meter and passengers per seat. “A” Level of Service is for the case of rail transit vehicles as empty and/or with a few passengers; Level “E-2” represents maximum scheduled load and it is the last allowable case for operational planning. Level “F” indicates the “crush load” and it is undesirable and not considered as an operating margin. In spite of this case, lots of rail transit system in North America being operated closely to their maximum capacities encounter with “F” Level. Mentioned levels of services and their passenger comfort standards, obtained from Highway Capacity Manual 1985 (p12-9) are given in Table 4.1.

Table 4.1: Levels of Service for Rail Transit Systems (HCM, 1985)

Level of Service in Peak Hour	**Passenger Comfort Values**		
	ft^2/pas.	**m^2/pas.**	**Pas./seat**
A	>= 15,4	>= 1,43	0,00-0,65
B	15,2-10,0	1,41-0,93	0,66-1,00
C	9,9-7,5	0,92-0,70	1,01-1,50
D	6,6-5,5	0,61-0,51	1,51-2,00
E-1	4,9-4,0	0,46-0,37	2,01-2,50
E-2 (max. scheduled load)	3,9-3,3	0,36-0,31	2,51-3,00
F (crush load)	3,2-2,6	0,30-0,24	3,01-3,80

The capacity is calculated via passenger comfort values given on the table and a simple assumption of hourly trip number for the rail transit considered system. A basic multiplication of some system variables is enough for this method:

Capacity (pas./h) = [trains per hour] x [vehicles per train] x [seats per vehicle]
x [passengers per seat]

For İzmir LRTS, minimum applicable headway can be estimated as 2 minutes. The system is controlled by fixed-block signalization and so shorter values than 2 min. are not possible for the control safety point of view. Then the trains per hour will be “60/2=30” for the system. For the being operated case, vehicle number of trains is “3”, and number of seats per train is “44”. The maximum capacity, can be obtained via only for the upper bound of the “E-2” Level of Service(3,00 pas./seat) which gives allowable maximum load. According to this, the maximum capacity of İzmir LRTS can be calculated as follows:

$$C_{max} = 30 \times 3 \times 44 \times 3{,}00 = 11.880 \text{ pphpd}$$

Levels of service method gives a more realistic result than the first method. It is the most useful and practical method, only if the analysis is done for obtaining the capacity value. But for the operating point of view, it neglects lots of critical margins.

5. Capacity calculation via passenger area acceptance

A lot of studies are realized on necessary area for acceptable comfort conditions of passengers in public transit and they converge nearly on the same results. This method originates from some of these studies and also similar to given two methods below-especially to the first one. But a different vehicle capacity method is used for seeing a different application.

Different passenger area acceptances of different studies are given in Table 5.1. It is seen in the table that, the values does not show any considerable differences between each other.

Table 5.1: Passenger Area Acceptance of Different Studies (Candemir, 2000)

Study of	**Comfort Level (m^2/pas)**		
	Comfortable	**Tolerable**	**Unacceptable**
Institute of Batelle	0,40	0,20	< 0,125
University of Indiana	0,50	0,35	< 0,20
Prof. Young	0,40	0,22	< 0,22
USA D.O.T.	0,38	0,30	< 0,17
Transportation Institute of Europe	0,40	0,20	< 0,142

Vuhcic offers 0,55 m^2 per seating passenger and 0,15-0,25 m^2 per standing passenger. Vuhcic has developed an empirical formulation to calculate vehicle capacity based on passenger area acceptances:

$$C_V = m + \frac{e \cdot A_g - A_l - m \cdot r}{s}$$

where

m : number of seats in vehicle

e : lost area factor caused by outer walls of the vehicle

A_g : vehicle gross floor area

A_l : internal lost areas like driver cabinets, stepwell etc.

r : area occupied by one seat

s : average area per standing passenger

These terms are obtained for İzmir LRTS as follow:

$m = 44$

$e = 0{,}90$ (chosen)

$A_g = 25 \times 2{,}767 = 69{,}175\ m^2$

A_l = [driver cabinet] + [devices] $= 1{,}55 \times 2{,}65 + 0{,}5 \times 2{,}65 = 5{,}433\ m^2$

$r = 0{,}45 \times 0{,}80 = 0{,}36\ m^2$

$s = 0{,}20\ m^2$/pas (average value of Vuhcic assumptions for standing)

Vehicle capacity of İzmir LRTS according to Vuhcic formulation is calculated below:

$$C_V = 44 + \frac{0{,}90 \text{ x } 69{,}175 \ - \ 5{,}433 \ - \ 44 \text{ x } 0{,}36}{0{,}20} = 44 + 204{,}92 = 248{,}92 \approx 248 \text{ pas/veh}$$

Then the maximum peak hour capacity can be obtained from vehicle peak hour capacity like the formulation given in second method.

Capacity (pas./h) = [trains per hour] x [vehicles per train] x [passengers per vehicle]

$$C_{max} = 30 \text{ x } 3 \text{ x } 248 = 22.320 \text{ pphpd}$$

Passenger area acceptance method gives the maximum value of considered methods which is seem to be as not applicable for İzmir LRTS. It is found as an insensitive method which neglects quality of service.

6. TCQSM method for capacity analysis

As it was seen above, maximum or design capacity of a rail transit system can be calculated via simple multiplication processes of some physical characteristics and some assumptions related operating issues. But they are not sufficient and reliable for an operational planning analysis purpose. Because there are more variables effecting performance of the system and it is essential to know that which component of operational plan how affects the capacity.

Transit Capacity and Quality of Service Manual (TCQSM) provides four different capacity calculation methods for four distinct rail transit categories based on alignment, equipment, train control and operating practices. İzmir Light Rail Transit is a “light rail system” according to its equipment configuration. But TCQSM describes “light rail” as having on street operations and right of way with grade crossings. Because of fully segregated, signaled and double track right of way configuration of İzmir Light Rail Transit, it must be evaluated in “Grade Separated Rail” category, according to TCQSM classifications.

6.1. Simple procedure

Taking advantage of relative performance uniformity of electric multiple-unit trains in urban rail transit service, TCQSM provides a simple procedure to obtain capacity of rail transit system via some prepared charts. For this simple application, some physical and operational properties of the considered system, such as grade into headway critical station, maximum line velocity, dwell time etc., must be within the specified limits. Given charts are arranged for two different train control and signaling systems; cab control and moving block. Fixed-block control systems are not considered in the procedure because of its more limited and more expensive conditions. In spite of its constrained conditions and old technology, İzmir Light Rail Transit, as a new designed system, is controlled by fixed-block system. Hence, given simple procedure for grade separated rails in TCQSM can not be applied for İzmir Light Rail Transit.

For the being operated part of İzmir LRT, fixed block control doesn’t create any problem, owing to low demand and fully segregated right of way. However, when the system is completed and started to operate, some operational problems will occur based on the right of way with grade crossing and the demand coming close to achievable capacity.

6.2. Complete procedure

The complete procedure recommended in TCQSM for grade separated rails is more suitable for optimization of operational planning of the system. Because many variables related operation can be changed to maximize capacity and possibilities can be seen for this. Simple Excel Spreadsheets are composed for this aim. Some situations in question are determined about given equations in the methodology which are considered in the following sections of the study.

Seven main steps must be followed according to the procedure:

i) Determining the maximum load point station,
ii) The close-in time at the maximum load point station,
iii) The dwell time at this station,
iv) Assigning a suitable operating margin,
v) Determining the peak-within-the peak train passenger load,
vi) Calculating the loading diversity factor to translate from peak-within-the peak hour.
vii) Calculating maximum train throughout

According to TCQSM, maximum throughput of a rail transit system can be limited by three different constraints; the close-in time at the busiest station, junctions and turn-backs. Owing to its fully segregated and double track right-of-way, any junction doesn't exist in İzmir LRT. Also, for the actual trip time, turn-back operations are applied on just one station orderly and they don't cause any time lost, because of suitable line design and fully controlled conditions. Therefore, the factor affecting system capacity is only close-in time for İzmir LRT and the complete procedure for calculation of the system maximum throughput is based on close-in time constraint.

6.2.1. Determining the maximum load point station

For an existing and being operated system, it is easy to determine the maximum load point station. Passenger counts of İzmir LRT realized via digital prepaid ticket machines at the entrance of the stations which can transfer the data to the center for each 5 minutes periodically. In the procedure, passenger load of 15 minutes peak-within-the peak is shown as preferable for this determination. Any monday of the month (March 2003) having maximum passenger load is chosen as a criterion. Because it is seen that the maximum demand occurs on monday of each week. The day realizing maximum passenger load can be chosen within the year but it is not preferred. It can be a good choice for a maximum capacity calculation. But for the operational analysis purpose of this study, it is aimed to obtain more consistent passenger loads in more realistic conditions. Each of peak and 15 minutes peak-within-the peak loads indicate Üçyol Station as the maximum load point station which is the one of end station of the İzmir LRT. Hourly passenger load distributions of each ten stations are shown in Table 6.1. Digital prepaid ticket machines of İzmir LRT can not differentiate the entering passengers according to their trip direction. Therefore given loads at the table can not be thought as boarding to one of the tracks, except for end stations. So it is a chance to obtain the maximum load at an end station for the easy analysis point of view. Load distributions for 15 minutes time intervals of the day show the same determination with more certain characteristics. Table 6.1 indicates passenger load distribution of each station of the system with this certainty. The system is operated between 6:00 AM and 12:00 PM in a day and this time reveal is divided to quarters for each hour in the chart. The maximum load point station of the system appears to be Üçyol with 1320 passenger per direction for 8:00-8:15 AM time period.

Table 6.1: Hourly Load Distributions For Each Station of İzmir LRTS
(İzmir Metro A.Ş., 2004)

	Stations										
Time Reveal	ÇY	ON	NK	SM	L	KA	AD	AN	ÖL	RN	OT
6:00 - 7:00	395	9	48	51	23	16	43	18	77	184	864
7:00 - 8:00	2799	111	239	234	91	110	293	120	559	1219	5775
8:00 - 9:00	4136	208	295	351	135	167	454	152	779	1537	8214
9:00 - 10:00	1746	215	329	181	49	117	284	85	303	782	4091
10:00 - 11:00	1007	424	439	184	60	102	295	94	280	798	3683
11:00 - 12:00	1096	326	515	189	53	111	293	95	259	968	3905
12:00 - 13:00	1147	353	640	180	53	157	317	123	283	1111	4364
13:00 - 14:00	1194	467	767	189	64	165	328	120	360	1339	4993
14:00 - 15:00	1132	594	949	221	89	152	330	113	242	1317	5139
15:00 - 16:00	939	621	1033	233	79	172	323	116	233	1708	5457
16:00 - 17:00	772	744	1242	316	95	199	619	129	233	2012	6361
17:00 - 18:00	768	875	1265	328	83	307	380	176	267	1834	6283
18:00 - 19:00	671	860	1955	386	128	724	566	298	273	1331	7192
19:00 - 20:00	450	566	1035	261	42	315	314	118	202	871	4174
20:00 - 21:00	279	213	447	137	27	105	190	78	95	620	2191
21:00 - 22:00	177	124	257	102	18	49	81	19	56	505	1388
22:00 - 23:00	138	60	122	79	8	29	41	15	60	361	913
23:00 - 0:00	112	43	56	37	4	17	22	10	23	141	465

6.2.2. Calculation of control system's minimum train separation

Different types of train control systems affect the applicable minimum train separation time. Fixed-block control system is the most disadvantageous one. Because, position of the train can not be known in a block except for passing on transition between two blocks and minimum block numbers for a safe separation is two. Bu it is simple to use and doesn't create any other problem for the systems being operated with much smaller demands than the capacity and fully segregated right-of-way.

Necessary variables to calculate minimum train separation for fixed block systems, their default values for nominal purposes and obtained values from İzmir LRT are listed in Table 6.2.

Stations and other infrastructure details of İzmir LRTS are designed for 125 m maximum train length. But, for the current operation of the system, maximum train length being used is 75 m. This situation presents some alternatives to optimize operational planning of the system based on to minimize train separation time. Because attainable values of some terms spread in a wide range. This flexibility gives a chance for seeing possibilities to develop the operational conditions of the system via attaining the most desirable values in the possible ranges. In reality, for a calculation just aimed to know achievable capacity of a rail transit system, the worst conditions of these terms must be considered for being on the safe side. However, in this study, capacity calculations are used to optimize operational planning and given equations are examined for this kind of purposes.

The case of maximum train length gives alternatives to minimum train separation calculations for operation point of view to adjust two main terms; distance from front of stopped train to start of station exit block (D) and station approach speed (v_a). "D" distance can be arranged between 5-30 m range. Signalization equipments and length of the stations allow this adjustment. Long station length and some other geometric design conditions, like grades at the stations, also provide a freedom to change station approach speed. Speed restriction for the station approach is 55 km/h. It can be reduced to 15 km/h for a practical lower bound.

Given equation for minimum train separation time for fixed block controlled systems is:

$$T(s)=\sqrt{\frac{2(L+D)}{a_s\,(1-0{,}1G_o)}}+\frac{L}{v_a}+\left(\frac{100}{K}+B\right)\left(\frac{v_a}{2d_s}\right)+\frac{a_s\,(1-0{,}1G_i).l_v^{\,2}.t_{os}^{\,2}}{20000\,v_a}\left(1-\frac{v_a}{v_{max}}\right)+t_{os}+t_{jl}+t_{br}$$

As it was seen at the equation, “D” distance affects minimum train separation with its square root even proportionally. It means, longer “D” distances increase minimum train separation orderly. For an average station approach speed like 35 km/h, minimum train separation changes between 42,0 and 43,8 seconds for lower and upper limitations of the “D” distance(5-30 m). This time difference with 1,8 seconds is not affected by station approach speed in the formulation mathematically. But in practice, higher approach speeds make difficult to protect this distance as constant. So it must be a compromise and mathematical relationship between approach speed and “D” distance. It is seen as a deficiency of the formulation. Because of negligible effect on separation time (smaller than 2 seconds) distance from front of stopped train to start of station exit block (D) is not arranged as an operating margin and chosen as 20 m as the current applied value.

According to the formulation, the effect of station approach speed to minimum train separation is more complex than the effect of “D” distance because of its two-way effect. For the braking safety point of view, rise of approach speed increases separation time. But for the other factors of the formulation related with system dynamics, approach speed has inverse proportional effect. For the determination of optimum approach speed providing minimum train separation, 15-55 km/h speed level is tried with 2,5 km/h intervals. While the all other variables are constant, the relationship between station approach speed and minimum separation time is seen on Figure 6.2.

Table 6.2: Terms and Their Values For Minimum Train Separation Calculations (TRBNRC, 1999)

Term	**For İzmir LRT**	**Default Value**	**Description**
T(s)	calculated	calculated	train control separation in seconds
L	75	200	length of the longest train (m)
D	5-30	10	distance from front of stopped train to start of station exit block (m)
v_a	4,17-15,28	calculated	station approach speed (m/s)
v_{max}	22,22	29,20	maximum line speed (m/s)
K	75	75	braking safety factor-typically 75%
B	2,4	2,4-3,0	separation safety factor—equivalent to number Of braking distances that separate trains
t_{os}	3	3	driver sighting and reaction time (s)
t_{jl}	0,5	0,5	time lost to braking jerk limitation (s)
t_{br}	1,5	1,5	brake system reaction time (s)
a_s	1,0	1,3	initial service acceleration rate (m/s^2)
d_s	1,1	1,3	service deceleration rate (m/s^2)
G_i	0,2	0	grade into station, downgrade = negative
G_o	-0,2	0	grade out of station, downgrade = negative
l_v	91	90	line voltage as percentage of specification

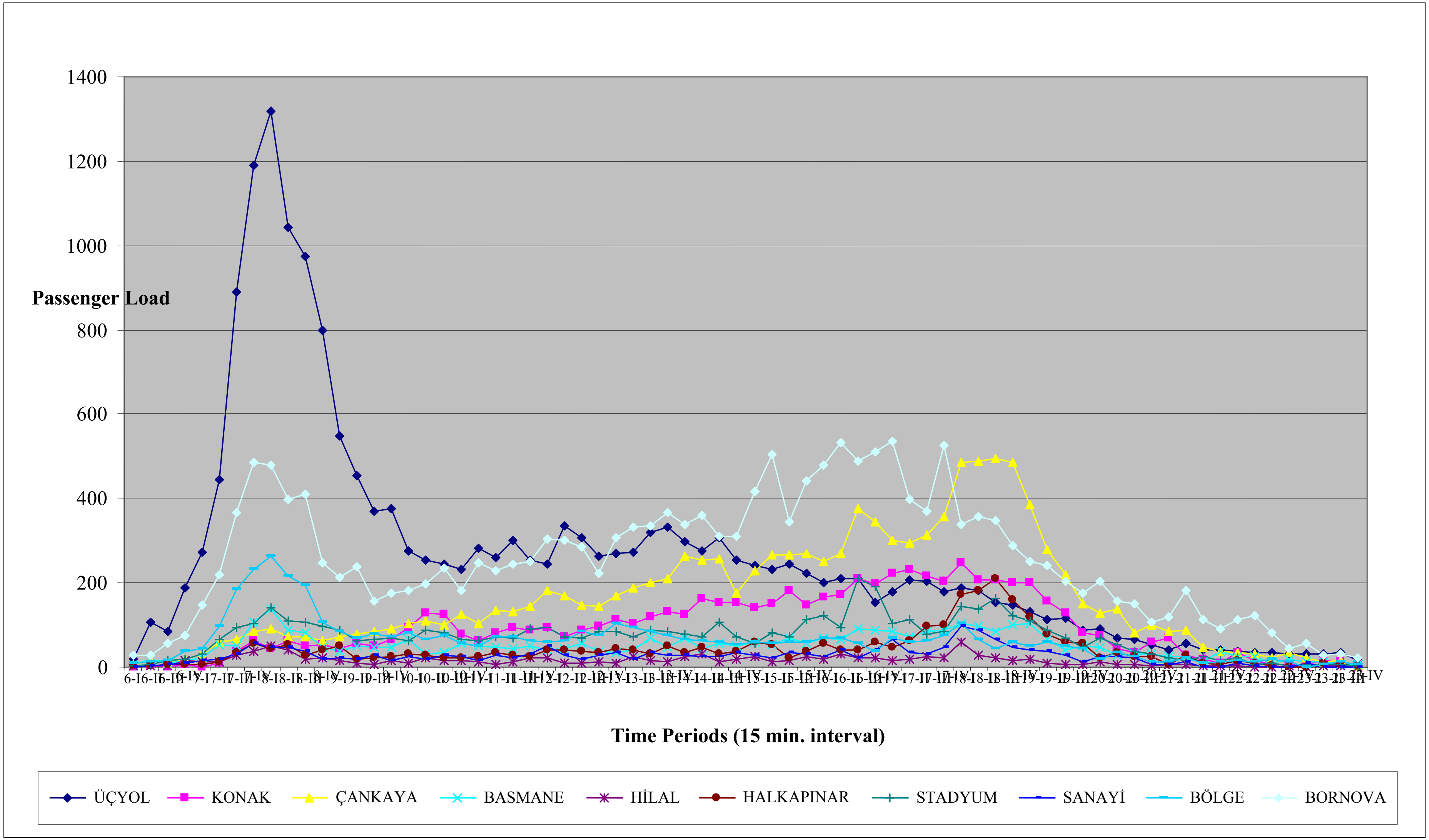

Figure 6.1: Passenger Load Distributions of Each Station of İzmir LRT (for 15 min. time periods)

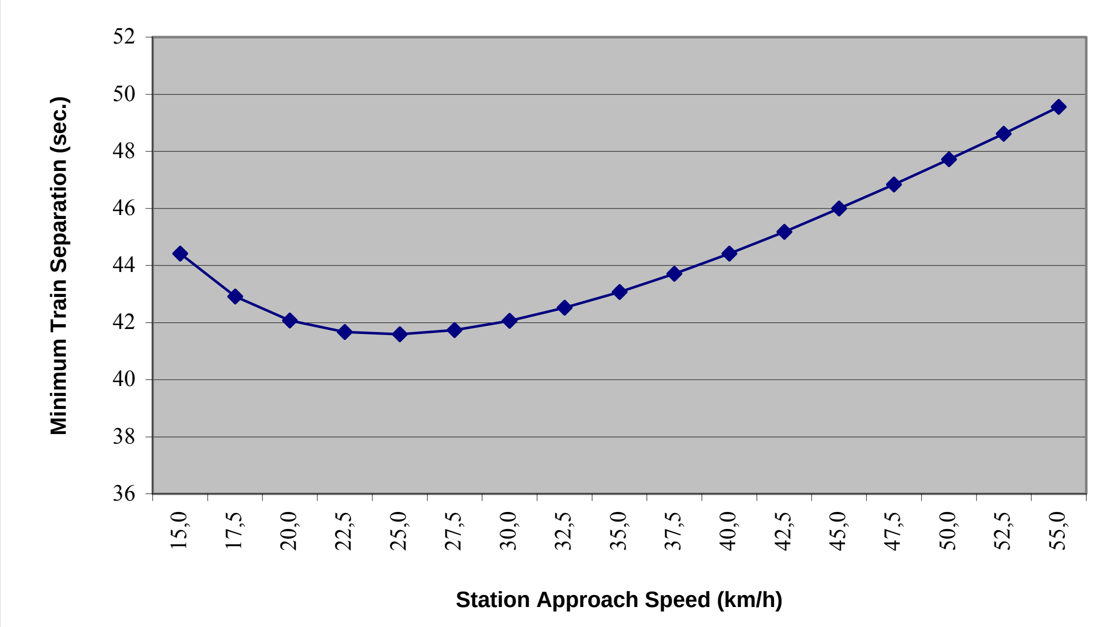

Figure 6.2: Station approach speed vs. minimum separation time for İzmir LRTS

The minimum train separation time occurs for 25 km/h approach velocity with 41,6 seconds for İzmir LRTS. It is show that, braking safety has a bigger affect on operational planning and higher capacities can not obtained via increasing speed restrictions for the whole sections of the rail transit system.

According to the formulation, grade into and out of the maximum load point station affects minimum train separation positively for the case that the station is designed on the top of a vertical curb. Namely, positive grades before and negative grades after the station are desirable. This situation originates from the ease of acceleration and deceleration movements at this kind of station approaches. The given formulation considers this case but there must be an upper limit for these approach grades. Because, bigger grades than an optimum value may create difficulties for operating point of view especially for power controls of accelerating or decelerating trains. But, even for great approach grades, minimum train separation time decreases, according to given formulation. It must be a more realistic approach to grade issue for rail transit systems.

6.2.3. Selecting an operating margin and calculation of dwell time at the maximum load point station

Dwell times of the stations are designated by the operational departments of İzmir LRTS and they are applied orderly. These values are given on Table 6.3. But for the end stations there is not any certain and critical dwell time assigned. Because trains are positioned at the end stations with open doors for a longer time (approximately 2 min.) than the actual dwell time before trip is started. The maximum load point station of İzmir LRTS is an end station (Üçyol). There is not an explanation in the method for this special situation. It is thought to calculate a dwell time value via given formulation for new systems according to passenger demands at this station. Because Üçyol Station will not be an end station when the whole of rail transit system is completed. Also the actual part of this applied 2 minutes must be known since it is a very long time for a dwell time to consider directly.

Before the calculation of dwell time, an operating margin must be selected. Because it is used in the formulations. For the evidence of TCQSM, the systems being operated at capacity and automatically controlled have systematic operating margins according to the other systems, owing to their regular passenger demands. For manually driven and having low demand systems causing disordered passenger flows like İzmir LRTS, it is difficult to attain an operating margin, because of scheduling too few trains to meet demand resulting in extended dwells and erratic services. Therefore, an operating margin and schedule recovery times are most needed to correct service irregularities.

In fifth part of Rail Transit Capacity Chapter of TCQSM, a method is given to estimate operating margin. The formulation is given below:

Operating Margin = [average headway] - [average station dwell]
- 2 [standard deviation of station dwell] - [train control separation]

This calculation doesn't give a reasonable value for the system having big trip frequencies like İzmir LRTS. Because average headway for the maximum load point station of the system is calculated as 469,6 seconds and it is a very long time for given example systems being operated in North America. (Maximum average headway for given transit systems is 241,3 seconds.) So, a simple attainment must be done to operating margin for İzmir LRTS.

Table 6.3: Assigned trip and dwell times for each station of İzmir LRTS

Station	**Trip Time (sec.)**	**Dwell Time (sec.)**
Üçyol		-
	116	
Konak		40
	76	
Çankaya		30
	64	
Basmane		30
	84	
Hilal		20
	97	
Halkapınar		20
	96	
Stadyum		20
	81	
Sanayi		20
	81	
Bölge		20
	79	
Bornova		-
TOTAL	774	200

TCQSM recommends that, where the demand is unknown or uncertain in the long term future, then 25 sec. or more should be used. 25 seconds seem to be sufficient for İzmir LRTS, because peak-within the peak period occurs orderly for the same station and applied minimum headways(5 min.) are long enough to recompense any possible problem originating from inadequateness of operating margin.

TCQSM has developed complex regression equations to relate passenger flow times to the number of boarding, alighting or mixed flow passengers, and, in turn, to convert this flow time to dwell time. Firstly, number of double stream train doors must be calculated via the formulation given below:

$$D_{15} = \frac{900 \,.\, D_n \,.\, N_c}{T(s) + t_d + t_{om}}$$

where
D_{15} : the number of available double stream doors
$T(s)$: train control separation in seconds
t_d : dwell time in seconds
t_{om} : operating margin in seconds
D_n : number of double stream doors per car
N_c : number of cars per train

In the formula, T(s) is applied train control separation, but in this study, it is chosen as calculated minimum train separation time for seeing under achievable capacity conditions. Operating margin has attained as 25 s. Number of double stream doors per car is 4 and number of cars per train is 3 as it was mentioned before.

The passenger flow at the busiest door of the train in the peak-within-the peak, F_{max} is:

$$F_{max} = \frac{R \,.\, P_{15min}}{D_{15}} = \frac{R \,.\, P_{hour} \,.\left[T(s) + t_d + t_{om}\right]}{3600 \,.\, D_n \,.\, N_c \,.\, D_{ph}}$$

where
R : ratio of busiest door usage to average door usage
P_{15min} : the peak 15 minutes movement of passenger on a single station platform.
D_{ph} : diversity factor-peak hour
P_{hour} : peak-hour movment of passengers on a single station platform

A value of 1,5 to ratio of busiest door usage to average door usage is recommended by TCQSM for light rail systems. Diversity factor indicates the unevenness of the passenger loading of transit vehicles in peak time. It is a ratio of peak hour ridership to a virtual the peak-within-the peak flow(15 min.) being thought as existing in whole quarters in an hour:

$$D_{ph} = \frac{R_{hour}}{4\,R_{15min}}$$

where
R_{hour} : ridership in peak hour
R_{15min} : ridership in peak 15 minutes
For İzmir LRTS, it is calculated as given below:

$$D_{ph} = \frac{9135}{4 \text{ x } 2614} = 0{,}874$$

Peak-hour movement of passengers on a single station platform is obtained for Üçyol Station which occurs in 7:45-8:45 time period as 4527 passengers.

Flow time is obtained from a parabolic function of F_{max} which differs with type of flow; alighting, boarding or mixed. Trains at the Üçyol Station wait for departure in a different single station platform. Therefore, only dwell time must be calculated for only boarding passengers.

$$\ln\left(FT_{max}^{board}\right) = 1,380 + 0,124\, F_{max}^{board} - 0,00124\left(F_{max}^{board}\right)^2$$

TCQSM methodology makes a logarithmic relationship between dwell time and flow time which is given blow.

$$\ln\left(t_d\right) = 3,168 + 0,0254\, FT_{max}^{board}$$

The open form of the equation is:

$$\ln\left(t_d\right) = 3,168 + 0,0254\, e^{1,380 + 0,124\left(\frac{R \,.\, P_{hour} \,.\, [\,T(s) + t_d + t_{om}\,]}{3600 \,.\, D_n \,.\, N_c \,.\, D_{ph}}\right) - 0,00124\left(\frac{R \,.\, P_{hour} \,.\, [\,T(s) + t_d + t_{om}\,]}{3600 \,.\, D_n \,.\, N_c \,.\, D_{ph}}\right)^2}$$

The equation have to be solved for the value of the dwell time contained as both a natural logarithm and as an exponential. It is not possible to solve in closed form but it can be easily obtained via recursive numeric assumptions. For a value of 20 seconds as an initial value, iterative solution of dwell time is obtained as 38,7 s. for İzmir LRTS. The values of calculated iteration steps are given in Table 6.4. F_{max} calculation of first step is shown below as an example.

$$F_{max} = \frac{1,5 \quad 4527 \quad 41,2 \quad 20 \quad 25}{3600 \quad 4 \quad 3 \quad 0,874} \qquad \frac{551388,6}{37756,8} \qquad 15,503$$

Table 6.4: Iteration steps of dwell time calculation

t_d	F_{max}^{board}	$\ln(FT_{max}^{board})$	FT_{max}^{board}	$\ln(t_d)$	t_d
20,0	15,503	2,78804	16,249	3,58072	35,9
35,9	18,363	2,9354	18,829	3,64626	38,3
38,3	18,794	2,95458	19,194	3,65553	38,7
38,7	18,866	2,9577	19,254	3,65705	38,7

6.2.4. Selecting passenger loading level and loading diversity factor

Passenger loading level selection is a simple attainment of a passenger number to per meter of the train. Complex vehicle capacity calculations are also possible but they do not give an idea about being applied loading levels for being operated systems like İzmir LRTS. Space requirement of people for acceptable trip comfort conditions is essential criterion for passenger loading level selection. Pushkarev suggests gross vehicle floor area as a readily available measure of car occupancy, recommending the following standards:

- Adequate: 0,5 m^2 provides comfortable capacity per passenger space.
- Tolerable with difficulty: 0,35 m^2 is the lower limit with “some touching”
- Totally intolerable: 0,2 m^2 is the least amount of space that is occasionally accepted.

TCQSM recommends 0,5 m^2 per passenger medium comfort level averaged over peak period for new systems where attempts are being made to offer a higher quality of service. This provides a recommended linear loading level of 6 passengers per meter of train length for heavy rail and 5 for light rail.

Peak hour flow of maximum load point station of İzmir LRTS is 4527 pphpd for 7:45-8:45 time period in which the applied headway is 5 minutes. Train length is 75 m with 3 vehicles. Passenger load level of the system in practice can be calculated via this data as follows:

$$P_m = \frac{P_{hour}}{\frac{60}{H_{mnts}} . L} = \frac{4527}{\frac{60}{5} \text{ x } 75} = 5{,}03 \text{ pas/m}$$

As it was seen, loading level in practice is very close to recommended value for light rail systems. It shows that, headway adjustments of İzmir LRTS in the peak hour is successful for the quality of service point of view.

The difference of peak-within-the peak flow from peak hour flow is indicated by loading diversity factor. TCQSM offers the use of calculated diversity factor if it is determined for dwell time calculations. It is obtained as 0,874 for İzmir LRTS in preceding paragraph. The recommended default value of the factor is 0,75 for light rail systems in the case of impossibility to calculate it. Obtained diversity factor is bigger and closer to “1” than the recommended one. It shows that, the passenger flow is more regular for İzmir LRTS, according to general light rail systems.

6.2.5. Calculation of capacity

The final step to complete TCQSM method of determining a grade separated rail transit line’s maximum capacity is to determine the closest(minimum) headway as the sum of the calculated value of the minimum signaling system train separation, plus the calculated or estimated value of dwell time plus the assigned operating margin.

$$H_{min} = T(s) + t_d + t_{om} = 41{,}6 + 38{,}7 + 25{,}0 = 105{,}3 \text{ sec.}$$

Then the maximum number of trains per hour Tmax is:

$$T_{max} = \frac{3600}{H_{min}} = \frac{3600}{105{,}3} = 34{,}2 \approx 34 \text{ trains/h}$$

Finally, maximum capacity is obtained by the multiplication of maximum train number per hour, train loading and loading diversity factor:

$$C_{max} = T_{max} . L . P_m . D_{ph} = 34 \text{ x } 75 \text{ x } 5{,}0 \text{ x } 0{,}874 = 11.143{,}5 \approx 11.140 \text{ pphpd}$$

The obtained value will be discussed with other capacity calculations in latter paragraph.

7. Evaluation of İzmir LRTS

Calculated capacity values are given on the Table 1.1. Some basic relationships can be produced from the results. Vehicle dimensions method gives a value of 501 passengers per vehicle which is smaller than the current operating assumptions of the system (538 pas./veh.). This method gives a more reasonable vehicle capacity because of more detailed considerations of characteristic for the system. Applied value is just based on passenger numbers per square meter (4 pas./m^2). As it was mentioned, TCQSM method is the most realistic method for the operation point of view, owing to consideration of various operating criterions. Trains per hour for peak hour can be obtained via these values:

$$N_T = \frac{11.140}{3 \times 167} = 22{,}24 \approx 23\, \text{train/h}$$

It gives an applicable headway for a fixed-block controlled system. But its necessity must be examined. 15 min. peak-within-the peak flow is a useful criterion for this. A quarter of TCQSM capacity is 2785 passengers. Total entrance from prepaid ticket machines for every station in the 15 min. peak is 2614. This shows that, even if the whole of passengers go to same direction and trip to the till station, TCQSM capacity is sufficient for İzmir LRTS with 6% flexibility.

The applied headway of İzmir LRTS is 5 min. in peak-within-the peak period. If the passenger flow is uniform in this period, 440 passenger will board into each train in the period and it is a big load for a station which is the start point of the trip when the vehicle capacity is taken as 167 passengers. For the worst case, trip number in the peak period must be 2614/501 which can be done in practice as 6 trips. It corresponds to 2,5 minutes of headway and it is smaller than calculated minimum headway with 105,3 seconds. As a result, the operational plan of İzmir LRTS must be regulated for the peak-within-the peak period. As it was seen in the Figure 6.1, distribution of passenger flows is very irregular; average flow is smaller than a quarter of the peak-within-the peak flow for the general sum. Therefore, a regulation seems to be necessary for non peak times. However, applied headway with 15 minutes is already a long time for a light rail transit and a regulation to increase this headway will be harmful for quality of service point of view.

8. Conclusion

In this study, TCQSM method for capacity analysis is found to be the most suitable for the optimization of operational planning. Because it considers many important factors such as train control and signaling system, service speed, diversity factor etc. Also, all these criterions are based on reasonable calculations which are dependent on some basic estimations and assumptions or neglected for the other three methods. This property of the TCQSM method gives possibility to planners to see which variable how affects the operation in use and to obtain optimum values for maximization of system productivity. For the case study, some proper regulations are found for not only scheduling of the system but also, physical conditions such as approach speed at stations, minimum train separation etc. As a conclusion, it can be said that, the capacity calculation is not a criterion for just the rail transit system which is operated as close to maximum capacity; it is also necessary for the systems with irregular passenger flows.

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