THE EVOLUTION OF THE RIO DE JANEIRO SUBWAY SYSTEM

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ABSTRACT

Subway systems are the most important means of transportation in the main cities around the world. They generally carry more people than any other system and have a more extensive network, such as in Moscow and Paris (2,475.6 and 1,335.7 million passengers per year and 278.8 and 211.3 km, respectively). However, the subway system does not have the same importance in Rio de Janeiro. Other Latin America cities, like São Paulo and México City, which started building subway systems at the same time as in Rio de Janeiro, have more extensive networks (61.3 and 176.8 km) and carry more passengers per year (611 and 1,417 million, respectively).This article examines the history of the subway in Rio de Janeiro, its operational data (yearly growth of passengers, fleet, kilometers of track, passengers entering stations and daily passenger flow per line) and analyzes its contribution to the mobility of Rio de Janeiro's populace, in light of the population shifts shown in the Rio de Janeiro Metropolitan Area Transport Master Plan. A case study is presented of Botafogo Station, which is located in the south zone of Rio de Janeiro, on Line 1. This case study analyzes whether or not the station have the necessary infrastructure according to international subway station design standards and a minimum service level to meet the new demand generated by the end of 2010. The results suggest this will not occur.

Keywords: Transport Planning, Subways.

INTRODUCTION

The year 2008 marked the first time in history that more than half the world's population lived in towns and cities. Urban growth is increasingly the result of internal growth rather than migration from rural areas, even though rural-to-urban migration is still an important force in some regions (United Nations Population Fund, 2007). Urban growth of either kind creates opportunities but also presents challenges that governments must be prepared to meet, by offering adequate services, such as water, sanitation, health, education and transport.

In the transport area, the public transport system must offer high-quality service at an accessible cost to allow adequate mobility and reduce the air and sound pollution caused by buses and cars.

According to Garcia (2005), intermodal integration is one of the ways to reorganize public transit systems, to rationalize the routes, reduce costs and increase mobility though a greater supply of services (more trips and wider geographic coverage). It can also be seen as a way to improve the organization of land use and supervise the public transit system. Each city, depending on its size and geographical features, has an optimal transport network configuration, to provide mobility and take best advantage of the available resources.

The increase in the size of cities and changes in their population density patterns (with higher density from more people counteracted to varying degrees by urban sprawl) obviously have a direct influence on the transport system, which must meet an increasingly complex combination of needs. While a transport system grows linearly, the problems grow geometrically, consisting of constraints to economic growth and negative environmental effects, among others. Therefore, the configuration of the transport system and its coverage are fundamental for the quality of life in cities.

The growth of cities, increasing demand for mobility and growing need for high-performance transit that is independent of frequently congested urban streets have resulted in construction of subways[1] in a large number of cities in recent decades. In 1950, only 17 cities in the world had subways; in 2005, that number exceeded 100 cities.

Nowadays subway systems are the means of transportation carrying the most passengers in the entire world. The table 1 presents information on the biggest subway systems in the world.

[1] We use the term subway in this paper to cover all metro-rail systems that are mainly underground. Many cities have mixed systems, where a portion of the routes are on the surface (or elevated) and other parts are underground. This is the case of Rio de Janeiro, where all of Line 1 is underground but most of Line 2 runs on the surface.

Table 1: Characteristics of the subway system in some cities of the world

Location	Area (km^2)	Pop. (mi) 2006	Demog. Density (hab/km^2)	Start of operation	Existing transport system (2006)			
					Ext.(km)	No. of lines	No. of railcars	No. of passengers carried (year -million)
Mexico City (DF)	1,479.0	8.80	5,965	1969	176.8	11	355	1,417.0
Ile-de-France	12,012.0	11.49	957	1900	211.3	16	3,553	1,335.7
Moscow	1,081.0	10.44	9,660	1935	278.8	13	n.a.	2,475.6
Seoul metropolitan area	605.0	10.29	17,019	1974	286.9	8	399	2,023.8
Tokyo city	621.5	8.57	13,720	1927	289.4	12	n.a.	2,929.8
New York - New Jersey metropolitan area	10,101.0	8.00	1,700	1904	368.0	27	6,494	1,499.0
Greater London	1,579.0	7.50	4,758	1900	408.0	12	4,070	1,014.0

SUBWAYS

Subways utilize high-capacity electric trains with high acceleration and braking rates. They are the highest-performance transit mode with the lowest operating cost per space-km. However, building them is expensive and complicated, including disruption of areas along future lines. However, subway systems have virtually unlimited lifetimes and exert a strong, permanent impact on mobility and traffic circulation patterns in cities (Vuchic, 2005).

According to Alouche (2005), subway technology is directly linked to the transport capacity, demand profile, type of rider and routes along which the system will be constructed. The choice of technology should be carefully studied, since the installation of new lines is a lengthy process and the rolling stock and other equipment have relatively long useful lifetimes. Nevertheless, in terms of systems and equipment used by subway systems, there is a good deal of similarity among the various modes, with the differences mainly being the carrying capacity, supply of service and type of riders served.

The determining parameter in the choice of a transit mode (be it light rail, subway, elevated monorail, etc.), on any line, is mainly its peak-hour carrying capacity. This is determined by the vehicle capacity, number of vehicles per train and maximum number of trains circulating per hour. Rail transport can be classified into the following categories: urban metro, regional metro, metropolitan commuter train, light rail vehicle (or light metro), regional train and trolley.

An urban rail transport system must be designed to operate with the following main characteristics:

1. To guarantee services with adequate quality at an accessible price.
2. To guarantee acceptable levels of operational safety and security against vandalism and criminality.
3. To guarantee good environmental quality, mainly regarding air and sound pollution and vibrations.
4. To guarantee convenient integration with other means of transport, with logical connections, simplified fare systems and quick, safe and comfortable changes between systems.
5. To meet the needs of all people, even those with physical disabilities or reduced mobility, such as the elderly.
6. To provide easily understandable information to users in attractive formats.
7. To maximize the comfort of users in trains, stations and integration terminals.
8. To minimize operating costs.
9. To minimize energy consumption.

According to Litman study (2005), rail systems significantly improve the performance of transportation in cities. This study investigated the impacts of rail transit on urban transportation system performance for U.S. cities. The systems were divided into three categories:

1. Large Rail – Rail transit is a major component of the transportation system.
2. Small Rail – Rail transit is a minor component of the transportation system.
3. Bus Only – City has no rail transit system.

When these groups were compared, Large Rail cities were found to have significantly better transport system performance. Compared with Bus Only cities, Large Rail cities were found to have:

- 400% higher per capita transit ridership;
- 887% higher transit commute mode split;
- 36% lower per capita traffic fatalities;

- 14% lower per capita consumer transportation expenditures despite residents' higher incomes.
- 19% smaller portion of household budgets devoted to transport;
- 21% lower per capita motor vehicle mileage;
- 33% lower transit operating costs per passenger-mile;
- 58% higher transit service cost recovery.

Many of these benefits result from rail's ability to create more accessible land use patterns and more diverse transport systems, which reduce per capita car ownership and distance traveled. The larger and denser the urban area, the greater the need for having integrated transport networks. For this integration to be complete, it is fundamental to integrate the physical-operational, fare and institutional aspects. The difficulty of this grows as the number or entities and stakeholders involved increases.

THE RIO DE JANEIRO METRO SYSTEM

When it was opened in March 1979, the "Metrô Urbano do Rio de Janeiro" had only 4.3 kilometers of track, connecting five points in the downtown area (Figure 1). In its first ten years of operation, its trains carried over a half million people, for a daily average of 60 thousand riders. Of the first stations, the busiest was Cinelândia Station, accounting for slightly over one-third of the passenger flow, followed by Praça Onze, Central, Presidente Vargas and Glória stations. At the time of opening, the system operated with only four trains of four cars each, circulating at average intervals of eight minutes between 9:00 a.m. and 3:00 p.m. This was soon extended to 11:00 p.m. in December that 1979.

Figure 1: Rio de Janeiro subway system and its first five stations (circled in red).

Source: Metrô Rio

Note: Only Lines 1 (orange line) and 2 (green line) have been completed. The other lines shown in the map (blue and yellow) and the "Integrated Stations" (*Estação com Integração)* represents integration with regular and express bus service and commuter trains (SuperVia) running to outlying suburbs in the city of Rio and neighboring cities.

Economic and operational feasibility study preceding construction

In 1968 the government of the state of Guanabara (the former name of the city of Rio de Janeiro, a legacy of its period as the nation's capital until 1961, during which the Federal District was called Guanabara) concluded an economic and operational feasibility study for building a subway system. The purpose, based on a quantitative prognosis of the city's socioeconomic development and traffic flows over the next 20 years, was to choose a subway system that would be as adapted as possible to the peculiarities of Rio de Janeiro and to integrate the system in the context of an overall traffic flow network.

According to the study, between 1920 and 1968 the city's population had grown more than fourfold, from about 1 million to 4.1 million people. The population forecasts were for 5 million people in 1975 and 7.4 million in 1990. The number of private cars circulating in the city in 1968 was 189,360, a figure that was projected to increase 176% in 1975 (333,000 cars) and 521% in 1990, (986,000 cars). These forecasts served as the basis to justify the need to build a metro system in the city, because its roads would not be able to carry the growing number of vehicles without causing intolerable delays.

Based on the traffic conditions in the city, a "Priority Line" was identified, planned to link Ipanema in the city's south zone (Praça[2] Nossa Senhora da Paz) to the Tijuca district (Praça Saens Pena), with a total of 22 stations and 18.037km of track. Its construction was to start as soon as possible, so that it could start operating in 1975.

According to this study, with the conclusion of the subway in 1975, the city's traffic flow breakdown would be the following (Figure 2):

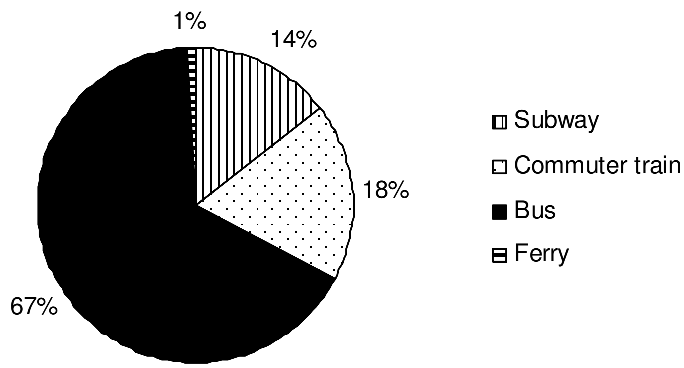

Figure 2: Modal division forecast for 1975

Plans were for the subway system to be expanded by 1990 to 66.9 km, and that by 1990 a line would be built under Guanabara Bay to link downtown Rio to the city of Niterói[3], with the ferry only running from Praça Quinze de Novembro on Rio's waterfront to Paquetá Island in the middle of the bay.

In operational terms, the maximum performance of the system envisaged in the study was 2,000 passengers in each direction every 90 seconds, with a permissible index of 7.24 passengers riding standing up per square meter. These two figures allowed calculating the carrying capacity of the planned system: 2,000 passengers/train * 40 trains/hour = 80,000 passengers per hour in each direction. Since according to the experience of other rail systems, the practical carrying capacity was lower than the theoretical one, the dimensioning of the system in Rio de Janeiro was based on a practical capacity of 64,000 passengers per hour in each direction. A traffic planning technique then current internationally in the field was used, by which the practical carrying capacity would be 20 to 25% lower than the theoretical performance, to provide a realistic basis for sizing the system.

[2] *Praça* means public square.
[3] At the same time, a project was under way to build a bridge connecting the two cities. Construction started on the bridge in 1969 and was completed in 1974. The subway connection has not yet been built, though it is still included in some long-range plans.

Since consideration must also go to rush hour capacity, which was estimated to correspond to 12% of daily traffic, the practical capacity was planned to reach 533,000 passengers per day, based on a theoretical performance of 666,000 passengers per day in each direction.

Evolution of the subway system

The subway system was expanded each year between its opening in 1979 and 1983, with the conclusion of additional stations. From 1983 on the growth became irregular, with new stations opened in intervals of three to five years (Figure 3), including on Line 2 (running on the surface from just before São Cristovão Station to Pavuna Station).

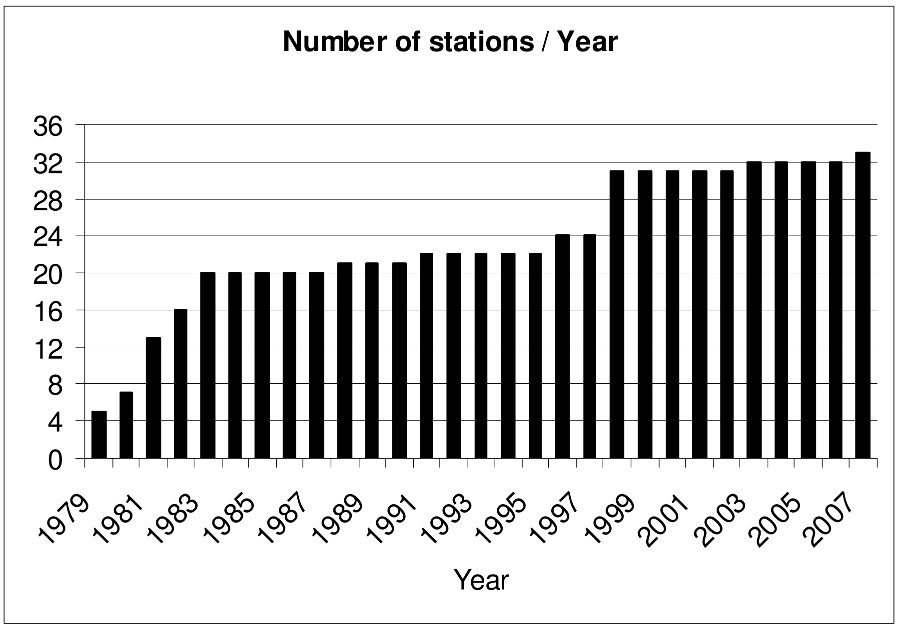

Figure 3: Evolution of the number of stations

From its start-up until 1998 Rio's metro system was operated by the state government. On March 31, 1998, the government signed a concession contract for operation of Lines 1 and 2 for a period of 20 years with Opportrans, the company that won the tender. It was contractually required to operate and maintain the network (rolling stock, stations, rail infrastructure and systems). The contract also called for investments in expansion and technical upgrade.

On December 27, 2007, the concession contract was extended for 20 years (until January 27, 2038), under the condition that the concessionaire make the investments stipulated in the contractual addendum, to expand the system by building two new stations and an interconnection between Lines 1 and 2, to end the need to change trains at Estacio Station.

In 2009 the system still extended only 36.9 km, 55% of the total originally planned to be completed 19 years beforehand.

Current metro system

The metro system in Rio de Janeiro is currently operated by the company Metrô Rio (renamed from the original Opportrans). The system has 19 stations on Line 1 and 15 stations on Line 2, with total trackage of 36.9 km. It provides 17 connections to bus lines (integrations), at the following stations: Saens Pena, Del Castilho, Largo do Machado, Estácio, Cardeal Arcoverde, São Francisco Xavier, Botafogo, Siqueira Campos and Coelho Neto. Besides this, at Pavuna Station there are connections to three intermunicipal bus routes, running to neighboring municipalities (such as Nilópolis, Mesquita and Nova Iguaçu).

The busiest stations are Carioca, Botafogo, Central, Saens Pena and Uruguaiana. Figure 4 shows the evolution of the number of passengers entering the busiest stations in 2007. After the expansion of the system under private operation, the number of users has increased at all stations.

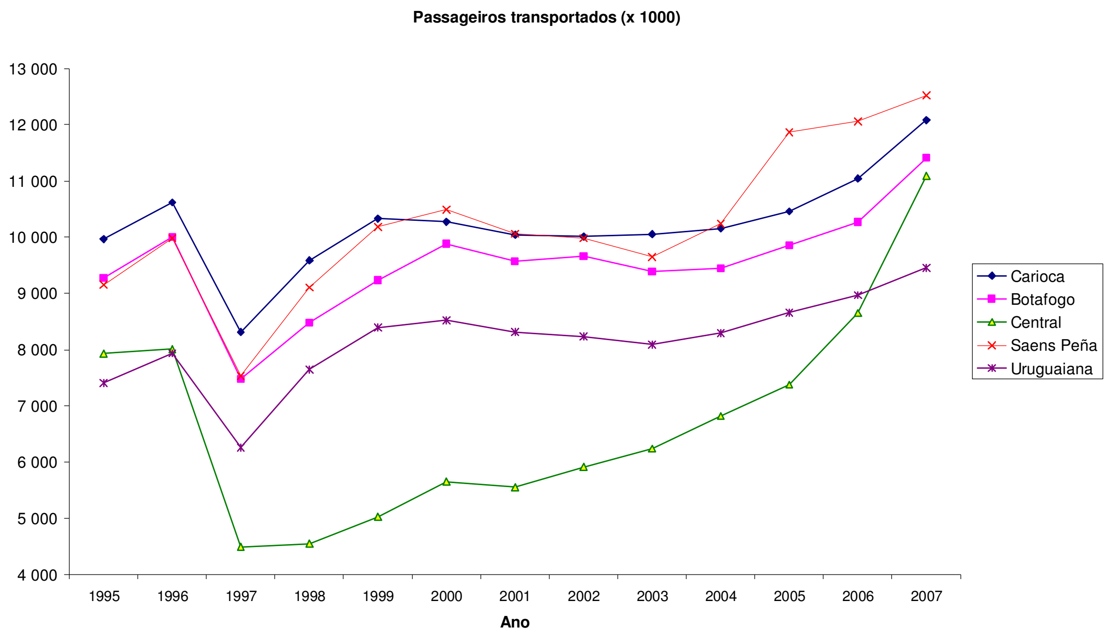

Figure 4: Evolution of the number of passengers per year entering the busiest stations.

Metrô Rio has 182 cars (32 trains) operating daily and 19 more trains are being built, scheduled for delivery in 2011. Currently trains of six cars travel on Line 2 (Pavuna – Botafogo) and of five cars on Line 1 (Saens Peña – Ipanema/Gen. Osório). Lines 1 and 2 interconnect at Central Station, using the same tracks until Botafogo Station (Figure 5), with Line 1 and Line 2 trains interspersed.

Figure 5: Map of the Rio de Janeiro metro system (2010).* Scheduled to open in 2010.

Source: Metrô Rio

The metro system and mobility in the Rio de Janeiro metropolitan region

In 2003, the Rio de Janeiro state government, through the Secretariat of Transportation and the state-owned Companhia Estadual de Engenharia de Transporte e Logística, presented an Urban Transport Master Plan for the greater metropolitan region. This plan was based largely on the results of an origin-destination survey. Table 2 presents the modal division of motorized trips. The metro, the system with the highest capacity, accounted for 4% of these trips that year. This relatively low figure can be taken to indicate the system has insufficient scope and/or service.

Table 2: Public transport trips

Main mode	Trips taken	(%)
Municipal bus	5,302,081	57
Intermunicipal bus	1,331,894	14
Alternative transport*	1,630,985	18
Metro	355,404	4
Commuter train	303,578	3
School transport (bus/van)	190,262	2
Chartered transport (bus/van)	92,150	1
Ferry (traditional, hydrofoil and jumbo catamaran)	82,091	1
Trolley	2,195	0
Total	9,290,640	100

*Alternative transport consists mainly of vans, some legalized and some operating clandestinely.

Another aspect presented by the Plan was the distribution of trips for each mode of transport, according to the municipality of origin. The results obtained revealed a high number of non-motorized trips of 32.87% (Table 3), a figure that can reflect the large number of short-distance trips in certain areas of the greater metropolitan region, or the efforts of low-income people to save on commuting costs by riding bicycles or going on foot.

Table 3: Distribution of trips transport mode according to municipality of origin

Municipality of origin	Non-motorized		Collective Transport		Individual Transport		
	Trips	%	Trips	%	Trips	%	TOTAL
Rio de Janeiro	3,653,306	32.87	5,275,329	47.46	2,185,995	19.67	11,114,630

CASE STUDY

The case study consists of analysis of whether Botafogo Station meets its passenger demand adequately, according to four criteria:

1. Rio de Janeiro Metro Technical and Economic Feasibility Study;
2. Transit Capacity and Quality of Service Manual (TCRP, 2003);
3. National Fire Protection Association (NFPA 130: Standard for Fixed Guideway Transit and Passenger Rail Systems, USA, 2000);
4. São Paulo State Fire Department Legislation (*Legislação do Corpo de Bombeiros do Estado de São Paulo*, 2001, 2004ab).

We chose this station because of the opening in December 2009 of a direct link between it and Pavuna Station (Line 2). Previously passengers traveling between stations on Line 2 and Line 1 had to transfer at Estácio Station. With the opening of the direct connection, this no longer is necessary as far as Botafogo Station. Those wanting to continue to other stations in Rio's south zone still have to change trains, but now from the same platform instead of having to walk to another platform level at Estacio Station as in the past.

Our purpose is to analyze the relevant aspects of the station's capacity to offer adequate service for the end of 2010. However, due to the lack of recent data, we had to estimate demand in 2010 by extrapolation from figures for 2007, based on the evolution of passengers entering the station since 1995.

Figure 6 shows the number of riders of the Rio metro system since 1995. There is an increase since privatization (1997).

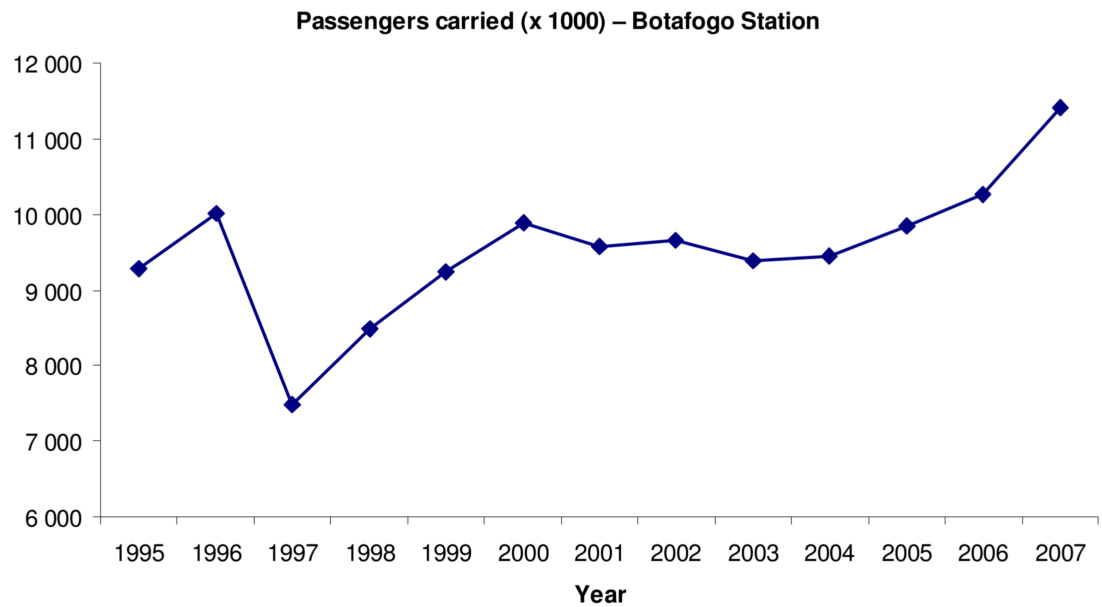

Figure 6: Evolution of the number of passengers entering Botafogo Station

Over the previous five years through 2007, the average increase in passengers entering Botafogo Station was 4.69% a year. This leads to an estimate of traffic at the end of 2010 of about 6,650 passengers. We should point out that in the middle of August 2005 an express bus line started to operate between Botafogo Station and the Urca district, and in 2009 because of the direct Pavuna-Botafogo connection, there was an atypical increase in users of the station, neither of which are considered here.

The primary purpose of a station is for the use of passengers. They normally stay in a station structure for no longer than necessary to wait for and enter a departing transit vehicle or to leave the station after arriving. However, some stations offer public services and/or small commercial enterprises (newsstands, flower stands, snack bars, etc.) that can draw some visitors who are not passengers. Botafogo Station has a few such enterprises located on the level above the platform.

Botafogo Station has a central platform, where passengers board trains of the two lines in both directions, and two lateral platforms for disembarking, one for each direction (Figure 7).

Figure 7: Botafogo Station – View 1

Figure 8: Botafogo Station – View 2

This study is focused on the central platform, because it gathers passengers headed in both directions and because of the existence of sufficient data for analysis.

Dimensions of Botafogo Station:
Platform length:
137.16 meters (six times the length of a typical train)

Platform width:
Central platform: 6.00m, including safety strip
Lateral platforms: 3.25m, including safety strip

Central platform area: 822.96m^2

Unusable area because of pillars, benches, fire fighting equipment, vending machines and advertising/informative displays (central platform only): 34.69m^2.

Criteria According to the Rio de Janeiro Metro Technical and Economic Feasibility Study:

This study, used for the original design of the station, considered the following dimensions:

Platform Length:

The platform length was designed to serve the length of a typical train of six cars (130.4m). With the recommended tolerance for stopping, the platform length was established at 136.00m, or a distance of 2.8m between the end of the first and last car and the respective platform end. However, the distance between car ends and the respective first/last doors is 2.45m (taken up mainly by the drivers control cab, at each end of the train so it can go in both directions without turning). Thus the distance between the endmost entry/exit door and the platform end is given by the equation ½ * (136.00 – 130.40) + 2.45 = 5.25m.

Platform Width:

The following assumptions were used to determine the platform width:

a. At the moment a train entered the station, all the passengers would already be waiting on the platform, so no consideration was given to the possibility of more people entering the platform during boarding.

b. No consideration was given to deboarding passengers lingering on the platform before heading for the exit stairs.

c. No consideration was given to the parts of the platform occupied by vending machines, trash cans and signs, since a margin was already assumed for these in items "a" and "b".

d. The trains would run at regular intervals.

e. In dimensioning the central platform, consideration was given to the fact that trains coming from opposite directions arrive at the same time.

f. At the edge of the platform that is facing the track must be discounted a safety strip of 0.65 m wide.

g. The occupation rate on the platform should not exceed 1.5 persons /m^2.

The study recommended the following platform widths: 4.00m for lateral platforms and 9.00 or 8.00 m for the central platform, depending on the placement of the stairs. At the ends of the central platform a minimum width of 7.00 m was considered sufficient.

Criteria According to the Transit Capacity and Quality of Service Manual:

This study considers the following dimensions:

Platform Size

Since arrivals exceed departures at the station in the morning and departures exceed arrivals in the evening, the peak platform condition in the station will be in the evening peak period when passengers are queuing on the platform to wait for trains. Therefore, the platform analysis will focus on that period.

a. To achieve LOS "C," at least 0.7 m^2/p is required for queuing space (Figure 9) and at least 1.4 m^2/p is required for walking space (Figure 10).

LOS	Average Pedestrian Area		Average Inter-Person Spacing	
	(ft^2/p)	(m^2/p)	(ft)	(m)
A	≥ 13	≥ 1.2	≥ 4.0	≥ 1.2
B	10 - 13	0.9 - 1.2	3.5 -. 4.0	1.1 - 1.2
C	7 - 10	0.7 - 0.9	3.0 - 3.5	0.9 - 1.1
D	3 - 7	0.3 - 0.7	2.0 - 3.0	0.6 - 0.9
E	2 - 3	0.2 - 0.3	< 2.0	< 0.6
F	< 2	< 0.2	*Variable*	*Variable*

Figure 9: Queuing Space

Source: Transit Capacity and Quality of Service Manual.

LOS	Pedestrian Space (ft^2/p)	Expected Flows and Speeds		
		Avg. Speed, S (ft/min)	Flow per Unit Width, v (p/ft/min)	v/c
A	≥ 35	260	0 - 7	0.0 - 0.3
B	25 - 35	250	7 - 10	0.3 - 0.4
C	15 - 25	240	10 - 15	0.4 - 0.6
D	10 - 15	225	15 - 20	0.6 - 0.8
E	5 - 10	150	20 - 25	0.8 - 1.0
F	< 5	< 150	*Variable*	*Variable*
LOS	**Pedestrian Space (m^2/p)**	**Expected Flows and Speeds**		
		Avg. Speed, S (m/min)	**Flow per Unit Width, v (p/m/min)**	**v/c**
A	≥ 3.3	79	0 - 23	0.0 - 0.3
B	2.3 - 3.3	76	23 - 33	0.3 - 0.4
C	1.4 - 2.3	73	33 - 49	0.4 - 0.6
D	0.9 - 1.4	69	49 - 66	0.6 - 0.8
E	0.5 - 0.9	46	66 - 82	0.8 - 1.0
F	< 0.5	< 46	*Variable*	*Variable*

v/c = volume-to-capacity ratio

Figure 10 – Walking Space

Source: Transit Capacity and Quality of Service Manual.

b. Estimate the maximum passenger queuing demand for the platform: under typical conditions, with trains running on schedule, up to 1,165 passengers would be on the platform when trains arrive (a total of 2,330 people enter the station during the peak p.m. 15 minutes, two trains arrive in each direction during the 15 minutes, and thus one-half of 2,330 people could be present).

$$P_{15} = \frac{P_h}{4*(PHF)} \Longrightarrow P_{15} = \frac{6654}{4*(0{,}714)} = 2330p$$

c. Calculate the required waiting space: multiplying 1,165 passengers by 7 ft^2/p results in a required area of 8155 ft^2 (757.62 m^2) under typical conditions.

d. Consider the additional platform space that will be unused: a typical rail transit car has multiple doors along its length, minimizing dead areas. However, an underground station with a center platform will have other unused platform space, including elevator shafts, stairs and escalators, benches, and potentially advertising or information displays, trash cans, or pillars. In this case, a total of 550 ft^2 (51m^2) will be assumed to be used by the central stairs and escalators, the elevator shaft and assorted benches and displays.

e. Calculate the total platform area: adding up the results of steps a through d, and rounding, results in a 8,705 ft^2 (808.72m^2) platform area for LOS "C" conditions.

Criteria According to NFPA 130: Standard for Fixed Guideway Transit and Passenger Rail Systems

According to the standard, there should be sufficient exit lanes to evacuate the station occupant load from the station platforms in four minutes or less and the maximum distance to an exit from any point on the platform should not exceed 300 ft (91.4 m).

The capacity in persons per inch per minute (pim), passenger travel speeds in feet per minute (fpm) and for gates in people per minute (ppm) should be as follows:

Stairs

Exit stairs should be a minimum of 44 in. (1.12 m) wide
Up direction:
Capacity: 1.59 pim
Travel Speed: 50 fpm (15.24 m/min - indicates vertical component of travel speed)

Test: Evacuate platform occupant load from platform in four minutes or less:

Table 4: Characteristics – Stairs

Element	Direction	No. Units	Width	pim	= ppm
Platform to concourse Stairs	Up	2	145 in (3.7 m)	1.59	446.60

$$W1 \text{ (time to clear platform)} = \frac{\text{Platform occupant load}}{\text{Platform exit capacity}}$$

$$W1 = \frac{2330}{446.60} = 5.22 \text{ minutes} = 5 \text{ minutes and } 13 \text{ seconds}$$

Hence, 5 minutes and 13 seconds would be necessary to evacuate the central platform at Botafogo Station, 1 minute and 13 seconds longer than the standard and only 47 seconds less than the tolerated maximum to evacuate the platform occupant load from the most remote point on the platform to a point of safety.

Criteria According to São Paulo State Fire Department Legislation

Because of the absence of specific legislation in the state of Rio de Janeiro, we decided to use the legislation of the state with Brazil's largest subway system, São Paulo. Technical Instruction 12/2004, "Capacity and Emergency Exits in Sports and Exhibition Centers", Technical Instruction 11/2004, "Emergency Exits" and State Decree 46,076 of 2001 provide the main rules on the size of exits and escape routes.

Among other aspects, they determine the specific conditions for egress of people from closed (delimited by physical barriers) and covered spaces, both for normal outflow and emergency escape. According to these regulations, the maximum evacuation times and route distances are 6 minutes and 120 meters to the furthest stairway/ramp or discharge area for installations classified as F-3 (sports and exhibitions centers), and 3 minutes and 60 meters for classifications F-2 (houses of worship), F-4 (passenger terminal stations), F-5 (art exposition halls and auditoriums), F-7 (provisional structures) and F-10 (exposition areas of objects and animals).

The pertinent classification for this study is F-4, which covers railway, ferry and metro stations, airports and similar places for handling passengers.

According to Technical Instruction 11, determination of the dimension of emergency exits must consider one person per 3 m^2 of area and a passage unit capacity of 75 persons per meter for ramps and stairs and 100 persons per meter for doorways and access/egress openings.

The width of these exits is given by the following formula:

$$N = \frac{P}{C}$$

Where:
N = Number of passage units (width in meters), rounded to the nearest whole number.
P = Number of persons.
C = Capacity of the passage unit

$$N = \frac{263}{75} = 3.5 \rightarrow 4 \text{ meters}$$

According to all the technical instructions, the minimum widths of emergency exits must be 1.2 meters for occupied spaces in general.

According to Technical Instruction 12, to establish the dimensions for evacuation of structures, the unitary flow (F) must be utilized, which indicates the number of people who pass per unit of time (persons/minute) through emergency exits, using the formula:

$$F = V.D.W.$$

Where:
F = Flow (in persons per minute)
V = Velocity (in meters per minute)
D = Density (number of persons per square meter)
W = Width of the path (in meters)

In our case the passengers waiting on the platform are nearly all standing, and the narrowest exit-way width is 3.7 meters (with a maximum evacuation time of 3 minutes). This permits a flow of:

F= V.D.W., where

V= 20 m/min (maximum velocity)
Dmax = 4 persons / m^2 (people standing)
W = 3.7 m (exit width)

$F = 20$ m/min. 4 p/m^2 . 3.7 m
F= 296 persons / min

Considering a maximum evacuation time of 3 minutes, the exit can handle:

E (persons evacuated) = t (time). F (flow)

E= 3 x 296
E= 888 people per 3.7 m of exit space (width)

The effective width of the exits is calculated so as to permit a flow of 296 persons/min through 3.7 m of passage, considering a velocity of 20 m/min.
Wt = Total width of the exits, where;

Wt = (P / E). $width_{min}$
P = people in the structure
E = people evacuated
$width_{min}$ = minimum exit width (3.06 m)
P = 3153 persons
E = 888 persons

Wt = (3153 / 888) . 3.7
Wt = 13.14 m

Analysis of the Results

In this item we analyze the results obtained in the items above for the size of the central platform of Botafogo Station.

a. The size obtained by the Rio de Janeiro Metro Technical and Economic Feasibility Study corresponds to an area of 952 m^2 (136m * 7m = 952m^2). This is larger than the actual station by 129.04 m^2. The platform should have been built larger than it is. Besides this, the minimum platform width is less than that proposed in the study.

b. The adequate size obtained from applying the Transit Capacity and Quality of Service Manual is 757.72 m^2. The total platform area of Botafogo Station is 788.27 m^2, only 30.55 m^2 greater than required for a platform to be classified as providing service level C.

c. According to the Standard for Fixed Guideway Transit and Passenger Rail Systems, the stairs leading to the central platform at Botafogo Station are not sufficient to evacuate it within the maximum time recommended by the standard. The time calculated is 1 minute and 13 seconds over the limit set in the standard.

d. According to the technical instructions issued by the São Paulo State Fire Department, 4-meter wide emergency exits are necessary, with a total of 13.14 meters of stairs for users to evacuate the station. The actual stairs at Botafogo Station are 5.74 meters less wider.

e. As stated, we did not use standards set by the Rio de Janeiro State Fire Department because there are none for this type of structure, even though the station is in Rio.

CONCLUSIONS

In large urban areas with over two million inhabitants, a subway system is in most cases essential due to its high capacity and speed, allowing greater mobility in densely populated areas (Vuchic, 1981).

However, subway systems, because of their inherent rigidity, depend on passengers from other more flexible means of transport, unless they are located in areas with very high population densities that can provide a sufficient number of riders without feeder systems. Despite the advantages of integration, it can face strong resistance because unified fares can mean lower revenue for other systems, such as buses.

Analysis of urban mobility both in the city of Rio de Janeiro and the greater metropolitan region shows a significant lack of integrated transport planning. This is evident at all levels, from the conception of the infrastructures, which do not favor intermodal integration, to the overlapping of bus and metro or metro with commuter trains. In most cases these overlaps do not constitute a broader range of options for riders, but rather just competing, often unnecessarily redundant, systems. The effects of this situation are felt by users and are reflected in operational costs. The set of networks, neither conceived nor operated as a whole system, has economically irrational aspects that affects overall costs and contributes to environmental degradation and traffic congestion.

This article shows that Rio de Janeiro's Subway System is in a slow and insufficient evolution since most projects made in 1968 have not yet been completed, most trains travel (in the peak-hour) with more than 5 persons per m^2 and some stations cannot accomplish minimum levels of security according to the selected standards. This is the case of Botafogo Station.

This article focused specifically on Botafogo Station, mainly its central platform. We found that this station has evacuation problems caused by insufficient stairs both in number and width and the width of the platform itself. Besides these problems, the platforms contain a large number of spaces taken up by advertising displays, pillars, benches and informative panels, which hinder circulation, as shown in Figure 8. We should point out that the passenger numbers used in this study may not faithfully reflect the true number of users of Botafogo Station. Because the most recent figures for the station date from 2007, we had to estimate the evolution from the trend over the five years preceding that year. We were also unable to consider the new demand generated by the modification of the system, whereby riders no longer have to change trains between Lines 1 and 2. So, our estimates of the number of users may be too low.

Large urban centers need an efficient transport system that offers convenience, comfort and reasonable cost. In most cases a properly designed and sufficiently comprehensive subway system can best provide these qualities. However, in the Rio de Janeiro metropolitan region, the metro system (part subway and part surface) only accounts for 4% of the motorized trips, according to data contained in the Transport Master Plan of 2003. To overcome these drawbacks, there needs to be better planning and reformulation of the system's operating parameters so it can carry more people and provide better service. Mobility of the population is a key to the balanced and equitable development of any large metropolis.

According to Alouche (1981), economic crises, pollution of cities and saturation of road systems make developing and improving high-capacity mass transit an increasing priority, despite the high initial cost. The rational integration of all transport modes, permitting each to contribute in the most efficient way possible, is path to follow to make Rio de Janeiro a more livable city.

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