BB&J Consult, S.A.

Implementation of Rapid Transit

December 2000

Urban Transport Strategy Review

Abstract

Madrid's recent experience of subway extension (56 km in 40 months) has been compared with the experiences of Mexico City, Caracas and Santiago de Chile.

The Madrid experience involved ten different line extension projects, nine of them carried out by the Regional Authority, totally underground, and one carried out by a private company (TFM), in which the Metro de Madrid is a shareholder, mostly on surface.

Two items are particularly significant: Procurement and project management arrangements, which allowed a very short design and construction period (less than 4 years), resulting in an average cost of 22.8 US$ million/km, a figure significantly lower than other cases studied (40.9 MUS$/km for Mexico, between 58 and 94 for Caracas, and 43 to 70 in Santiago).

Even when considering only underground sections, Madrid's implementation averaged 31.2 US$ million/km, well below the Latin American experience.

- The analysis of various aspects of this enormous investment project shows that the main reason for Madrid's quick and low-cost implementation are:
    - Full commitment at regional political level (President of Regional Authority, Minister of Public Works), ensuring project financing, on-time payments and full confidence from the contractor on getting a profit.

- A small and highly experienced project management team with full power both for technical and financial on-the-spot decisions.

- Contract procurement based not on the cheapest bid, but on sound technical and experience reasons, with the construction method specified by the administration.

- Fair prices allowing construction and supplier companies to have a normal profit in the projects.

- Strong involvement and direct regular presence in the field, of top management officials.

- Other specific cost reductions in civil works, mainly by extensive use of Earth Pressure Boring Machines, (EPBMs), strong geotechnical supervision monitoring and standardised station design concept.

- Equipment cost was kept low by (a) a phased approach to power supply, installing only the current requirement but permitting future capacity expansion when needed; (b) appropriate signalling and communications technology; and (c) choosing steel-wheel instead of rubber-tyred superstructure.

- The cost of rolling stock was relatively low, because (a) fewer trains per km were required than in the Latin American cases, and (b) there was the option of extending a previous supply contract.

- Low design, supervision and management costs, due to the existence a small in-house project management team, reducing the need for much technical assistance.

Finally, simple guidelines are formulated as recommendations to be followed in order to reduce costs for new metro projects in developing countries, in two different groups:

a) guidelines regarding project finance, administration and management

b) technical guidelines for design and construction

The first group guidelines are:

1. Ensure maximum commitment at the political level.

2. Promote customs duty exemption for imported equipment.

3. Appoint, or, if not possible, contract a small experienced management team, committed to the project objectives.

4. If an external team has to be involved, suggest that they are paid on a lump-sum basis, time independent, with a bonus-malus incentive system for on-time completion and on-budget completion, within a specified margin.

5. Empower this team to take both technical and financial decisions, in order to solve unexpected problems in an expeditious manner.

6. Differentiate what the line costs are, independently from works on the road system.

7. Do not base contract procurement only on the cheapest bid, but also on sound technical and experience reasons.

8. Ensure that financing is available for the entire project, including possible contingencies

Technical guidelines for design and construction are:

9. Look carefully at all tunnelling-related elements and costs.

10. Try to adopt single tunnel cross-sections, being significantly cheaper than twin tunnel ones.

11. Alignment depths should be big enough to allow the use of tunnelling machines, but shallow enough to permit good, passenger accessibility and low station construction costs.

12. Adopt EPBMs whenever possible. They will provide an extra level of safety, good response to uncertain or unexpected conditions, and, according to the Madrid experience, better performance and shorter construction times than other tunnelling methods.

13. Adopt a standardised module for the functional design and construction of stations.

14. Whenever possible, adopt diaphragm walls for station construction, minimising the impact (and costs) at surface level.

15. Arrange for extensive geotechnical supervision and monitoring during construction.

16. Recommend the adoption of steel-wheel technology rolling stock rather than rubber-tyred systems.

17. Ask for detailed rolling stock maintenance plans in advance. Peak-hour availability is essential, defining rolling stock needs.

18. Examine overhead classic or rigid catenary as a smaller cost alternative to third rail technology.

19. Analyse convenience of equipment phasing .Dimensioning of needed capacity for the first project phase may yield substantial savings in equipment costs.

The World Bank Group
Urban Transport Strategy Review

Implementation of Rapid Transit

Final Report

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1.- Background

The World Bank contracted BB&J Consult, S.A. in May 2000 to study the "Implementation of Rapid Transit", with the participation of the *Dirección General de Transportes, Comunidad Autónoma de Madrid* (CAM) to provide data on Madrid's experience.

2.- Objective

The study, according to the terms of reference and the inception report submitted in June 2000, aims to compare Madrid's metro extension experience with other cases in Latin American cities, and to determine in which way this experience could be applied elsewhere.

3.- Field survey

An initial written and phone contact was established with metro builders and operators in the following cities:

- Buenos Aires
- Santiago de Chile
- Mexico City
- Caracas
- Rio de Janeiro
- Sao Paulo

Existence of disaggregated data and interest in participation in the study were requested.

After getting answers from all of them, the World Bank selected Mexico City, Caracas and Santiago de Chile as the sites to be finally visited, their construction data to be compared with the case of Madrid.

A trip was made during August 2000 to collect data and meet officials in those three cities.

We acknowledge and are very grateful for the collaboration, hospitality and essential data provided by DGCOSTC of Mexico City, C.A Metro de Caracas, and Empresa de Pasajeros METRO, S.A of Santiago.

4.- Contents

The report is contains four monographs that describe generally the systems of each city and analyse in detail the most recent extensions.

A comparative chapter then presents homogeneous data about the four cities.

Finally, conclusions are presented identifying the key factors that explain differences in construction costs among the different systems.

5.- The Mexico City metro system, and the construction of line B

5.1 Network description

The metro network operating in Mexico City consists of 11 lines totalling 191.5 km in length.

Lines 1 to 9 are entirely within the limits of Mexico D.F., and Lines A and B connect Mexico D.F. with the neighbouring Mexico State.

Metro operation started in 1969 and has followed an unsteady growth rhythm depending on political and financial issues.

Until 1997 metro construction was financed by the Federal Government, but since then Mexico D.F. has assumed these responsibilities. A department of Mexico D.F. DGCOSTC (Dirección General de Construcción de Obras del Sistema de Transporte Colectivo) is responsible for construction, while planning is carried out by the operator (STC).

An additional light rail line, not integrated in the metro network and operated by a different company (STE) run from Tasqueña to Xochimilco, with a length of 12.7 km and 18 stations.

Other public transportation networks in the city include 17 lines of electric trolleybuses, extending over 200 km, and more than 60,000 mini buses (peseros), most of them, military or pickup trucks converted rather precariously for passenger service. Metropolitan buses serving neighbouring cities are connected to the metro network in transfer stations, called CETRAM (centros de transferencia modal).

A dense taxi service, with more than 60,000 vehicles (most of them Volkswagen beetles) completes the public transportation system.

Roughly 30 millions trips are made daily, with the metro accounting for around 5 million, or 16% of the total market.

5.2 Line B construction

Line B, the latest metro line built, runs east-west in the northern part of the city, with a total length of 23.7 km.

It covers 13.5 km (from Buenavista to Villa de Aragón) in Mexico D.F., and 10.2 km (from Villa de Aragón to Ciudad Azteca) in the State of Mexico.

Its design started in 1993, and construction began in 1994. Initially planned to start operation in 1997, service started in the Mexico D.F. section in December 1999, and is planned to start in the Mexico State section in November 2000.

5.2.1 Objectives

Its extension into Mexico State will provide a backbone trying to catch a substantial share of the 5 million daily trips estimated from Mexico State into the city centre.

5.2.2 Functionality

The line is designed for a capacity of 39,300 passengers/hr/direction when in full operation, with 38 trains running, when it will carry 600,000 passengers per day.

The first stage is planned for a capacity of 19,500 passengers/hr/direction, using 16 trains, and it was planned for 250,000 passengers per day.

The line includes its own depot.

5.2.3 Relationship with other lines

It is conceived as a transversal line, providing connection with lines 1, 3, 4, 5 and 8 that run on a north-south alignment, than reinforcing the role of line 9, in providing relief to over congested line 1.

5.2.4 Infrastructure

Total line length is 23.7 km. The first section in operation runs along 13.5 km within Mexico D.F.

Underground section of the line, between Buenavista and Morelos, at the city centre is 5.92 km long, with a deep section between Guerrero and Garibaldi (≈ 15 m depth) and a small depth section (≈ 9 min) the remaining underground part.

There is an elevated section, also in the urban area, 4.46 km long, between connection with line 1 at San Lázaro and line 5, at Oceania.

The remaining 13.34 km are built at grade, constructing new bridges at crossings with main roads, as seen in the schematic longitudinal profile.

5.2.5 Stations

The line has 21 stations, six of them underground, 4 elevated, and the remaining 11 at grade.

They follow a standard pattern, basically the same since line 1 with wide ticketing halls, a distribution mezzanine or underpass and two lateral platforms.

Stations are 150 meters long, to hold 9 car rubber-tyred wheel trains totalling 147.62 metres.

According to their function there are so called “metropolitan” stations (San Lázaro and Ciudad Azteca) that provide interchange with metropolitan bus services, “zonal” stations, with demand from other areas of DF, and “neighbourhood” stations which serve an area around 500 meters from the station.

Stations are designed with very wide corridors (10-12 meters) in order to cope with the extraordinary peak-hour demand.

Passenger signing is quite poor, the criteria being “follow the mass”. Each station has its own pictogram, in order to make the system understandable for a high percentage of illiterate citizens.
There are turnstiles and magnetic band tickets, although there is only a single type of ticket costing 0.50 pesos. The use of monthly cards was abandoned being unable to cope with the large lines at the beginning of the month, and by fraud reasons.

There are projects to make a monthly ticket payable with a phone card.

Metro fare is flat, and valid for an unlimited number of transfers, within the metro network. Light rail, trolleybuses and buses have their own fare scheme, much more expensive (2.50 for light rail, 2.50 for trolleys or 2.00 for buses up to 5 km, reaching 3.50 beyond 12 km) with no combined or integrated tickets.

5.2.6 Rolling stock

Trains are formed by nine-car sets of rubber-tyred vehicles, with a length of 147.6 metres. There are sliding automatic doors embedded in the cars, and a total of 1,530 passengers per train, at a density of 6 standing passengers/m^2.

Motorization is MTMMTMMTM with only two cabins at ends.

No interconnection between cars or air conditioning are provided.

Trains run on 750 V DC collected from a third rail (only line A run on steel wheels and overhead line).

5.2.7 Superstructure

It is formed by ballast bi-block concrete sleepers and two concrete tracks for rubber tyre support plus two security rail (39.6 kg/m) for eventual steel-wheel support and the lateral guideways that provide guidance.

Maximum gradient is 7% and minimal curve radius is 150 m.

5.2.8 Other equipment and installations

Electrification is 750 V DC. There is one substation 230/23 kV located at Oceania and 19 rectifying stations of 4000 kw.

Current is provided by means of a third rail.

Each station has two substations for lighting and energy purposes 23000/220-127 volt, 60 Hz, with 225, 300 or 500 kVA depending on the type of station, and 1000 KVA for the depot/workshop.

Other systems are:

- Train radio phone system
- Phone au
- Central dispatching centre (PCC)
- Automatic guidance (SACEM)
- Signalling system
- Loud speakers
- Clocks
- Interphone system
- Turnstiles

5.2.9 Construction phases

The line has been built in two phases.

Phase I covers the Mexico DF section, with 13.5 km, and it is in operation since December 1999.

Phase II, under construction, completes the section along Mexico State, long 10.2 km, and is scheduled to start operation in November 2000.

Phase II was not initially planned, but occurred when in 1997, the Congress decided a strong shortage of funds as a consequence of strong peso devaluation.

Contracts had to be renegotiated and line length was restricted to the section within Mexico DF, then nominated Phase I.

5.2.10 Unit and total costs

According to the information provided by DGCOSTC on line B costs, total line cost has been 970 US$ millions, including rolling stock, which means a unit cost of 40.92 million US$ per line km.

Infrastructure costs are 13.37 MUS$/km (32.7%), while equipment (both for line and stations) account for 8.58 MUS$/km (21%), the 17.3 MUS$ per km being for rolling stock (42.3 %), and the remaining 1.62 MUS$/km (4%) is dedicated to technical assistance.

A significant part of the civil works cost goes for road structures and new coincident roads at the surface sections of the line.

If we allocate all these "road system" costs to the surface sections, we find that construction unit costs at the surface sections becomes comparable to costs at underground sections.

5.2.11 Construction timing

The line started to be designed in 1993, and its first section opened in December 1999, thus taking six years to be designed and built in its first section.

Construction started in 1994, but big delays arose in 1997 as a consequence of contract renegotiations by shortage of funds due to devaluation.

Phase II is scheduled to start operation in November 2000.

5.2.12 Construction management

Financing of metro construction, since 1997, is not anymore made by the National Federal State, but by Mexico DF state. This has implied a change in funding schemes, worsened, as explained before, by the 1997 devaluation, that resulted in a shortage of funds for the construction of the line decided by Congress.

Responsibility for the design, construction and supervision of the line relies in DGCOSTC, a General Direction of the Mexico DF state, within the Secretary of Public Works, that is formed by some 250 persons, and subdivided in 10 areas:

- civil engineering design
- electromechanical design
- civil works
- electromechanical works

- service deviations
- acquisitions
- procurement and cost control
- administration
- accounting
- legal matters

DGCOSTC relied in consultants for the following tasks:

- basic design (one single contract)
- final design (one contract per section, underground, elevated, surface), including technical advice during construction phase
- technical assistance for equipment design and supervision

5.2.13 Construction lots and contracts

Civil works have been divided in sections according to the engineering characteristics in underground, elevated, and surface sections.

Underground section has been divided in 4 lots, by distance.

Elevated section in 3 lots, one for pillars and foundations, another for beams and a third one for service deviations.

Surface section divided in 5 lots, by distance.
Track and Power Supply has been divided in two different contracts (North and South).

Signalling, Communication, and Passenger toll contracts directly by Acquisitions Dept.

Rolling Stock is contracted directly by the operator STC.

5.2.14 Main constraints

DGCOSTC officials claim an increasing opposition from population to locate station entrances location close to their houses, due to concentration of ambulant vendors and "shops" in the vicinity of metro stations.

Same problem arises in final location of pedestrian bridges over the metro alignment in open air sections.

Geotechnical conditions are a big problem, some areas of the city literally sinking several centimetres per year, on top of drainage problems, and seismic constraints.

They claim also disloyal competence from bus services, not just feeding the metro stations, but competing with metro ridership. Buses stop like taxis, at customer demand for boarding and alighting passengers, and do not meet standards for a public service, most of them being industrial vehicles adapted as buses.

Structure contracts lot division keeping apart beams and pillars have proved to be inefficient, causing delays and lack of responsibility.

Future network plans are made by the operator. The last revision dates from 1997 trying to build a network more demand- based, rather than a strict grid pattern as initially planned. Imminent projects are extension to the south of line 7 and 8, and construction of line 12 using a part of present line 8.

Several light rail lines are also planned.

6.- Caracas

6.1 Network description

Caracas metro network is formed by 3 lines totalling an extension of 42.5 km.

Metro operation started in 1983, line 2 starting operation in 1997 and line 3 inaugurated on December 1994.

Total number of stations of the system is presently 39.

C.A. Metro de Caracas, planners builders and operators of the system is owned 99% by the State, 0.5% by Centro Simon Bolivar CA and 0.5% by Instituto Autónomo de Ferrocarriles del Estado.

Financing of the metro system comes from the following sources:

1. Civil works design, technical assistance and engineering services by state credits both at internal and external markets.

2. Appropriations by the Government (Bonds).

3. Equipment acquisition by Metro de Caracas, using external credits, with State warranty.

4. Construction administration and pre-operation, by resources included in State Annual Budget.

Planning follows the initial 1979 plan, a total of 6 lines being planned. Lines to be constructed at short term are Line 4 (pre-construction already started, and 86% of contracts signed) and extension of Line 2 to Los Teques from Las Adjuntas, to serve an estimated 400,000 population.

Other public transportation networks in the city include METROBUS operated by the metro company, a bus-feeding system of Metro stations, with integrated fares, that includes 26 lines and a 528 km network.

Besides, more than 15,000 minibuses (many of them pirate), compete with metro on a deregulated basis.

Metro transports 285 million passengers a year (1,100,000 daily passengers), 15% of them using metrobus services.

6.2 Line 3 construction

Line 3, the latest metro line built, runs from North to South, in the central part of the city, with a total extension of 4.38 km and four new stations.

It is part of the initially planned line La Rinconada-Panteón.
It provides connection with line 1 at Plaza de Venezuela.

Its construction began in 1988 and operation started in December 1994.

6.2.1 Objectives

Line 3 extends metro accessibility to the University area as well as El Valle district.

Interchange at Plaza de Venezuela provides access to line 1, the backbone of the system.

Its extension to La Rinconada, already planned, will serve some 500,000 habitants.

6.2.2 Functionality

Although designed for higher capacity when it is extended, the line is presently operated with 4-car trains holding 720 passengers, at a peak-hour headway of 3.5 minutes.
. Capacity is calculated at a density of 4 standing passengers/m^2.

Its present capacity is, therefore, 12,960 pax/hr and direction.

6.2.3 Relationship with other lines

It has an interchange station at Plaza de Venezuela with line 1.

Access to line 2 has to be made by mean of two transfers at Plaza de Venezuela, and Capitolio.

6.2.4 Infrastructure

Total line length is 4.38 km, all of them underground.

Construction length involves a total of 6.417 km considering line and connections.

Line runs at variable depths between 16 and 28 m below surface.

It runs in two independent 5.6 diameter single track tunnels (one for each direction) built with tunnelling boring machines.

Small sections at El Valle terminal and stations have been built by cut and cover method.

6.2.5 Stations

The line has a total of 5 stations, including the Plaza de Venezuela transfer station with line 1 (Plaza de Venezuela, Ciudad Universitaria, Los Símbolos, La Bandera and El Valle).

They are central platform stations, given the two tunnel pattern adopted, built by cut and cover method.

Stations are 150 meters long, to hold 7-car trains when it is extended, even when only 4-car trains are presently operating.

Station design provides wide mezzanines, two to three station levels, and two/three accesses per station. Stations are provided with air treatment (chilling water).

6.2.6 Rolling stock

Trains are formed by 4-car sets on steel wheels, 21.36 m long and 3.50 m wide, providing 54 seated places, and a total capacity of 180 passengers per car, at a density of 4 standing passengers per m^2.

Rolling stock for line 3 considered 35 new cars (8 four car trains plus 3 reserve cars).

Structure is in aluminium, and air conditioning is provided to ensure 25ºC. All cars are motor cars, in two different types A (with cabin) and B (without).

Trains run on 750 V DC collected from third rail.

6.2.7 Superstructure

Track is conventional steel rail, gage 1.435 m, laid over concrete slabs. There are 10 switches, located at three connecting points and one crossing.

6.2.8 Other equipment and installations

Electrification is 750 V DC. There are three substations 30,000/750 V DC plus an interrupting station 750 V DC at Plaza de Venezuela.

Third rail distribution at 750 V DC to trains is provided along superstructure.

Other systems are:

- Train control: includes all signalling, control and telecommunications systems both on board of the trains, along the lines and at the central control centre (Centro de Control de Operaciones).

- Major ventilation: includes fans, ducts and louvers at the stations, both for emergency and usual service totalling 27 emergency tans, 7 service fans and 10 extract fans below platform.

- Escalators. In the 5 stations are provided 35 escalators (13 of them external).

- Passenger toll equipment: 35 turnstiles, 8 ticketing machines, 4 info panels and 4 codifying reading machines.

- Air conditioning (chilling) at stations and minor ventilation. Plaza de Venezuela station was connected at the system of line 1. For each one of the other stations the whole system (chilling units, pumps, tubes, ducts and louvers were provided.

- CCTV. Including 77 cameras and 3 monitors per station.

- Time clock system: 26 clocks plus time central.

- Information and signalling passenger system.

- Fire prevention, and control: 4 fire control rooms, hydropneumatic system, detection system, water and foam system plus pumping of sewage waters, and drainage.
- Emergency power supply: one UPS per station and emergency equipment.

- Central Data Acquisition: computers, printers and multiplexer for each station and at the control centre.

6.2.9 Construction phases

Line 3 has been built in one single phase.

Nevertheless, as in other metro line contracts, pre-construction phase (that involves expropriations, rentals, demolitions, services deviation and traffic deviation) is differentiated from the Civil Work phase and Post-construction phase.

6.2.10 Unit and total cost

According to the information provided by C.A. Metro de Caracas, total line cost has been 47,117,169 Bolivares, year 94, which stands for 372 MUS$.

This implies a total unit cost of 57.98 million US$ per line km, construction length being 6.417 km.

Infrastructure costs, including expropriation and service deviations explain 44.2 % of the cost, with a unit cost of 25.66 M US$/km the whole line being underground, except a small section at El Valle Terminal.

Equipment (both for line and station equipment) explain 31.1 % of the total cost, with a unit cost of 18.05 M US$/km. Notice that chilling system at stations is not provided at any other of the metro systems analysed.

Rolling stock costs to provide a capacity of 12,960 pax/hr and direction has been 75 million US$, with a unit cost per operational km of 17.14 M US$/km, being responsible for a 20.1 % of the unit cost.

Design, technical assistance, inspection and supervision costs totalled 16.43 million US$, with a unit cost of 3.75 M US$/km, per operational km, thus implying a 4.6 % of the total line cost.

6.2.11 Construction timing

Line 3 design started in 1980´s.

Construction time was around four years starting in 1988. The longest civil engineering contracts were around 40/41 months. The line started operation in December 1994.

6.2.12 Construction management

Responsibility for design, construction and supervision relies on the operator CA Metro Caracas.

Metro personnel is in charge of preliminary design.

For line 1, North American consultants were contracted.

Line 2 was designed by local consultants. Lines 3 and 4 preliminary design were made by CA Metro Caracas.

After preliminary design is finished, two big contractors are contracted: Civil works and integral system.

Integral system includes track, power supply, signalling and communications, as well as station equipment.

Supervision and control of construction is made by specialised metro personnel (200 persons).

Special technical assistance contracts are signed with different experts.

6.2.13 Construction lots and contracts

Line 3 civil works were divided in three sections. Each section was subdivided in sectors, each one taking care of one station or interstation, and according construction method (tunnels or cut and cover).

The total construction work consisted of 15 sectors.

Several sectors were built by the same construction company.

Unit cost of the different sectors were monitored independently.

6.2.14 Main constraints

No major constraints have been registered by metro officials.

They claim their dependence on foreign equipment, national production of specialised equipment being scarce.

6.3 Line 4 estimations

The line Capuchinos-Parque del Este has an extension of 12.3 km with 9 stations, and will run parallel to line 1.

The first Phase Capuchinos-Plaza Venezuela is in the expropriation process and 86% of the contracts have been signed. The length of the line is 5-9 km long.

6.3.1 Objectives

The main objective of line 4 is to relief congestion in line 1, and provide capacity to undertake construction of extension of line 2 to Los Teques.

Presently line 2 cannot be extended, because it ends at Capitolio, where a transfer is provided with line 1, already congested. Line 4 is planned to be in extension of line 2, parallel to line 1, even with joint operation thus saving transfer time for line 2 passengers.

It is designed to transport an additional 550,000 daily passengers.

It intends to provide a relief on traffic congestion as well.

Phase II will serve also the South East Caracas area not covered by line 1 (Bello Monte, Las Mercedes, Tamanaco, Chuao).

6.3.2 Functionality

Phase I is 5.9 km long and has 4 stations. It is intended to allow continuous operation for line 2 trains to Plaza de Venezuela from Caricuao, thus, saving the present transfer needed at El Silencio-Capitolio.

It is completely parallel to line 1, and needed to provide higher capacity on this major east-west-corridor.

A further third line is planned parallel to line 1, this time on the north side.

Starting from Capuchinos station, a new connection has to be provided with line 1 at Plaza de Venezuela.

Line is planned to provide 21,600 passengers/hr, running 7 6-car trains with individual capacity of 1,080 passengers at headways around 3 minutes.

Further capacity could be achieved increasing rolling stock, minimum headway being 120 sec.

6.3.3 Infrastructure

Line alignment is totally underground, and different construction methods will be used.

Stations will be constructed by cut and cover as in the previous lines.

Tunnelling will be made by three different methods: 380 m mining for connection with line 2 sections, twin tunnels with shields (3,722 m) and cut and cover sections (820 m).

6.3.4 Stations

The whole line will have 9 stations, Phase I having 5 stations, one of them existent (Capuchinos) and four new (Teatro, Nuevo Circo, Parque Central and Zona Rental).

6.3.5 Rolling stock

44 new cars will be provided this time including 14 trailer cars (before were all motor cars). It will be provided by ALSTHOM, renegotiating an existing supply option in line 3 contract.

6.3.6 Superstructure and installations

Same principles will be applied as for line 3, with new quantities.

- Track switches: 14
- Substations 30,000/750: 3
- Substations 69/30 kV: 2
- Escalators 28 (11 externals).
- Major ventilation fans 38
- Chilling and minor ventilation (4 units)

6.3.7 Construction phases

As said, Phase I will cover the Capuchinos to Plaza de Venezuela sector, and is now in the bidding/contracting process.

Phase II will be contracted later.

6.3.8 Timing and management

No significant changes provided, excepted an increasing role of CA Metro personnel.

6.3.9 Lots and contracts

A similar system to line 3 is applied, again with 3 sections subdivided in sectors according to construction method.

A single contract has been signed for the whole civil works line construction with ODEBRECHT.

6.3.10 Unit costs estimate

Infrastructure, including services deviation and expropriations is estimated at a unit cost of 40.68 M US$/km (43.5%).

Equipment is estimated at a unit cost of 22.48 M US$/km (24.0%).

Rolling stock is estimated being a line 3 extension option at a unit cost of 25.77 MUS$/km (27.5%).

The remaining 5% is dedicated to design, supervision and technical assistance (4.64 M/km).

Equipment cost has been estimated to follow line 3 structure.

7.- The Santiago metro system and the construction of line 5

7.1 Network description

Santiago metro network in operation is formed by 3 lines, totalling an extension of 37.6 km.

Line 1 started operation in 1975, line 2 in 1978, and line 5 in 1997, with an extension to the city centre just opened in March 2000.

A new alignment was decided for the third line in 1990, and it was designed as number 5, to match the planning scheme, ant to avoid legal confusions with studies and contracts already prepared for line 3.

Until 1990 metro was depending on the Secretary of Public Works. In 1990 it became a corporate company Empresa de Pasajeros Metro, S.A., its stakeholders being the Corporación de Fomento (72%) and Ministerio de Hacienda (28%).

Other transportation systems in the area

There is a single railway commuter line (METROTREN), that runs services to Rancagua (100 km South of Santiago) with Spanish gage (1,668 mm) and has been recently renewed.

The rail line to Valparaiso is not running anymore.

There are studies about reopening this line taking advantage of the existence of an underground tunnel across the city interconnecting both lines. A huge rail station would be constructed in the centre, and the metro line 5 further extended to connect both systems.

METROTREN system runs two services an hour with prices higher than those of metro. Its demand is 3.5 M pax/yr.

Bus services were deregulated between 1973 and 1980 and the number of buses skyrocketed, with big traffic congestion and emissions problems. In 1991 2,600 buses older than 15 years were “bought out” by the Government. Nevertheless, there are still more than 14,000 buses in the urban area, with up to three bus-lanes in the same street in central avenues.

Concessions are granted favouring large buses, automatic fare collection and low fares. Standard fare is now 250 pesos, as compared with 300 pesos of metrotren, or 270 pesos of Metro at peak-hour.

Metro has an agreement with several private bus operators, and operates “METROBUS”, blue buses feeding metro terminals at a fare of 230 pesos.

7.2 Line 5 and its extension

Line 5 runs from La Florida to Baquedano, where it intersects with line 1. Operation started in April 1977.

It covers 10.3 km with 12 stations, and was designed in 1990. The go-ahead decision was taken by the President of the Republic in 1991, and final alignment was approved in December 1992.

Construction started in January 1994 and finished April 1997.

During the construction period, in 1996, it was decided to extend the line 2,8 km under the city centre, with three new stations, interconnecting with line 2 at Santa Ana station.

Along 1996 and 1997 extension design proceeded, construction started in 1998, and operation in March 2000.

Line 5 local currency financing (55%) was done by the State, will the foreign currency component (45%) was financed by the Metro Company.

It has to be said that Santiago Metro is one of the very few operators in the world with profits in its annual balance, covering more than 100% of their expenses by passenger faces and commercial revenues.

7.2.1 Objectives

The line was based on the alignment of an existing railroad that was dismantled in the 1940´s. It serves La Florida, a quarter with an impressive growth during the last twenty years, against prognoses of urban planning.

La Florida was founded in 1899. Located in the South East of the urban area, it is the most populated urban area in Santiago (6.6% of the population). Household increase in the area between 1982 and 1992 has been 77%, growing at a 5.5% per annum while the whole Santiago was growing at 2% per annum.

The objective of the line is to serve the nearly 500,000 daily trips from La Florida, 54% of them being made in public transport. (Plan ´68 Metro did not consider this line).

Car ownership in Santiago was 50 vehicles per 1000 inhabitants in ´91.

On its way between La Florida and the centre the line serves other communities (Ñuñon, San Joaquín, La Granja and Macul) less important in population but adding other 500,000 inhabitants to the influence area of the line.

7.2.2 Functionality

The line is designed for a capacity of 29,370 pax/hr/dir, with a total of 12 6-car trains running at 2 min headway.

This figure considers a density of standing passengers of 6 pax/m^2.

If we consider 4 pax/m^2, the train capacity is 714 passengers instead of 979, and the line capacity will drop to 21,420 pax/hr.

A depot has been built at the open air section.

Lines started operation between Florida and Baquedano in April 1977 being extended to Santa Ana in March 2000.

7.2.3 Relationship with other lines

Line 5 allows transfer with line 1 at Baquedano, where a multilevel station was built.

Lately, line 5 extension provided further interchange with line 2 at Santa Ana.

7.2.4 Infrastructure

Total line 5 length is 13.2 km. The first section (Florida to Baquedano) is 10.3 km long, and the extension to Santa Ana added 2.9 km to complete the 13.2 km.

While the extension is underground, the initial line has 3.2 km in tunnel, 6 km in viaduct and 1.1 km at surface level.

Tunnelling sections, normally 16-17 m deep, have been constructed using the New Austrian Tunnelling Method (NATM) starting with circular access shafts of 15 m diameter.

Viaduct sections are standard 36 m span units with that include 14 m wide stations.

Maximum grade used has been 3.5% and minimal radius 240 m.

7.2.5 Stations

The line has a total of 15 stations, 12 of them being in the first section (La Florida-Baquedano) and 3 more in the extension to Santa Ana.

Six stations are located in the viaduct section and one at grade, adjacent to the workshop.

Station at Bellavista-La Florida includes an underground metrobus interchange terminal.

Stations in the extension section, Museo de Bellas Artes and Plaza de Armas an also underground.

The transfer station with line 2, at Santa Ana Station, is also underground for line 5, although in open air for line 2.

Train interconnection between both lines is made by an open air section. Station length is 135 m.

7.2.6 Rolling stock

Trains, similar to Paris Metro rubber-tyred ones, are formed by six cars, 15.38 m long and 2.5 m wide, providing a total capacity of 979 passengers, at 6 pax/m^2 for standing passengers.

Rolling stock order for line 5 consisted of 12 trains (72 cars) with 5 additional trains being ordered for line 5 extension.

Structure is in aluminium, and the late series are equipped with interconnection between cars. They are not air conditioned, but a powerful ventilation system (150 renovations/hr) is provided.

7.2.7 Superstructure

It is formed by engraved steel tracks for rubber type support plus two lateral guideways for guidance and current collection and the security conventional rails (40 kg/m). Track is laid on bi-block concrete sleepers, that rely on a concrete slab.

7.2.8 Other equipment

Electrification is 750 V DC. There are 8 substations of 4000 KVA each.

Third rail distribution is made along the same lateral guidance rails.

Other systems are:

- Train control: includes signalling, control and communication equipment. SACEM system for automatic operation is provided.
- Ventilation shafts and fans in tunnel sections.
- Escalators and elevators at underground stations.
- Passengers toll equipment: automatic ticket machines (13), turnstiles (63).
- CCTV at stations.
- Information, signalling and emergency passenger systems.
- Lateral guideway in viaducts for emergency evacuations.

– Fire prevention and control equipment.

7.2.9 Construction phases

Line 5 was built first until Baquedano, and then extended to Santa Ana.

Extension was decided in August 1996, less than one year before first phase started operation.

7.2.10 Unit and total costs

According to the information provided by Gerencia line 5, an independent unit from Empresa de Pasajeros Metro, S.A. (the operator of Santiago Metro), total line cost of line 5 has been 15,220 UF (Unidades de Fomento), equivalent to 424 MUS$. Line 5 extension cost has been 7.086 UF, equivalent to 197 MUS$.

This implies a total unit cost of 40.91 million US$ per line km for line 5 and 70.11 for the extension.

Line 5 having only a small underground section, is not therefore directly comparable with the extension.

In graph 2 can be seen that civil works costs are 41.6% of the total cost in the extension, while only 33.4% in the initial line.

Equipment, and rolling stock values are much more similar on both lines.

Technical assistance almost doubles its share in the extension, presumably by the high monitoring cost, and the technical assistance involved in using the NATM method, but no collapses, casualties or delays were reported in the construction.

7.2.11 Construction timing

Line 5 construction decision was taken in 1991. Studies about rubber-tyred system or steel wheel were undertaken first, and design started after confirming rubber-tyred system election in 1993.

Construction began January 27, 1994 and operation started April 5 1997, taking therefore 38 months to complete 10.3 km, most of them in prefabricated viaducts.

Line 5 extension decision was made in August 96, construction began in 1997 and operation started March 3rd, 2000, again some 38 months to complete, this time for 2.8 km, almost totally underground.

7.2.12 Construction management

Responsibility for design, construction and supervision relies on Gerencia Línea 5, an independent management unit depending directly from a Committee that included seven Government Ministers, to prevent any misappropriation risks.

First, a study was contracted to Electrowatt, to decide whether rubber-tyred or steel wheel should be considered (Santiago had already two rubber-tyred lines).

Later, a call for rolling stock tenders was issued.

24 international firms concurred, seven were prequalified and 4 submitted their bids. Alsthom was awarded the contract in 1993.

Once decided the rolling stock, preliminary design was contracted, specifically for the rolling stock decided. Sofretu was appointed for their job.

Two main contracts were established: civil engineering and railroad equipment.

As far as railroad systems and equipment are concerned the line 5 project asked for turn-key projects for each system, involving detailed final design, equipment fabrication, mounting, guarantee, and spare parts strategic lists, but not maintenance.

The same contract structure was adopted for all systems.

Strict time planning and cost control were adapted, with a separate accounting new system for line 5 construction, that resulted in a 0.6% deviation in cost, and on-schedule commissioning of the line.

Line 5 extension to Santa Ana was considered as an option in the initial project, and decided in 1996 negotiating directly with contractors.

Technical assistance was contracted with Sofretu, while inspection and supervision was carried out by Gerencia línea 5 with some metro personnel and external assistance contracts.

An 8% savings is reported in the extension of line 5, when compared with budget, that was planned to attend unexpected costs, and not needed finally.

7.2.13 Construction lots and contracts

Final design was divided in sectors (viaduct, surface and 2 underground sectors), and civil engineering construction in 9 lots (A to I) that were awarded to 6 different contractors (bidding for more than one lot was allowed).

Equipment supply was contracted independently, as turn-key projects with the same contract structure.

7.2.14 Main constraints

In order to minimise impacts on traffic and urban life, a new version of NATM was adapted for the underground sections, with 15 metre diameter shafts being the only surface access connection.

Seismic risks in the area involved extensive research for viaduct sections, two of them being equipped with special controls in order to monitor seismic behaviour of the structures.

8.- The extension of Madrid Metro System 1995-1999

8.1 Network description

Madrid underground network is formed by 12 lines.

The first line started operation in 1919.

Before the ´95-´99 extension plan the network totalled 120 km, with 164 stations.

The extension plan involved 56 km and 38 stations in 8 different lines (see general map). While seven of them were built by the Regional Authority (Comunidad de Madrid) the extension of line 9 to Arganda del Rey (mainly at grade) was built in a public private partnership by TFM (Transportes Ferroviarios de Madrid) a private company formed by Madrid Underground, S.A., Caja Madrid, and three civil engineering construction companies.

Financing on the construction of the 37 km underground section was made by Arpegio (a company 100% owned by Comunidad de Madrid) that raises loans from the open market to pay for the works, being paid by CAM annually. Arpegio owns large urban area land plots and guarantee credits.

Presently, a second extension plan 2000-2004 is being built, totalling 50 km and involving three new lines.

Madrid underground transports daily 2 million passengers.

Other public transportation networks include Cercanías, the commuter railway system with 850,000 daily passengers, 485 km and 10 lines, and the urban bus system, with a 180 line network totalling 2,915 km and 2 million daily passengers.

Besides, interurban buses serve the metropolitan area with 309 lines, totalling 3.200 km network and 800.000 daily passengers.

Fare integration is total between the four systems for monthly tickets, the most widely used ticket type.

In addition 10 trip tickets at high discounts are available for each one of the systems, or combined metro-bus tickets.

8.2 The metro extension plan ´95 - ´99

Data have been arranged by line, involving 8 different lines (1, 4, 7, 8, 9, 10, 11 and Arganda extension of line 9).

Generally, extensions were made at one end of an existing line, and once in the central section (connecting two existing lines with a new stretch to become a single "new" line). Line numbers used are the present ones, after the extension took place. Two short new line (8 and 11) were built.

While the CAM-built lines are 100% underground, the extension to Arganda has only a small part underground, the majority being a surface line running along a scarcely populated area (only 4 stations in almost 20 km).

Therefore, two different average value have been used for Madrid data, including or not the Arganda line.

8.2.1 Objectives

The extension plan was designed both to increase accessibility to underground network, deserving new areas, and to enhance functionality of the existing network.

The ultimate objective is to promote the use of public transport.

Eight new districts are being served now by the metro network.

8.2.2 Functionality

Madrid underground has two different types of rolling stock and tunnel sections, using the same 1,435 mm gage. The "narrow" lines (1 to 5 and 10) use 2.30 m width series 2000 cars, while the "large" lines (6 to 9 and 11) use 2.80 m width series 5000 and 6000 cars.

Therefore, when extending old lines, both types of sections and rolling stock have been used, to provide continuity with existing lines operations.

Besides, station length is also different between lines.

While lines 1 to 4 were originally built for 4-car trains with station lengths of 60 m, from line 5 on, (1960´s) lines were built for 90 or 105 m long trains, and line 1 stations were extended to 90 m.

The extension also provide connecting of two north-south lines by means of a central section that forms a single north-south through new-line 10 with interchanges to all the others.
The existing north line was a “large one” while the existing south line was a “narrow one”. Therefore, the connecting section was built with the large section, but initially equipped with the “narrow” trains. In the second extension plan 2000-2004 old narrow tunnels and station are being enlarged to be able to use the series 6000 wider trains, in order to increase capacity.

Depending on existing headways, capacity varies in the different lines from 4,537 pax/hr and direction in the Arganda line, to 18,573 pax/hr/line in line 1 (calculated at 4 pax/m^2/standing).

8.2.3 Relationship with other lines

Line extensions and new lines are interconnected with existing lines. Of the 38 new stations, ten are interchange stations with other lines.

8.2.4 Infrastructure

Table presents lengths, station number, capacities and data of each one of the lines.

	L 1	L4	L7	L 8	L 9	L9 Arg.	L 10	L 11
Length in km	2.83	4.35	11.43	7.98	4.6	18.3	4.22	2.6
Number of stations	3	4	14	2	6	4	1	3
Number of cars	53	48	54	22	24	14	53	4
Line capacity per hour	18,573	10,170	14,003	6,045	14,682	4,537	15,900	4,608
Construction start date	15.2.97	15.3.96	10.6.96	15.2.97	13.7.96	9.4.97	20.4.95	15.2.97
Operation start date	11.3.99	15.12.98	12.3.99	7.9.99	1.12.98	7.4.99	22.9.98	16.11.98

There is a wide variety, as explained before, depending on the characteristics of previously existent lines.
Nevertheless, some general principles have been adopted for construction, being adapted later to specific dimensions and requirements of each particular line.

The most important, in relation with time and cost results is the adoptions of EPBMs for construction, the administration directly involved in their design and specifications. Eight tunnelling boring machines were used simultaneously in the construction works. 23.7 km (64% of tunnelling length) has been built using EPBM, while 21% with diaphragm walls (stations) and only 15% by traditional Madrid method including "manual" excavation.

Normally, single 9.5 m diameter double track tunnel was adopted, for wide rolling stock, and 7.6 m diameter for "narrow" rolling stock lines.

8.2.5 Stations

Stations have been built with diaphragm walls, allowing quick traffic restoration on the surface streets.

The method also allowed for new designs with spacious mezzanines, and easy access and interchange.

All stations are provided with elevators from street level to ticketing halls, and from ticketing hall to platforms.

Normally stations have two lateral platforms, although there have been some exceptions in interchanges, were central platform stations have been used.

8.2.6 Rolling stock

Depending on the line, trains are formed by 4 or 6 cars, either narrow (series 2000) or wide (series 6000).

Series 2000 are 2.30 m wide, 15 m long cars, with 24 seated passengers, and a total capacity of 98 passengers at 4 pax/m^2.

Series 5000 and 6000 are 2.80 m wide, 10 m long cars with 26 to 34 seated passengers and a total capacity of 150 passengers at 4 pax/m^2.

Train sets are formed by 2 car units (Arganda) 4 car units (lines 4, 8 and 9), 5 car units (line 7) or 6 car units (lines 1 and 10).

Rolling stock acquisition for the different lines is as follows:

L1	53 series 2000 cars
L4	48 series 2000 cars
L8	22 series 2000 cars
L10	53 series 2000 cars
	176 series 2000 cars

L7	54 series 6000 cars
L9	24 series 6000 cars
L11	4 series 6000 cars
L9 Arganda	14 series 6000 cars
	96 series 6000 cars

All new series are air-conditioned, and provide 8 doors per car.

8.2.7 Superstructure

Track is conventional welded steel rail 54 kg/m, 1,435 mm gage, embedded in concrete slabs using concrete blocks, a corkelast material and VOSSLOH fasteners.

8.2.8 Other equipment and installations

Electrification is 600 VDC supplied by overhead rigid rail in aluminium or conventional overhead catenary line. In the extension line 12 substations have been built.

Other systems included are:

- Train control: signalling, control and communications system with CTC, ATP and ATO.
- Ventilation shafts and fans both at stations and tunnel.
- Escalators: 229 for the 38 stations plus 8 horizontal travelators.
- Lifts: 122 units for the 38 stations.
- Passenger toll equipment: turnstiles, and ticketing machines in all stations.
- CCTV, clock systems.
- Fire prevention and control systems.
- Information and signalling passenger systems.
- Emergency lighting and power supply.
- Evacuation photoluminiscent system at both stations and tunnels.

8.2.9 Construction phases

The whole extension plan has been built simultaneously, under different lots and contracts as explained later.

Infrastructure contracts include pumping stations, track laying and tunnel lighting, in order to have tunnels ready for later equipment installations.

8.2.10 Unit and total costs

Average implementation costs, including the Arganda line, have been 22.79 million US$ per km.

When considering only the underground extensions, without the Arganda line, average implementation costs have been 31.19 million US$ per km. (1 US$ = 189.70 pts).

Infrastructure costs, including expropriation and services deviation are responsible, for 62.1 % of the cost, with a unit cost of 14.15 M US$/km including the Arganda line, and 19.83 M US$/km excluding it (only underground sections).

Equipment explain 18.2 % of the total cost, with a unit cost of 4.13 M US$/km including Arganda line and 5.13 M US$/km excluding it.

Rolling stock costs to provide capacities matching the different line requirements (between 4,537 pax/hr and direction at the Arganda line and 18,573 pax/hr and direction on line 1) at 4 standing passengers/m^2 are responsible for a 17.7 % of the total cost including the Arganda line with a unit cost of 4.03 M US$/km, and 5.54 M US$/km when the Arganda line is excluded.

Design, technical assistance, inspection and supervision costs explain 2.1 % of the total cost, with a unit cost of 0.48 M US$/km when including the Arganda line, and 0.69 M US$/km excluding it.

Units costs per line are given in graph. MAD 2, showing values according with the different characteristics of each line.

8.2.11 Construction timing

Extension designs started almost jointly in 1995. Construction works started and finished (commission dates) at the following dates.

km		start date	finish date
2.83	Line 1	15.02.97	11.03.99
4.35	Line 4	15.03.96	15.12.98
11.43	Line 7	10.06.96	12.03.99
7.98	Line 8	15.02.97	07.09.99
4.6	Line 9	13.07.96	01.12.98
4.22	Line 10	20.04.95	22.09.98
2.6	Line 11	15.02.97	16.11.98
18.3	Line 9 Arganda	09.04.97	07.04.99

It is to be noted the extremely fast performance of EPBM (Earth Pressure Boring Machines) with a maximum performance of 39 m/day and an average exceeding the 9,5 m/day specified. Eight EPBMs were used, six of them 9,5 m diameter and two of them with smaller diameters (7,4 and 6,5 m).

Although final design timing is included in the 4 year extension program, preliminary design was included at planning stage and was already available in 1995.

8.2.12 Construction management

Responsibility for planning relies on Consorcio de Transportes de Madrid. Design, construction and supervision were made by the regional government, Comunidad de Madrid, Consejería de Obras Públicas, Urbanismo y Transportes.

Metro personnel co-operated in supervision and commissioning task.

External consultants were employed for final designs, quality control and job supervision, although administration technical team was directly involved both in design, machinery specifications and construction supervision.

8.2.13 Construction lots and contracts

Civil works were divided by lines, and each line in different lots. Total number of lots have been 14.

Final design, supervision and quality control were split according to the some lots.

Equipment contracts were divided in 6 systems: power supply, overhead line, escalators and lifts, signalling and automatic operation, radio and communications, and ventilation, matching each lot.

Two general contracts were signed, one for automatic vending machines and other for toll passenger control (turnstiles).

Rolling stock was acquired by two different contracts (series 2000 and 6000). The series 2000 contract was an option of an old contract for renovation of Madrid rolling stock, which explain the extremely convenient price.

Series 6000 contract, for larger and larger units, was, comparatively much more expensive.

8.2.14 Main constraints

Imposing construction methods, machinery and specifications on constructors was one of the big constraints that proved to be very effective, both in construction time and cost results.

Geotechnical problems were overcome by an extensive real-time centralised monitoring.

8,255 sites were real-time monitored in Madrid.

5,400 subsidence sensors, more than 300 buildings monitored, 52 instrumented tunnel sections, 65 instrumented diaphragm wall sections and more than 43,000 samples tested.

Overall construction time was a major constraint, the metro extension being a political promise to be performed in 4 year time, needing to be in operation well before election date.

On the other hand, this fact acted as a general motivation for all teams, constructions and administrations that helped the project to be on-time and without substantial cost deviations.

9.- Comparative report

9.1 Comparison structure

In order to compare the different systems, several factors have been homogenised.

Besides considering unit costs per km, we have split civil works costs in order to compare cost for tunnelling sections.

Expropriations and services deviation have always been included under civil works.

Equipment and installations have been subdivided in seven general subsystems (track, power supply, signalling, station equipment, escalators and lifts, toll equipment and workshop equipment), putting together figures of several much more detailed classifications.

Rolling stock unit costs per km have been calculated both at their general value, and for a unit capacity of 10.000 pax/hr and direction quality level of 4 standing passengers/m^2. Before this homogenisation there were big differences, some networks considering 6 pax/m^2 (and transporting even more) and different train length and composition being considered.

Technical assistance includes administration, preliminary and final design, construction supervision, management, inspections, and quality control both internal and contracted.

All figures include taxes, and customs duties when applicable under each one of the items.

Costs have been included as given by the respective administrations and US$ exchange rates applied as of September 2000. Despite our effort, figures given might not be strictly comparable, due to different criteria of exchange rates applied. In Caracas line 3 there are 1994 figures, while in line 4 there are expected costs in 2000 for future construction. Mexico figures were provided directly in US$, and we presume that they reflect the exchange rates at the time the payments were made in the different contracts.

In some cases, with extended construction times and important local currency depreciation against the US dollar, costs in dollars might be underestimated for quantities paid in local currencies. We include graphs of exchange rate evolution between local currencies and US$, to remind of this effect, but do not have the level of information required to homogenise all figures correctly.

Results are presented in graphs showing different aspects:

- Total unit cost comparison in millions US$/km
- Unit costs for each one of the four big chapters considered:
    - Civil works
    - Equipment and installations
    - Rolling stock
    - Design, supervision, and management

Most significant items of each one of these chapters have been compared:

- Tunnelling costs within civil works
- Main systems in equipment:
    - Track
    - Power supply
    - Signalling and communications
    - Station equipment
    - Escalators and lifts
    - Passenger toll equipment
    - Workshop equipment when applicable
- Unit cost per same capacity provided in rolling stock

9.2 Total implementation costs per km

Values presented include costs in Millions US$/km for

- Mexico City line B (2nd phase in construction)	40.92
- Caracas line 3 (1994)	57.98
- Caracas line 4 (construction to begin in 2001)	93.56
- Santiago line 5 (1997)	40.91
- Santiago line 5 extension (2000)	70.10
- Madrid extension average without Arganda (1999)	31.18
- Madrid extension average with Arganda (1999)	22.79

as given by the different administrations.

In part, the large cost differences arise from the physical differences among lines compared . The two lower Latin American figures (Mexico City and Santiago Line 5) include substantial sections on viaduct or at grade, as does the Madrid average with Arganda.

The more homogeneous numbers both because of similar line structure (100% underground), and recent cost figures, are Caracas line 4, Santiago line 5 extension, and Madrid average without Arganda.

Madrid extension unit costs are 30% those of Caracas line 4, and 45 % those of Santiago line 5 extension.

Let us analyse the four main cost components to explain these figures.

9.3 Civil works unit costs

When compared as a whole, civil works costs follow roughly the same structure of total costs.

Data referred only to underground tunnel sections, always in million US$/km are illustrative:

- Mexico City line B (2nd phase in construction)	11.69
- Caracas line 3 (1994)	24.46
- Caracas line 4 (construction to begin in 2001)	31.41
- Santiago line 5 (1997)	21.04
- Santiago line 5 extension (2000)	33.68
- Madrid extension average without Arganda (1999)	19.69

Figures become closer between the most recent data, Madrid costs being roughly 60% of those of Caracas line 4 or Santiago line 5 extension.

As stated before, figures might not be strictly comparable, due to exchange rates applied. In particular, we presume that Mexico figures, directly given by the administration in US$, reflect the exchange rates at the time payments were made in the different contracts

Specific reasons for Madrid lower tunnelling costs, besides general reasons explained elsewhere, are the adoption of single 9.5 m diameter tunnels, avoiding section changes, widespread use of specially designed EPBMs, an extensive geotechnical real time monitoring, anticipating potential problems and its solutions and diaphragm wall standardised design station construction, minimising road deviations and complementary works at surface level.

Nevertheless tunnelling costs are responsible only for one third to one fourth of the total cost difference per km between Madrid average and Latin American cities.

Madrid Metro line cost differences

Figures presented in graph MAD 2 can be explained as follows.

L1 built by Madrid method (no EPBMs) is the most expensive line with 23 MUS$/km, as an extensive soil treatment was needed in more than 2 km.

L7 costs are above average due to some unusual stations and complementary works:

- Islas Filipinas station combined with car underpass
- Magnetic field insulation under Hospital (1 km)
- Two other stations with underground parking lots

L 8 and 9 costs are about average.

L4 and L 10 costs are below average because of a smaller number of stations.

L11 costs are lower because of cut and cover construction (slabs and diaphragm walls), and very shallow alignment depth (around 10 m).

Arganda line low cost being surface line and with small number of stations.

Labour costs and unit prices

Although labour costs are much lower in developing countries than in Madrid, information requested from Spanish construction companies presently working in Latin America shows that construction unit prices are actually higher than in Spain.

This factor has a direct impact on construction costs and might explain by itself a significant part of cost differences in civil works.

For instance, price for structural concrete according to this information rated at the following prices per cubic meter.

Madrid	69.18 US$
Mexico	114.65 US$
Venezuela	149.75 US$
Chile	82.98 US$
Colombia	96.53 US$
Brazil	75.62 US$

It can be seen that prices for this basic construction unit are 10% to 200% higher in Latin American countries than in Spain.

The average labour cost is significantly smaller than in Spain:

Madrid	17.95 US$
Mexico	4.26 US$
Venezuela	4.40 US$
Chile	2.37 US$
Colombia	1.30 US$
Brazil	2.15 US$

But the cost of some materials on site is more expensive. For instance, concrete cubic meter (250 kg/cm^2) prices are the following

Madrid	50.00 US$
Mexico	98.82 US$
Venezuela	118.00 US$
Chile	79.82 US$
Colombia	56.65 US$
Brazil	67.52 US$

Showing increases of 40% to 100% in concrete costs in different Latin American countries when compared to Madrid.

This is not general for all materials. For instance, steel prices are much more similar

Madrid	0.44 US$/kg
Mexico	0.38 US$/kg
Venezuela	0.43 US$/kg
Chile	0.39 US$/kg
Colombia	0.31 US$/kg
Brazil	0.43 US$/kg

The relatively high unit costs might be explained by the higher cost of materials, lower productivity rates and lower degree of mechanisation in Latin American countries, these factors counterbalancing the lower labour costs.

Cross-section at tunnel sections

As far as tunnel construction is concerned, all cases studied run under densely populated areas, with the exception of short sections under parks, or isolated terminals like Florida in Santiago. But in these cases, open air construction is normally adopted. Therefore, we have not found an urban density component explanation in unit cost differences between Madrid and Latin American cities as far as tunnelling is concerned.

In the cases studied, only Caracas went for twin single tunnels in some sections, while Mexico City, Santiago and Madrid are almost 100% double track single tunnel.

In Mexico City, the underground section of line B (6 km) runs at variable depths between 9 and 15 m and was built with rectangular sections (7.20 x 4.90 m), at open air, using diaphragm walls. The deeper sections are used to cross below lines 3 and 8.

On line 3 in Caracas, 3.544 km of twin tunnels were built using shield TBMs, and 1.156 km using the cut and cover method. Tunnels have a diameter of 5.60 m, and the separation between twin tunnels is 6 m. Stations were built by cut and cover method.

In Santiago's Line 5, 3.02 km are underground, running below Parque Bustamante. A variant of NATM was used, including circular access shifts.

Stations have been built using cut and cover method.

Construction methods

The extension of Madrid's metro system was built mainly with Earth Pressure Boring Machines (EPBM).

They proved to be no more expensive than other open face tunnel methods like NATM, TBM open face shields or precutting.

But EPBMs were not chosen to save cost, but for safety and reliability reasons. (See specific article by Manuel Melis in www.comadrid.es/cmadrid/metro/principal.html).

Open face section in tunnel construction can cause geotechnical uncertainty, and for safety reasons it should be minimised, especially in urban areas.

Under difficult conditions, the use of EPBMs minimises the collapse risk. Statistically, a series of NATM collapses seems to show the higher risk it involves. Of course, this does not mean than NATM use implies collapses, but only that collapse risks are higher than with EPBMs. In the Madrid extension case, NATM was forbidden for this reason.

On the other hand, EPBMs are most appropriate for double-track tunnels, where the cross-section remains constant for a longer part of the alignment, not needing structural changes for switches or stations, if side-platforms are adopted as is generally the case in Madrid.

Speed proved to be, at least in Madrid soils, impressive.

9.4 Equipment costs

Data provided present strong variations among the different cities when compared in general, in Millions US$/km:

- Mexico City line B (2nd phase in construction)	8.58
- Caracas line 3 (1994)	18.05
- Caracas line 4 (construction to begin in 2001)	22.48
- Santiago line 5 (1997)	9.60
- Santiago line 5 extension (2000)	11.56
- Madrid extension average without Arganda (1999)	5.13
- Madrid extension average with Arganda (1999)	4.13

Cost actualisation is not in this case as important a factor as it was in the case of civil works, equipment being paid mainly in foreign currency in Latin American countries, which implies a higher degree of stability when considering costs in US$.

A main reason for Madrid costs being lower is explained by the dependence on imported technologies and materials in Latin America. This implies not only higher costs for transportation and customs duties, but also for spare parts stock provision, training programs for operation, control and maintenance, technical assistance, and financial costs.

Another reason relates to higher passenger carrying capacity in Latin American metro lines, being discussed later.

In some cases, the equipment cost differences between Madrid and Latin American cities are even greater than the tunnelling cost differences previously analysed.

In order to identify these differences, we have analysed the composition of the systems included under the equipment cost chapter.

Caracas split costs for line 4 were not available (only total equipment costs), and we have applied the same split between specific items as for line 3.

The analysis has covered seven big items:

- Track superstructure
- Power supply
- Signalling and communications
- Stations equipment
- Escalators and lifts
- Passenger toll equipment
- Workshop equipment, where applicable

Cost differences among Madrid Metro lines

Figures presented in graph Mad 2 can be explained as follows:

More expensive in Line 4 because of depot and workshop installation.

Smaller in Lines 8 and 10 because fewer stations involved.

Remaining lines very close to the average.

Overhead catenary versus third rail

In the Madrid case, most tunnel cross-sections being circular, the use of overhead current supply does affect the tunnel diameter. The diameter is determined by the rolling stock dimensions plus the lateral guideway for passenger evacuation.

Even in other types of section, adopting of overhead rigid aluminium rail minimises the impact on tunnel height.

Madrid metro extension is using in most of its lines a third rail current supply, but with the rail located overhead.

Operational failures are mostly caused by platform level events,. One more installation at track level is believed to increase such occurrences, and increase the difficulties and costs of track maintenance works (e.g. power needs to be cut for maintenance). This is offset by the more expensive maintenance costs on the overhead rail, requiring special vehicles, and of the vehicle pantographs.

We conclude overhead catenary has no impact in the Madrid case on tunnelling costs, and maintenance cost are similar in general terms (higher for catenary, and rolling stock because of pantographs but smaller on track and platform).

There is an important difference in terms of perceived safety: As power lines are not accessible from the platform, maintenance jobs, passenger falls or train evacuation are perceived as safer.

Madrid underground dates from 1919, and no “accessible” third rail has ever been used.

This cultural aspect was a strong issue when considering overhead power supply option in Madrid Underground in the 70s. Overhead versus third rail options were thoroughly analysed, concluding that biggest advantage of third rail were possible savings in the tunnel cross section, this advantage being minimised if circular sections were to be adopted.

Comparisons were made with the then existing types of third rail with upper, lateral or lower contact in different cities, in terms of investment, maintenance costs, reliability and safety.

It was decided to adopt overhead power supply for safety and reliability reasons, the smaller investment (40%) and maintenance costs being considered less important. Track maintenance costs are also lower because there is no need to cut power supply.

But the most important issue was safety, Madrid metro operation being accustomed to power supply being out of reach of personnel or evacuated passengers at track level.

Rolling stock interoperability within lines of the same network, and shared use of depots and workshops for different types of rolling stock were also reasons in favour of continued use of overhead power supply.

In the Madrid extension plan this discussion arose again, deciding in favour of rigid aluminium overhead catenary as compared with classic railway catenary, because of its advantages in terms of safety, investment and maintenance costs (avoiding the need for feeder lines) while keeping interoperability both in lines and depots.

9.4.1 Track costs

Track costs in millions US$/km are the following:

- Mexico City line B (2nd phase in construction)	2.55
- Caracas line 3 (1994)	2.10
- Caracas line 4 (construction to begin in 2001)	2.67
- Santiago line 5 (1997)	3.65
- Santiago line 5 extension (2000)	3.57
- Madrid extension average without Arganda (1999)	1.27
- Madrid extension average with Arganda (1999)	1.27

While the Mexico City and Santiago systems are rubber-tyred, Caracas and Madrid are conventional steel wheel systems.

Rubber-tyred superstructure needs three sets of rails, for support and guidance, and therefore should be more expensive. The Mexico system is laid on ballast, while Caracas and Madrid are laid on concrete slabs, and Santiago varies between the tunnel or viaduct sections.

Third rail costs are considered under power supply system, but in the case of Santiago, guidance rails are being used as well for energy distribution and communications, this cost being considered within superstructure.

These facts could explain bigger unit costs for Mexico and Santiago, while Madrid remains below Caracas perhaps more due to general procurement and management reasons than due to specific components involved in track superstructure.

Anyhow, track costs explain only about 1 million US$/km in the difference between Madrid and other cities.

9.4.2 Power supply system costs

Power supply system costs in million US$/km are:

- Mexico City line B (2nd phase in construction)	2.47
- Caracas line 3 (1994)	6.62
- Caracas line 4 (construction to begin in 2001)	8.45

- Santiago line 5 (1997)	2.52
- Santiago line 5 extension (2000)	2.36
- Madrid extension average without Arganda (1999)	0.85
- Madrid extension average with Arganda (1999)	0.58

Power supply systems include substations, power distribution, and emergency systems.

The Caracas system includes uninterrupted power emergency supply that other systems do not have. Another big difference is Madrid's use of an overhead aluminium distribution line instead of third rail, that might explain, besides general imported technology reasons, its lower costs.

Power supply costs are also affected, to a lesser extent, by passenger capacity provided, larger capacity systems requiring bigger power supply equipment.

9.4.3 Signalling and communications systems

Their unit cost in million US$/km for the different cities are:

- Mexico City line B (2nd phase in construction)	1.96
- Caracas line 3 (1994)	5.10
- Caracas line 4 (construction to begin in 2001)	6.51
- Santiago line 5 (1997)	2.49
- Santiago line 5 extension (2000)	4.36
- Madrid extension average without Arganda (1999)	0.96
- Madrid extension average with Arganda (1999)	0.65

All systems might be considered equivalent in terms of automatic operation and minimum theoretical headway, but actual headways are smaller, and closer to the theoretical value, in the Latin American systems which require larger passenger carrying capacity.

Madrid's costs are significantly lower (2 to 5 times), explainable by a lesser dependence on foreign technology and its collateral reasons, as well as economies of scale in Madrid and Mexico City which have around 200 km of line with the same systems in operation.

9.4.4 Station equipment unit costs

Station equipment costs in US$/km are as follows:

- Mexico City line B (2nd phase in construction)	0.11
- Caracas line 3 (1994)	1.70
- Caracas line 4 (construction to begin in 2001)	2.13
- Santiago line 5 (1997)	0.41
- Santiago line 5 extension (2000)	0.35
- Madrid extension average without Arganda (1999)	0.61
- Madrid extension average with Arganda (1999)	0.41

Escalators and lifts are considered as a separate item (see below).

The higher costs of Caracas are partly caused by major and minor ventilation systems, including station air treatment and chilled water units, ducts and louvers, not present in any other of the systems compared.

In this case, Madrid's costs are higher than those of Mexico City or Santiago, as it includes real time information systems at platforms to inform passengers of next-train destinations and arrival times, and electronic information screens in ticketing halls; with regard to public address, interphones, time clocks, lighting, fire protection and CCTV systems, Madrid's installations are comparable to the other systems.

Even with the air conditioned stations of Caracas, the additional costs amount to less than 1.5 million US$/km, and do not contribute considerably to the total unit cost differences.

9.4.5 Escalator and lift systems

Their cost in millions US$/km are:

- Mexico City line B (2nd phase in construction)	0.15
- Caracas line 3 (1994)	1.56
- Caracas line 4 (construction to begin in 2001)	2.00
- Santiago line 5 (1997)	0.11
- Santiago line 5 extension (2000)	0.72
- Madrid extension average without Arganda (1999)	0.99
- Madrid extension average with Arganda (1999)	0.67

It is to be noted that in Mexico escalators are very scarce, but in many stations the civil works have been carried out for their future installation. No lifts are installed.

Caracas has no lifts but only escalators, sometimes a smaller number because of central platform adoption.

Santiago has equipped escalators and lifts only in some stations (5 escalators and 6 lifts in line 5, for 12 stations), while Madrid has installed 229 escalators and 122 lifts for 38 stations.

Madrid unit costs per km are higher than those in Mexico City or Santiago, explained by the difference in equipment, but continue to be half of those in Caracas, even including lifts at all stations.

Again differences can be explained by the generally imported equipment and administrative reasons, but they do not contribute substantially to the total unit cost differences (about 1 million US$/km with Caracas, and even less with Mexico City or Santiago).

9.4.6 Passenger toll equipment

Unit costs in US$/km are:

- Mexico City line B (2nd phase in construction)	0.23
- Caracas line 3 (1994)	0.53
- Caracas line 4 (construction to begin in 2001)	0.68
- Santiago line 5 (1997)	0.28
- Santiago line 5 extension (2000)	0.20
- Madrid extension average without Arganda (1999)	0.12
- Madrid extension average with Arganda (1999)	0.08

All systems have magnetic code ticket control turnstiles and, except for Mexico, automatic ticket vending machines, as well as manned ticket booths equipped with ticketing encoded issuing machines.

The capabilities of the system are not used presently in Mexico, where one single flat fare ticket is being used, valid only for one trip, and with no combined or integrated tickets with other transportation means. Nevertheless, a future integration with phone cards is being studied.

Santiago is the only system to discriminate fares in different periods of the day.

Unit costs per km are 2 to 5 times smaller in Madrid, but figures can be misleading because of number of turnstiles and vending machines installed at each station (figures not available for all networks).

Anyhow, differences are very small in absolute figures (less than half a million US$/ km) and have a small contribution to explain total unit cost differences.

9.4.7 Workshop equipment

As already stated when dealing with infrastructure costs, workshops are not directly related with line construction in all cases, Madrid and Caracas having extra capacity at previous workshops for treatment of rolling stock related to the new lines.

Figures given for workshop equipment at Mexico City, Santiago and Madrid in million US$/km are:

- Mexico City line B	1.12
- Caracas line 3 (1994)	-

- Caracas line 4 (construction to begin in 2001)	-
- Santiago line 5 (1997)	0.15
- Santiago line 5 extension (2000)	-
- Madrid extension average without Arganda (1999)	0.23

These figures are not appropriate for comparison, due to aforesaid heterogeneity but once more, their values are not big contributors to total unit costs.

9.4.8 Equipment cost conclusion

After analysing the seven systems considered, the most relevant differences in equipment costs have been found in power supply and signalling systems, responsible for more than two thirds of the cost differences found (up to 12 million US$/km).

Track system is also significant but at a smaller scale (up to 2 million US$/km between rubber-tyred and steel wheel systems).

Station equipment, escalators and lifts are even more expensive at Madrid extension than in some Latin American cities because of higher standards applied (up to 1 million US$/km).

Passenger toll equipment and workshop equipment are not strictly comparable, but differences are not significant at the equipment unit cost per km level (less than 1 million US$/km).

9.5 Rolling stock costs

Rolling stock costs in million US$/km in the different cities are:

- Mexico City line B (2nd phase in construction)	17.30
- Caracas line 3 (1994)	11.70
- Caracas line 4 (construction to begin in 2001)	25.77
- Santiago line 5 (1997)	14.33
- Santiago line 5 extension (2000)	17.84
- Madrid extension average without Arganda (1999)	5.54
- Madrid extension average with Arganda (1999)	4.03

Rolling stock costs in Latin American cities are between twice and three times as high as in Madrid.

There are several reasons to explain this difference, which is as great as that found in the section on civil works.

Besides foreign technology dependence and import taxes, as in the equipment section, there is an important difference both in terms of capacity provided and level of service considered.

On the one hand, we must distinguish between maximal theoretical capacity (the one the line is designed for, if there were enough trains to operate at minimal headway), and actual capacity provided (attainable with the number of trains bought for this particular project at the figured costs). Even here, hidden factors might occur, depending on reserve trains at terminals and train availability at peak hour, being close to 100% at Madrid.

On the other hand, capacity figures must be homogenised, Mexico City and Santiago using 6 standing pax/m2, while Caracas and Madrid use 4 standing pax/m2 for their capacity figures.

Capacities are true in all cases, but level of service is not the same.

We have therefore calculated the rolling stock cost per km needed to provide a capacity of 10,000 pax/hr and direction at a density of 4 standing passengers/m2 assuming 100% availability at the peak hour as is the case in Madrid. Resulting figures are:

- Mexico City line B (2nd phase in construction)	4.49
- Caracas line 3 (1994)	9.69
- Caracas line 4 (construction to begin in 2001)	10.74
- Santiago line 5 (1997)	6.69
- Santiago line 5 extension (2000)	8.35
- Madrid extension average without Arganda (1999)	4.87
- Madrid extension average with Arganda (1999)	4.51

Using this ratio, costs comparison is homogeneous, and costs become much closer, explaining that one main reason for rolling stock cost difference is that Latin American systems are providing more capacity, and therefore, buying a bigger number of trains per km of line to operate.

Analysis of Madrid rolling stock cost, not as an average, but line by line illustrates the variation range depending on capacity and type of rolling stock required.

But even for the same capacity, Caracas and Santiago are showing that important differences between systems occur.

Differences, in our opinion, may be explained by several reasons:

1. Extra costs for imported materials (transportation, customs duty, spare parts, etc).

2. Technology dependency (training, technical assistance, etc).

3. Financial costs including higher risks.

4. Technological differences (air conditioning in Caracas and Madrid only), interconnection between cars in Santiago and Madrid).

5. Scale economies for big-fleet cases (Mexico City and Madrid).

6. Rolling stock bought at low unit price, being an option of an previous large contract (Madrid series 2000).

7. Actualisation of costs for older projects (explaining lower values for Mexico City, Caracas line 3 and Santiago line 5).

Rubber-tyred versus steel wheel technology

Rubber-tyred vehicle construction seems to be more expensive than steel-wheel but global rolling stock figures include many other concepts (air conditioning or interconnections for instance), which make difficult to state how much more expensive it is.

Supposedly extra investment costs are balanced by construction savings achieved by using steeper slopes and tighter curves.

If this was the case at the beginning (Mexico City metro started operation in 1969 using 7% slopes and 105 m radii), nowadays alignments use bigger radii and smaller gradients both for operational reasons and passenger comfort.

At the Santiago metro, also rubber-tyred, maximum gradient in line 1 was 4.8%. Line 2 used 4.3%, and line 5 maximum gradient is 3.5%, while minimal radius is 240 m.

In Caracas or Madrid, with steel-wheel technology, new lines minimal radius is 250 m, and maximum gradient is 4%. Therefore, recent constructions seem to be applying the same kind of geometric standards for alignments, thus not taking advantage of the higher adhesion possible with rubber-tyred vehicles.

As explained for the case of power supply, interoperability is a big issue for metro operators, and it applies also to infrastructure and rolling stock technology.

As a matter of fact, Santiago metro spent almost one year in a preliminary study, before building line 5, about whether to keep rubber-tyred technology, being used in lines 1 and 2, or change to steel-wheel technology.

Mexico city applied steel wheel technology recently for line A, as well as the Xochimilco tram line, whereas with the exception of Paris, we are not aware of any metro changing from steel to rubber.

Rubber-tyred technology implies also a more expensive track superstructure, with three sets of track instead of just one, combining lower weight steel rails for emergency and switch guidance with concrete or steel tracks for vertical and horizontal support and guidance.

At the beginning of its use, rubber-tyre adhesion provided for higher acceleration and braking performances than steel-wheel, thus achieving better commercial speeds and requiring fewer trains to provide the same capacity.

But conventional steel-wheel rolling stock kept increasing power and distribution among different wheels on the trains, and is now achieving similar acceleration (1.2-1.3 m/sq.sec) and commercial speeds as rubber-tyred systems.

Once acceleration, braking and maximum speed are similar, commercial speed depends on alignment characteristics and notably interstation distances and stop times at stations, rather than rolling stock technology.

Moreover, these values are limited for passenger comfort reasons, rather than for friction or adhesion reasons.

Another alleged advantage of rubber-tyred systems was precisely passenger comfort, based on suspension effects by tyres and noiseless operation. With the use of welded rails, track laid on concrete slabs, and pneumatic suspension, levels of comfort and noise in both systems are comparable, with noise being even higher in concrete-rubber systems at high speeds.

Operation and maintenance was thought to be much more expensive in rubber-tyred system, needing tyres to be replaced much more often than steel wheels. In Santiago, support tyres last for 200,000 to 260,000 km, and guidance lateral tyres last for 400,000 to 500,000 km thus reducing tyre changes and costs considerably. Nevertheless, steel wheels last for 1,200,000 to 1,500,000 km, needing reshaping at an average 300,000 km, usually performed at workshops underfloor wheel lathe, which is an expensive piece of equipment.

Energy consumption for rubber-tyred systems is bigger than for steel-wheel systems, but total consumption depends much more on the line profile and operation pattern (maximum acceleration or braking or not) than on the wheel-rail technology.

For instance, within the Santiago metro, energy consumption per car-km varies from 3.2 kWh/car-km in line 1 to 2 kWh/car-km in line 5 that has a flatter profile with smaller maximum gradient. Madrid metro average energy consumption is 2.8 kWh/car-km, Madrid topography being hilly, while Santiago is rather flat.

Summarising, rubber-tyred systems are, in our opinion:

- more expensive to build (track and rolling stock)
- allow for steeper grades and smaller radii, although not used normally for construction method limitations, and for reasons of passenger comfort or energy consumption

– more expensive to operate in terms of energy consumption and spare parts needed

– similar as far as commercial speeds or rolling stock needs are concerned

– similar in terms of passenger comfort when compared with modern steel wheel tracks

– they produce more heat to be evacuated from tunnels, needing to increase ventilation or air conditioning systems

9.6 Design, supervision and management costs

We have included under this chapter all costs related to preliminary and final design, technical assistance, project administration and management, quality control, construction supervision, and work inspections.

Unit costs per km in million US$ for the cases compared are:

- Mexico City line B (2nd phase in construction)	1.62
- Caracas line 3 (1994)	2.69
- Caracas line 4 (construction to begin in 2001)	4.64
- Santiago line 5 (1997)	3.16
- Santiago line 5 extension (2000)	8.54
- Madrid extension average without Arganda (1999)	0.69
- Madrid extension average with Arganda (1999)	0.48

The figures for Madrid are three to ten times lower than for the Latin American cities. At 2.2%, they account for a small percentage of total costs, compared with 4% to 12% in the other cities.

This important difference is explained because Madrid project management and administration cost, besides being low, is shared by 56 km of network extension, and lasted just four years. No external project manager was appointed, nor technical assistance teams for each system provided. Equipment and rolling stock design costs were kept to a minimum, taking advantage of previous successful experience in the 120 km network operation.

In the Madrid case, the planning and preliminary design was carried out by a different agency (Consorcio de Transportes), and the costs of feasibility studies have not been included in these figures.

Besides, technical assistance costs are lowest for Line 8, for time reasons. As the line was built in only 14 months, there was a saving in the supervision and quality control teams, whose payments are usually time-based.

9.7 Cost taxes and duties

In Mexico City's line B extension, all costs include 15% Value Added Tax (V.A.T.) which is applied for contracts both paid in national or foreign currency. No other duties were reported.

In the Caracas case, there are two kinds of taxes. ICSVM, which applies to payments in local currency (5.2% for infrastructure contracts, and 10.2% for equipment contracts); there is also a 1% customs tax (gastos aduanales). All of these are included in figures reported.

In Santiago, *derechos de internación* account for 11% of imported material or services, and V.A.T. for additional 18% always included in figures given.

In Madrid, a 16% V.A.T. applies and is included in all figures with no other duties for European Union imported goods or services.

If we take off all taxes and duties, net total costs per km of the different systems are:

- Mexico City line B (2nd phase in construction)	35.58
- Caracas line 3 (1994)	49.81
- Caracas line 4 (construction to begin in 2001)	80.38
- Santiago line 5 (1997)	33.66
- Santiago line 5 extension (2000)	66.18
- Madrid extension average without Arganda (1999)	26.87
- Madrid extension average with Arganda (1999)	19.65

10.- Conclusions

The comparative study detailed in previous chapters shows that the Madrid metro extension presents significantly lower unit costs per km than the Latin American cities studied (Mexico City, Caracas and Santiago).

Recent data on estimated costs of future projects, as Caracas line 4, now being contracted, present unit costs of 93.6 million US$ per km, three times bigger than the Madrid unit cost (31.2 million US$ per km considering only underground sections).

The just finished Santiago line 5 extension had a unit cost of 70.1 million US$/km, more than double that of Madrid.

Mexico City line B figures, at 40.9 million US$/km seem much closer to those of Madrid, but these figures were provided by DGCOSTC directly in US$, and we presume that they reflect the exchange rates at the time payments were made in the different contracts.

The comparative report has analysed the differences for each of the four big components of total unit cost: civil works, equipment, rolling stock and design, supervision and management.

General and specific reasons have been found to explain Madrid low cost experience:

A.- General reasons

Estimated to be responsible for 15 to 20 millions US$/km savings (15 to 25%).

A1.- Full commitment at regional political level **(President of Regional Authority, Minister of Public Works),** ensuring project financing, on-time payments and full confidence **from the contractor on getting a profit.**

The Madrid project being an electoral promise from last elections to be completed before election date, and a strong stake for re-election, all parties involved worked hard to meet dates, sure to get a fair compensation for their effort. As a matter of fact, a second extension plan is under way, 50 more km being built in the period 2000-2004.

Presidential announcements of new lines were also made in the three Latin American cases studied, even at a higher political level.

However, in the Mexico City case, Congress cut funds in 1997, which resulted in contract renegotiations, construction delays, and line restricted to a first phase almost half long while second phase is still being built.

In Caracas, the start of line 4 construction has been delayed.

Santiago line 5, on the other hand, was built on schedule. The extension was decided while construction of line 5 was going on, giving continuity to civil works, thus saving time and costs.

Risk analysis by the contractors, and prices, are influenced by these facts.

A2.-A small and highly experienced project management team (6 Civil Engineers) with full power both for technical and financial on-the-spot decisions.

Besides reducing substantially management and administration costs, the management team provided quick decisions when unexpected questions arose, both on technical solutions to apply and its economical consequences, saving time and avoiding expenses for legal advice for both parties, contract interpretations, or legal disputes.

A respected and widely experienced team understands the contractors' claims and is ready to agree on a fair evaluation of unexpected changes.

A3.- **Contract procurement based not on the cheapest bid**, but on sound technical and experience reasons, with the construction method specified by the administration (i.e.: EPBM).

It allowed to get best experienced contractors, and convince them of the need to invest in expensive machinery that proved to be cost effective.

Contracts were quite simple, planning for normal conditions, all unexpected matters being negotiated by the administration's project management team.

A4.- Fair prices allowing construction and supplier companies to have a normal profit in the projects.

Contract prices were not extremely low, but regular fair prices that allowed constructors and suppliers to earn a profit from the project. As a result, when special issues arise, claims can be reasonably negotiated by both parties, without the pressure of low prices in the general contract.

A5.- Strong involvement and direct regular presence in the field, of top management officials.

Besides technical supervision of each lot, carried out by external consultants, regular presence in the field of top management administration officials allowed for direct knowledge of work progress, anticipation of problems and assessment of possible solutions in discussions with all parties involved.

B.- Reasons for specific cost reductions in civil works

Estimated to be responsible for up to 10 million US$/km savings.

B1.- Use of twin track single tunnel, with extensive use of EPBMs.

By achieving high performances and reducing services deviation, expropriations, and surface works. No NATM related problems, such as collapses, technical assistance or extra costs.

B2.- Strong geotechnical supervision monitoring.

Real time centralised monitoring of more than 8,000 items, anticipating potential problems and allowing for solution evaluation, and discussion with contractors before they actually arise.

B3.- Standardised station design concept.

Use of diaphragm walls, and mezzanine levels, minimising mine construction, and different station architectural designs within the same concept.

C.- Reasons for specific cost reductions in equipment

Estimated to be responsible for up to 10 million US$/km savings.

C1.- Power supply adjusted needs.

No air conditioning at stations, uninterrupted power systems only for communications, and smaller power needs due to lower number of trains to serve existing passenger demand.

Overhead rigid rail or catenary for trains, instead of third rail.

C2.- Signalling and communications technology.

ATP and ATO tested technology (more than 1000 vehicles equipped in Madrid Underground) instead of SACEM technology, with slightly higher minimum headways allowed 138 seconds instead of 90/120 seconds.

C3.- Track technology.

Conventional steel wheel technology as opposed to rubber-tyred technology in the cases of Mexico City and Santiago.

C4.- Other equipment.

No significant cost savings except for absence of air treatment (chilling) at stations, as in the Caracas case. Train and passenger information systems at platforms and ticketing halls are responsible for a small additional cost.

Escalators and lifts provided at all stations with small cost increase as compared with systems without them (or partially equipped).

D.- Reasons for specific cost reductions in rolling stock

Estimated to be responsible for 10 to 20 million US$/km savings.

D1.- Smaller number of trains required.

Madrid's lines are requiring a smaller transportation capacity, on the average, at least in a first stage, than the Latin American cases studied. Even though level of service is higher (4 pax/m2) than in Mexico City or Santiago (6pax/m2), a smaller number of trains is required.

D2.- Previous contract options.

Series 2000 trains are supplied as an option of a previous big contract involving renewal of all Madrid Metro "narrow" rolling stock. A very competitive unit price has been obtained for this reason, even though the new trains are equipped with air conditioning and interconnection between cars.

E.- Reasons for specific cost reductions in design, supervision and management

Estimated to be responsible for 1 to 5 million US$/km savings.

E1.- Short time construction.

Four years for 56 km including design and procurement. Costs are directly proportional to construction time for overhead charges.

E2.- Small administration and project management team.

Small team of public administration officials. Low cost when compared to big external project management teams.

E3.- Reduced technical assistance.

Small number of experts, mainly for geotechnical and tunnelling matters consulted on specific case basis. Technical support of Madrid Metro staff for equipment and rolling stock.

E4.- Scale economies.

Both by sharing overhead costs between 10 different lines (56 km), and taking advantage of equipment and rolling stock programs for the whole Madrid network.

11.- Recommendations

The report has identified and analysed the main factors that explain why the extension of Madrid's Metro has been more economical than similar projects in Latin America.

Some of them result from particular factors inherent in extension of Madrid's old network, and therefore their replicability is limited when building metro networks in other cities, in developing countries.

According to the World Bank's Terms of Reference, several key factors have been identified that allow us to suggest some ways of applying this experience to rapid transit projects in developing countries.

We will present them proposing a set of simple guidelines that, if followed, will hopefully result in on-time, lower cost rapid transit projects.

These recommendations are somewhat subjective exceeding the direct extrapolation of Madrid results.

They have been grouped in two different sets:

a) guidelines regarding project finance, administration and management

b) technical guidelines for design and construction

1. **Ensure maximum commitment at the political level.**

   Try to involve local, regional or national authorities, international agencies, financiers. Negotiate risk clauses in such a way that contractors' risk is limited, and do not over rate their costs. Confidence in on-time payments is essential.

2. **Promote customs duty exemption for imported equipment.**

   It implies significant budget savings (up to 30%). It is not very sound that Government gets a tax to be paid by the same Govt, that might endanger the decision about building the systems. If a metro needs to be built it should not cross-fund via taxes other Govt activities. Public Transport is one of the services to be provided to citizens, and its construction should not be the source for funding other services.

3. **Appoint , or, if not possible, contract a small experienced management team, committed to the project objectives.**

   This means, of course, sharing safety objectives, proper construction methods according to specifications, and systems reliability, but also on-time development (while paying attention to the cost implications).

4. **If an external team has to be involved, suggest that they are paid on a lump-sum basis, time independent, with a bonus-malus incentive system for on-time completion and on-budget completion, within a specified margin.**

   Incentives could be given to the project management team, rewarding them for quick project execution and completion below budget. On the other hand, penalties would apply for delays or cost overruns, from a certain figure on.

   Although in the Madrid case no external project manager was contracted, the in-house team shared these time and cost objectives and was strongly motivated to fulfil them.

   The effect of management, inspection and supervision teams is strongly time dependent. Therefore, size of the team and length of services should be carefully examined. A team 30% smaller and a construction time 30% shorter imply a 50% saving in technical assistance costs.

5. **Empower this team to take both technical and financial decisions, in order to solve unexpected problems in an expeditious manner.**

   Negotiate solutions directly with the contractors, avoiding legal contract interpretation disputes that will increase time and cost.

6. **Differentiate what the line costs are, independently from works on the road system.**

   A rapid transit system should not be “the opportunity” to enlarge or expand the private car road system, but, on the contrary, to reduce it, promoting a more effective public transport and pedestrian transportation chain.

   Investments on rapid transit projects should be differentiated from collateral works undertaken taking advantage of works in the area, even if they contribute to the project success.

7. **Do not base contract procurement only on the cheapest bid, but also on sound technical and experience reasons.**

   Define contracts for normal conditions, providing the basis for a fair negotiation if unexpected problems arise.

   If contracts try to provide for solution of unexpected problems without negotiation, probably litigation will arise, implying delays and total costs increases

8. **Ensure that financing is available for the entire project, including possible contingencies.**

Shortage of funding and payments will increase costs and most probably delay works.

B) Technical guidelines for design and construction

9. Look carefully at all tunnelling-related elements and costs.

Tunnelling costs are responsible for up to 50% of the total project cost.

Tunnelling costs are influenced by five main factors:

- cross-section adopted
- alignment depth
- construction method
- geological-geotechnical characteristics
- unexpected problems : changes/decisions

10. Try to adopt single tunnel cross-sections, being significantly cheaper than twin tunnel ones.

This decision affects both station functionality (side vs. central platforms) and construction method.

As far as station functionality, the adoption of a central platform adoption results in more compact stations and provides savings in escalators and elevators; however, a design with side platforms can give functional solutions too.

Single tunnel cross-section allows for switches location at intermediate stations without extra costs, twin tunnels needing telescopes and connection tunnels.

In our opinion, tunnel cost savings when using single tunnel cross-section exceed the cost savings at stations using a central platform design.

11. **Alignment depths should be big enough to allow the use of tunnelling machines, but shallow enough to provide good, passenger accessibility and low station construction costs.**

Alignment depths have a double influence, both in terms of utilities relocation, station construction cost, and tunnelling construction method.

The use of EPBMs results in cost and time savings (no utilities relocation or surface-related costs). They work comfortably with an earth covering equivalent to 1.5 times the tunnel diameter (i.e. at a depth of roughly 12 to 15 m).

But the depth should be shallow enough to allow for good passenger accessibility, and station construction using diaphragm walls (smallest impact on surface traffic and escalator costs). Generally, big depths might result in lower construction costs but with negative impacts on passenger accessibility and operating costs of escalators

In some cases geotechnical conditions might strongly influence a particular alignment, but alternatives should be carefully evaluated, in terms of safety issues, construction methods, and effect on passenger accessibility.

12. **Adopt EPBMs whenever possible. They will provide an extra level of safety, good response to uncertain or unexpected conditions, and, according to the Madrid experience, better performance and shorter construction times than other tunnelling methods.**

    The use of EPBMs might allow the adoption of single tunnel construction even where geotechnical conditions are difficult.

    The level of safety, construction speed, cross-section and better depth adaptation compensates, according to Madrid experience, the extra investment needed for machinery acquisition. An extremely careful study should be made of machine characteristics and performance.

13. **Adopt a standardised module for the functional design and construction of stations.**

    It will save plenty of time and money, but this does not imply an "all-looking-the-same" approach.

    Design efforts should take advantage of each station opportunities (skylights, mezzanines, entrances, walls, floor and ceiling finishes, art work, etc,) but within a controlled concept and construction method framework.

14. **Whenever possible, adopt diaphragm walls for station construction, minimising the impact (and costs) at surface level.**

They combine rapid construction with low impact on surface traffic, do not constrain design aspects such as skylights, and can accommodate access to local urbanisation patterns.

15. **Arrange for extensive geotechnical supervision monitoring during construction.**

Uncertainty is one of the key facts of life in tunnel construction. To minimise it, and provide better safety, get as complete a survey as possible within the work progress, to anticipate potential problems and consider alternative solutions, to be discussed/negotiated with the contractor.

16. **Recommend the adoption of steel-wheel technology rolling stock rather than rubber-tyred systems.**

In terms of cost, rolling stock might become as important as civil works in a rapid transit system (over 40% in Mexico or 35% in Santiago, compared with 20% in Caracas or 18% in Madrid), and has a much bigger influence on the maintenance and operating costs for the life of the project.

Steel-wheel technology has proved to be as efficient as rubber-tyred technology. The advantages in terms of alignment (shorter radii and steeper gradients) inherent in rubber-tyred systems are currently not used in practice, for reasons of commercial speed, passenger comfort, or construction method limitations.

Track and rolling stock investment costs are lower for steel-wheel technology, and there is a wide variety of contractors and suppliers, which results in more competition and hopefully lower costs.

Operating costs are also lower in terms of energy consumption, generated heat evacuation, and spare parts.

Passenger comfort and noise levels reached by steel-wheel trains are similar to rubber-tyred ones.

Besides, steel-wheel technology is independent from decisions on signalling, communications or automatic operation systems, again providing a healthy competition of technology providers and suppliers and resulting in lower costs.

17. Ask for detailed rolling stock maintenance plans in advance. Peak-hour availability is essential, defining rolling stock needs.

“Reserve” rolling stock goes directly into the cost of the project. Night maintenance, combined with incentives and bonus-malus contracts may allow for 99-100% availability on the peak-hour according to Madrid experience. Providers sometimes include comfortable operational or reserve margins, accepted by operators, which means the same percentage accepted as extra costs.

18. Examine overhead classic or rigid catenary as a smaller cost alternative to third rail technology.

When adopting circular cross-sections for tunnels, Madrid experience shows no impact on tunnel diameter.

Pantographs for rolling stock are more expensive than other power caption devices, but in Madrid this is offset by savings in third rail costs and track maintenance, which can be performed under traction power.

Additional factors taken into account when defining the Madrid Metro extension were perceived safety for passenger evacuation or track personnel, as well as workshop savings.

19. **Dimensioning of needed capacity for the first project phase may yield substantial savings in equipment costs. Analyse convenience of equipment phasing**

Power supply, rolling stock, and even signalling systems costs are proportional to the passenger carrying capacity provided, including an extra capacity margin. Long term planning scenarios should be considered for land acquisition, design concepts and equipment rooms, but perhaps not for actual equipment supplied and installed in the first phase, unless it is to be used.

Many equipment elements can be "prepared for" in such a way that adoption in a later phase does not imply extra costs, especially in civil works or equipment schemes.

If this is the case, a two step approach will provide important savings for the first phase. Elevators, escalators, moving walkways, rolling stock air conditioning, mechanical ventilation, toll turnstiles, are examples to illustrate this point.