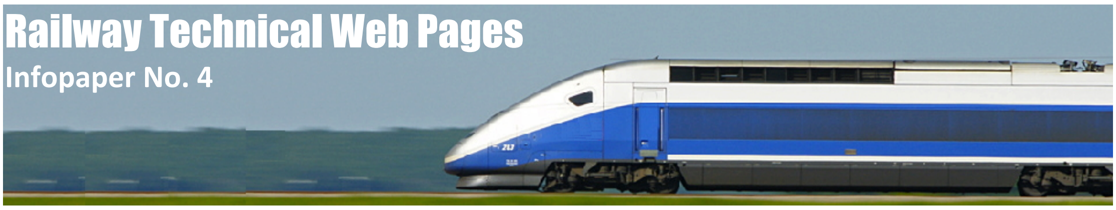

One of a series of papers on technical issues published by RTWP from time to time.

Metro Operations Planning

by

Piers Connor[1]

Summary

Most thinking urban planners have long recognised that the use of high capacity, electrically powered, rail systems is the optimum solution for long-term, sustainable mass transportation in the urban environment. This recognition has been around a long time. As far back as the 1880s, when the first electric powered tramway systems began to appear, the efficacy of frequent, clean and reliable rail operation was recognised as the best transport option for urban development and the safe movement of large numbers of people around cities.

Figure 1: Train of MF67 type on the Paris Metro, Line 12. This line operates on steel rails with steel wheels but some lines in Paris were converted to rubber tyres running on combined concrete/steel guides. Photo by Bernd Kittnedorf

The density of housing and commercial buildings in cities forced many urban rail systems underground, since ground level systems were restricted by other traffic and the early elevated systems were intrusive and noisy[2]. All three varieties of urban rail systems exist today and, with some variations, are all operated on the same basic principles. In this paper, I describe the major operating criteria for an urban railway and show how they are applied in some examples around the world.

What is a Metro?

It's always a good idea to start any article on a specific subject with some definitions. In our case, we should begin with a definition of the word "metro". It actually comes from the name of the first underground railway to be built in a city anywhere in the world. This was the Metropolitan Railway of London, England. The title spread to another line in London a few years later, the "Metropolitan District Railway" and was later adopted

[1] PRC Rail Consulting Ltd.

[2] Modern elevated systems are better but careful choice of location and design are essential.

in New York City and Paris. During the twentieth century it was shortened to "metro", as a marketing term, first in Paris and later in many other cities.

The term "metro" has come to mean "urban railway" - underground, elevated or at street level – usually with a high frequency service, frequent stops and with electric power as the means of traction. Generally, "metros" are separately operated from traditional main line railways, even those with well-developed suburban networks but there are some lines that share routes with main line railways and even some that share management. In many locations, the operational techniques adopted by metros are increasingly being adopted by main line railways, particularly suburban routes with high levels of traffic.

Figure 2: Light rail tram car of Siemens Avanto S40 type on Main Street, Houston Texas. The system was opened in 2004. The trams use a central reserved track for much of the route. The system is marketed as "Metro" by the operators, the Metropolitan Transit Authority of Harris County. Photo by Mike Harrington.

Metros are sometimes referred to a "heavy" or "light rail" systems, according to the volume of traffic or the size of the trains. The terms are not clearly defined and you will see London's Underground referred to as a heavy metro system and Manila's metro as a light rail system, even though some of the Manila routes carry more passengers than London's.

Why Urban Rail?

Moving people around cities has always been a problem. From the time of the Romans, when Julius Caesar is said to have banned wheeled traffic from the city on certain days[3], through the middle ages and the industrial revolution to the present day, people have complained about congestion and overcrowding on urban streets.

In the 21st Century, journey lengths for work and leisure are growing and not many passenger flows come in car-sized or even bus-sized chunks. The predictability of road traffic is poor and the land-take needed in most cities for sufficient car parking is just not sustainable. Finally, the noise and air pollution from road traffic is unfriendly and ecologically unsound in the long term. The solution is guided mass transport in one form or another.

Variations on the theme

As you might expect, there is a wide variety of metro designs around the world. They range from single lines a few kilometres long to large networks like Shanghai, which has over 400 kms. of route. The train lengths vary from 2-axle streetcars, like those seen in Lisbon, Portugal to the 12-car "heavy metro" trains in Hong Kong. Systems use different technologies, ranging from historic trams mixed with modern ones and normal road traffic, like Milan, Italy or modern, driverless, fully automated trains like those recently

[3] "Traffic & Congestion in the Roman Empire", Cornelis van Tilburg, Routledge, 2007.

introduced in Dubai. There are even non-rail guided systems like the trolleybus, the kerb guided bus and the "Translohr" slot guided system.

You can get an idea of the range of systems and their capacities from Figure 3 below. Note that the types of systems overlap, reflecting the wide variation and, some would say, misuse of the names by some administrations.

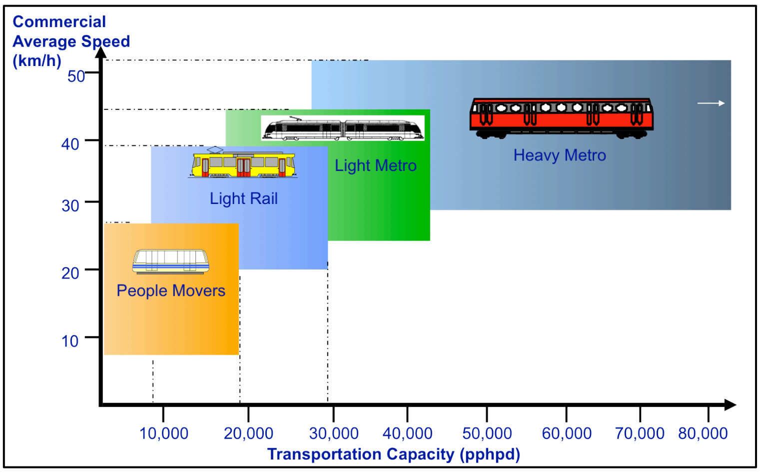

Figure 3: Graphic showing the ranges of metro and light rail system capacities. The ranges cover people movers, light rail, light metro and heavy metro systems. The borders of the ranges are fluid and the parameters vary from city to city, largely as a result of local custom and political or financial considerations. Drawing: Author.

PPHPD

In Figure 3, I introduce the term "pphpd". This is "Passengers Per Hour Per Direction" and it is one of the most important criteria upon which we base the design and operation of a metro. Many, usually imprecise and poorly understood numbers are thrown about by politicians and consultants when metro capacity is described and it is important to eliminate uninformed speculation and to understand clearly what capacity really means and how it is defined. For example, the "number of passengers" using a metro should refer to the number of passenger journeys. That means that a person taking a trip into the city will usually go in and then return later that day. This is two "passenger journeys" even though only one passenger is involved. After all we have to provide capacity for him for both trips.

Passengers per day are sometimes used to define capacity but this is a useless number in helping us calculate how many trains we need to run since the number of passengers carried in the peak hour is normally 10-15% of the daily number. Thus, for a 250.000 journey/day metro system, you can expect the pphpd to be 25.000 or more[4].

The capacity requirements for a metro will define its design and equipment, how it is built and how it will perform when passengers use it. The pphpd of a system is the maximum number of passengers that the route can carry in one direction along one track. By definition this will be during the peak hour, usually in the morning, since the evening peak tends to be more spread out and therefore lower than the morning's.

Once the number of pphpd is known, the number of trains per hour required to carry that number can be calculated. From that, we can derive the facilities needed and the systems required to operate our railway.

Metro planning

In order to get a reasonable estimate of the number of persons likely to use our metro, we need to do surveys to find out where people want to go and when. We will also need to get a reasonable estimate of the numbers of persons likely to use the stations at each location. There are many specialised consultants who have sophisticated computer programs that provide statistics for the number passengers likely to turn up to use our

[4] "Urban Transit Operation Planning & Economics", Vuchic R, John Wiley & Sons Inc., 2005.

system on a regular basis for work, pleasure or education. From one of these programs, the route and the location of stations can, to some extent be confirmed.

One feature of metro station locations that arises when looking at them from a system point of view is that most are planned on the basis that passengers are prepared to walk up to 500-600m to reach a station. Any further and they tend to find alternative transport or use another route. This drives station spacing to between 1000 and 1200 metres. Experience has shown that this distance just happens to match the ideal station spacing for a conventional, block-based train control system with a line speed of around 27mph.

Once the numbers of people have been determined, the next jobs are to:

- Set out route and stations;
- Calculate train service frequency & the number of trains required;
- Draft the timetable;
- Prepare rolling stock and crew diagrams;
- Determine the fare structure;
- Set up the operating management structure.

Assuming we already know the route and stations, we can plan the service and calculate the number of trains we need.

Service planning

If you don't like numbers, look away now but, if you want to understand the basics features of metro capacity and how it's calculated, read on.

To understand the basic calculation, we look at a simple, imaginary metro line called the Forest Line. We consider how many passengers will use the system, how the trains will operate and how many trains will be required to operate the system.

The line is a simple two-track railway (one track for each direction) with a simple two-track terminal and crossover at each end (Figure 4 below). The stations are marked by yellow rectangles and they are named after trees – hence the "Forest Line". The numbers of passengers expected between stations are listed together with a graph showing how the numbers build up towards the city centre which, on our route, is between Lime and Oak. This, being the busiest section, is the section that determines

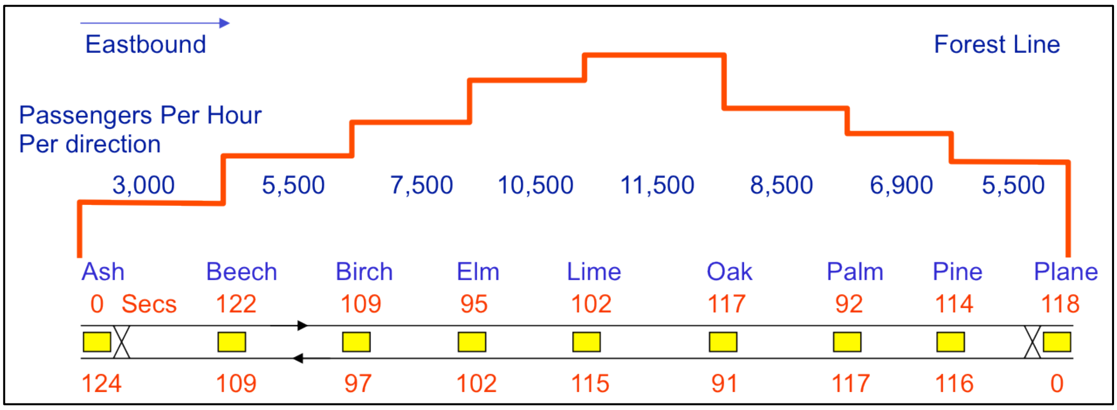

Figure 4: Diagram showing how metro train service levels are calculated for one direction, in this case the eastbound direction. The route itself is a simple 2-track line with 7 intermediate stations and two terminals. Each terminal has a crossover to allow change of direction. The times for the station to station sections include dwell times. The graph shows the build up of passengers between each station toward the city centre between Lime and Oak stations and how it tails off as the train moves away from the city to the eastern terminus at Plane. The service must be planned for the maximum passenger numbers between Lime and Oak stations. Note how the trip times vary between directions, due to gradient differences. Diagram by Author.

our capacity requirements, so our calculations will be based on the total of 11.500 pphpd expected between Lime and Oak.

The next step is to calculate the time it takes for trains to do a round trip. For a new metro, this will be done by simulation. We have the following figures to work with:

- Ash to Plane = 869 seconds;
- Plane to Ash = 871 seconds.

We have to allow time at the terminals for the train and, more important, its crew to change ends. In our example, we allow 5 minutes at each end of the trip. The total round trip time therefore works out at 869 + 871 + 300 + 300 = 2.340 seconds or 39 minutes.

Figure 5: Lisbon tram terminal in 2010 showing 4-wheeled trams at Plaza Comércio. Lisbon operates over 40 trams of this type. They were rebuilt in the mid-1990s from original vehicles dating from the mid-1930s. Photo by David Gourlay.

In making the calculation, which we call "round trip time", don't forget that the time is from wheel start at the first terminus (in our case Ash) to wheel start at the same terminus. It's easy to forget the second terminal dwell.

Train requirements

In order to work out how many trains must run to carry our 11.500 passengers over the peak hour between Lime and Oak, we need to fix a capacity for a train. In our case, I have chosen 700 as the "crush loaded" capacity. However, trains don't often load evenly so we must apply a load factor to get a more realistic view of how many passengers will actually be carried on each train. In our case we will use a factor of 85%, which will reduce the total on each train to 595 passengers. The number of trains with this capacity required to carry 11.500 passengers is 11.500/595 = 19.32 trains. This is rounded up to 20 trains in an hour. This is equivalent to a train every three minutes, what we usually refer to as a 3-minute "headway".

Now that we have established that we need a train every three minutes during the peak hour, we must calculate the number of trains actually needed to operate the service. This is another simple exercise, where the round trip time (39 minutes) is divided by the headway (3 minutes), giving a total of 13 trains[5]. We will add two more trains to allow a couple of trains spare to cover maintenance requirements. This gives us a total of 15 trains we need to buy.

[5] Although the traffic levels require a service of 20 trains per hour, we only need 13 trains to run it because the round trip time is only 39 minutes. Thus, each train gets round to its starting point in less than an hour, i.e. 39 minutes.

Stabling requirements

Now we need somewhere to put our fleet – a stabling area. Very often, there aren't enough spaces in one location for all the trains and sometimes trains have to be stabled in odd locations away from the main depot.

In our example, we can stable 8 trains in the main depot at Ash, four in a set of sidings at Elm and one train in another siding at Elm. To set up the service each day in preparation for the morning peak, we must prepare a timetable that will use all the trains stabled along the route.

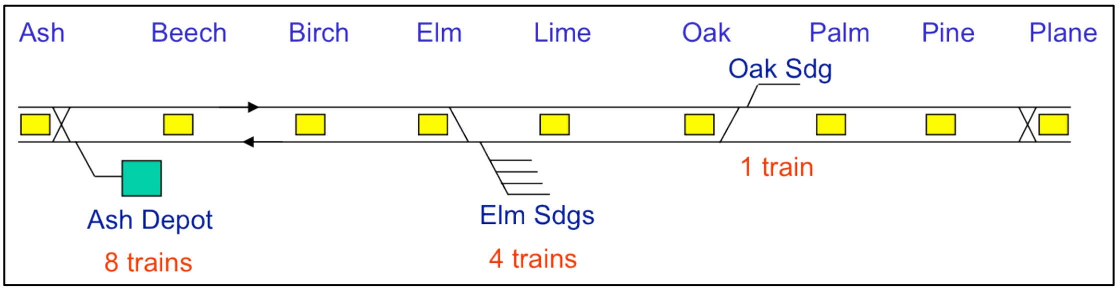

Figure 6: Diagram of the Forest Line showing the stabling locations of the 13 trains required to operate the peak hour train service. The main depot is at Ash, with four sidings at Elm and a siding at Oak. The locations are important for the compilation of the timetable. Drawing by Author.

Timetables

Column	**1**	**2**	**3**
Train/Trip No.		**1-2**	
Notes		*Ety.*	
Ash		*05:40*	
Ash Depot			
Elm		*05:44*	
Elm Sdgs			
Oak		*05:47*	
Oak Sdg			
Plane		*05:52½*	
Platform		1	
To Form		06:00	
Train/Trip No.	**1-1**	**1-3**	**1-4**
Notes	*Ety.*		
Plane		06:00	06:23
Oak Sdg			
Oak		06:05½	06:28½
Elm Sdgs			
Elm		06:09	06:32
Ash Depot	*05:31*		
Ash	*05:34*	06:14½	06:37½
Platform	1	1	2
To Form	*05:40*	06:23	06:43

Most railways issue two timetables – one for the public and one for the staff. The public timetable only covers those trips that the public can use and some metros don't even provide a full timetable, they just advertise their trains as running, "every few minutes" or "2-3 minutes". For the staff, a Working Timetable (WTT) is issued. This timetable shows all details of all train movements, including empty moves and times in and out of depots. It shows each train or trip identity and intermediate times for some, if not all stations.

A typical trip might be shown as in the table on the left. The WTT here is shown in two halves, each half covering a direction of travel. In our example, the top half covers trips from Ash to Plane, while the bottom half shows Plane to Ash trips. Depot and siding timings are also shown.

In this example, trains are identified by a two-part number; the first part identifies the train, the second shows the trip number since the train left the depot. Empty runs use italic text to distinguish them from passenger runs. Platform occupation and the train's next trip is also shown in the WTT.

So, the first train of the day, No. 1 as shown in the first column, starts its first trip (1-1) empty from Ash depot to Ash station, using Platform 1. It will form the *05:40* trip to Plane.

Its second trip, 1-2 is started in column 2 and the train runs empty from Ash to Plane so it can form the first passenger trip from Plane to Ash. This format continues until the train returns to depot. A expanded version of this timetable can be found in Appendix 1. There are variations on how timetables are displayed. Some railways use graphs, some display trips horizontally and there are various forms of train ID.

Recovery Time

In order to "improve" timekeeping, railways have always provided recovery time in timetables. This is extra time, above that usually required for a train to complete its trip on time, allocated in case of a small delay or temporary speed restriction. Unfortunately, it has become much abused in recent years in the UK and huge levels of recovery have been built in - as much as 15% in some cases.

It does not make for good public relations when trains arrive at the outskirts of a city 10 minutes early and the passengers have to cool their heels in a stationary train knowing that they are only a few minutes travel time from their destination. Recovery time should be strictly limited and eliminated altogether when possible. It should not be used as an excuse for bad timekeeping.

Rolling Stock Working

It's essential that we keep track of our trains. We need to know the duty that each train will carry out each day so we can track its mileage and dates due for maintenance. We also want to be able to rotate trains through the timetable so that all trains get back to the main depot at Ash for cleaning and maintenance on a regular basis. Some railways refer to rolling stock working as "diagrams" – each train is said to work to a diagram. The diagram is its duty for the day. Some railways include train diagrams in WTTs while others issue them as separate documents confined to the rolling stock department.

Here is a typical British main line train diagram from the East Midlands Train company:

Diagram No. NL083

ECS	*5C15*	*05:02 Neville Hill T&RSMD-Leeds*
	1C15	05:25 Leeds-St Pancras International
ECS	*5C15*	*09:07 St Pancras International-Cricklewood CS*
ECS	*5M66*	*18:01 Cricklewood CS-St Pancras International*
	1M66	19:00 St Pancras International-Corby
	1P79	20:42 Corby-St Pancras International
ECS	*5P84*	*22:52 St Pancras International-Cricklewood*

Source: http://www.thejunction.org.uk/index.htm

Notes: ECS = Empty Coaching Stock. The 4-digit train ID used as follows: The first number is train type, the letter is the route destination for the passenger trip and the final 2-digit number is the individual passenger trip number.

Train diagrams will also include coupling and uncoupling where train lengths have to be changed. Nowadays, most metros keep train lengths the same throughout the day.

Terminal Occupation

Terminals are usually located in densely occupied areas and often date from an era when land was cheaper than it is now. Opportunities for expansion are limited so, for busy terminals, efficiency of operations is very important. It is essential that trains do not occupy a platform for any longer than necessary to unload the arriving train and prepare it for departure.

For metro operations, terminals are usually small and can accommodate a much higher frequency of trains. No dwell time is lost at peak times because of cleaning or catering. A two-platform terminus with a scissors crossover of suitable speed (as provided for Central, Hong Kong MTR) can allow a service of 34 trains per hour to be reversed. A modern metro terminal will be designed for automatic reversing.

Figure 7: A 12-car train of Hong Kong MTRC East Rail stock near Fanlin on the Kowloon Canton Railway route. These trains were rebuilt in the late 1990s and are at the heavy rail end of the metro segment. Photo by Rick W, Flickr 12th March 2006.

A Few Notes on Train Crewing

The basic working day for industry world-wide is 8 hours. A break in the middle of this will usually be for at least 30 minutes. On a railway operating 18 to 24 hours a day, traincrew will have more flexible working conditions which might extend the working day to 12 hours with suitable rest breaks. Certainly, shift work is involved. Many countries have laws which limit working hours and which determine minimum rest periods.

Hours can now be a lot more flexible than used to be the case, since a lot of new agreements have been worked out between staff and managers of the new breed of commercially oriented railways. However, any disruption of the service can quickly disrupt the crewing as well as the train positions and action must be taken to adjust crews, working with the available staff.

It is necessary to keep some spare staff on duty at all times. Any level between a minimum of 10% and a maximum of 25% for special circumstances might be considered necessary. I have been amazed at the levels of spare crews allocated on some railways.

For an even interval service with peak and off peak frequencies, the number of crews required to be employed can be calculated by the number of trains for the peak hour times a factor of five. This allows for training, weekend cover, occasional days off, leave, compensatory leave for working public holidays, sickness, shunting duties and spare crews. Individual totals will vary with the service provided and the conditions of employment and you might get that factor down to 4.5 or even 4 on smaller operations.

A Systems Approach

My paper covers a few essentials for metro operations planning but there's a lot more to it than this. However, in any approach to metro planning, a systems approach is essential to ensure all issues are covered. Some basic considerations are as follows:

- Determine the traffic and route requirements;

- Calculate the train performance and run times;
- Determine number of trains required, their stabling and diagrams;
- Maximise train throughput in signalling design;
- Decide on terminal layouts;
- Ensure there is adequate infrastructure - communications, facilities, power;
- Calculate crew duties and resources;
- Ensure passengers and staff are properly managed.

This is not a comprehensive list but it offers a start for an operational planner. More information is available here: http://www.railway-technical.com/tr-ops.shtml.

Appendix 1: Sample Working Timetable (WTT) for a Metro System

Train/Trip No.									**1-2**	**2-2**	**6-2**	**3-2**	**8-2**	**4-2**	**7-2**	**1-4**	**2-4**	**5-2**	**9-2**
Notes									*Ety.*	*Ety.*									
Ash									*05:40*	*05:50*		06:00		06:10	06:17	06:23	06:29	06:35	
Ash Depot																			
Elm									*05:44*	*05:54*	06:02	06:05½	06:13	06:15½	06:22½	06:28½	06:34½	06:40½	
Elm Sdgs																			
Oak									*05:47*	*05:57*	06:05½	06:09	06:19½	06:19	06:26	06:32	06:38	06:44	06:47½
Oak Sdg																			
Plane									*05:52½*	*06:02½*	06:11	06:14½	06:25	06:24½	06:31½	06:37½	06:43½	06:49½	06:53
Platform									1	1	1	1	1	2	1	2	1	2	1
To Form									06:00	06:09	06:16	06:22	06:28	06:33	06:38	06:43	06:47	06:51½	06:55
Train/Trip No.	**1-1**	**2-1**	**3-1**	**4-1**	**6-1**	**7-1**	**1-3**	**8-1**	**2-3**	**5-1**	**6-3**		**3-3**	**8-3**	**4-3**	**7-3**		**9-1**	**1-5**
Notes	*Ety.*	*Ety.*	*Ety.*	*Ety.*	*Ety.*	*Ety.*		*Ety.*		*Ety.*								*Ety.*	
Plane							06:00		06:09		06:16		06:22	06:28	06:33	06:38			06:43
Oak Sdg																		*06:44½*	
Oak							06:05½		06:14½		06:21½		06:27½	06:33½	06:38½	06:43½		*06:45½*	06:48½
Elm Sdgs					*05:55*			*06:06½*											
Elm					*05:57*		06:09	*06:08½*	06:18		06:25		06:31	06:37	06:42	06:47			06:52
Ash Depot	*05:31*	*05:41*	*05:52*	*06:01*		*06:09*				*06:26*									
Ash	*05:34*	*05:44*	*05:55*	*06:04*		*06:12*	06:14½	06:13	06:23½	*06:29*	06:30½		06:36½	06:42½	06:47½	06:52½			06:57½
Platform	1	1	1	2	1	2	1	1	2	1	2		1	2	1	2		1s	2
To Form	*05:40*	*05:50*	06:00	06:10	06:02	06:17	06:23		06:29	06:35	06:40		06:45	06:49	06:53	06:57		06:47½	07:01

Bibliography

"The Luso Pages" http://www.luso.u-net.com/listrams.htm, accessed 10th September 2011.

"Traffic & Congestion in the Roman Empire", Cornelis van Tilburg, Routledge, 2007.

"Simplon Postcards", http://www.simplonpc.co.uk/T_Lisbon.html, accessed 11th September 2011.

"Urban Transit Operation Planning & Economics", Vuchic R, John Wiley & Sons Inc., 2005.

The Junction.org at http://www.thejunction.org.uk/index.htm accessed 12th September 2011.

Railway Technical Web Pages: http://www.railway-technical.com.