

IS RAILWAY CAPACITY UNLIMITED? (A practical analyse, applied to South African cases)

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ABSTRACT

Rail is said to have an almost unlimited capacity. The PRASA Technology Framework states that a rail corridor is able to carry 60 000 - 80 000 passengers per peak hour. This paper analyses the practical optimum capacity of metropolitan rail services: an Underground Metro, an All-Stop train, and an Express service. In a practical situation the capacity of rail systems seems to be limited to some 35 000 passengers/hr on one track per direction; only in crush situation the maximum capacity is approaching 50 000. It would need four tracks per direction over great part of a corridor, to accommodate almost 60 000 passengers/hr in a mix All-Stop and Express service, and 80 000 only as crush capacity.

1 INTRODUCTION

1.1 Rail capacity in context

Passenger Rail is said to have an almost unlimited capacity. Based on guided techniques coaches can be coupled into long trains, able to carry thousands of passengers per load. The Passenger Rail Agency of South Africa's Technology Framework states that a rail corridor is able to carry 60 000 - 80 000 passengers per peak hour. However, in practise rail planners are battling to accommodate these high passenger numbers and in some cases the practical capacity of a rail solution based on normal operational principles are at most half of the quoted figures.

The word 'Capacity' is used very loosely in transportation industry sometimes referring to the total passengers on the whole corridor, in both directions combined, per peak (instead of top peak hour) or per day, or with multiple tracks per direction. As a definition in this paper 'Capacity' is described as the maximum passengers transported per peak hour, per direction, and per track on the busiest section of a corridor (unless otherwise stated).

1.2 Aim and scope of this paper

This paper focusses around analysing the capacity of three different types of metropolitan commuter rail systems:

- An Underground / subway systems (currently not operational in South Africa; but worldwide known for its high capacity performances);
- An All-Stop train service (like South African's Metrorail);
- An Express service (like Gautrain, but to be introduced for Metrorail as well).

A precondition for any rail train system is to demonstrate optimal value for money through the implementation and operation. The key drivers can be linked to minimising operational costs (and subsidy) and capital investment (rail infrastructure and rolling stock). Three main capital cost drivers are considered in this paper:

- Rolling stock requirements, an efficient system can achieve more passenger trips per train set and operational staff.
- Station costs (number of stations, station length);
- Number of tracks ('standard' double track, passing loops or multiple tracks).

The capacity analysis will be performed in context of the above mentioned railway systems and main infrastructure components; in there South African context and with an international comparisons. The aim of the paper is to answer the following questions:

- What is the preferred rail service quality? (see section 2);
- What passenger capacity per train can practically be achieved? (see section 3);
- What is the maximum train capacity per track? (see section 4);
- What non-infrastructure related measures are available to increase passenger capacities? (see section 5).

2 PREFERRED RAIL SERVICE QUALITY

The main two main issues that connect capacity issue to quality levels of services are door-to-door trip times and comfort aspects.

The door-to-door trip time consists of three components: short access distance to the stations (station spacing, feeders), short waiting time (high frequency), and short trip time (high speed, little stops).

The main comfort issues influencing capacity are the provision of seating versus allocated standing area and vertical/horizontal acceleration experienced in the car body. Other quality aspects such as fare price, security, convenience and other system requirements are equally as important in generating demand, but have little impact on the capacity of the system. These items are therefore not discussed in this paper.

Some of the quality aspects are in line with the cost reducing principles identified. Higher speeds and Express trains are more efficient with relatively short single-trip operation times allow for quick turnaround times. Train sets that run in the early peak period can make a return trip and run another trip later in the same peak. This reduces the total number of train sets required, drastically reducing capital costs on rolling stock.

2.1 Short Walking Time

Walking distance to/from stations are directly proportional to the train trip length. Passengers commuting short distance want to walk short distances to access a stations.

Underground systems generally have a station spacing of some 1 km (with differences between systems of 500 m to 2 km), providing a maximum walking distance of 500 - 800 meter. Increasing the number of stations increases passenger quality but, especially underground or on viaducts, also increase capital costs.

An All-Stop train service would normally have station spacing of 2 - 5 km. Metrorail's minimum station spacing is partly dictated by the signalling system spacing of 1.8 km resulting in station placement 2 - 3 km apart. The maximum walking distance is therefore between 1 - 1.5 km. The All-Stop service in the Netherlands, for example, has station spacing of 3 - 5 km or more. The difference lies in the fact that many Dutch passengers come to the station cycling, increasing the catchment area of stations.

For longer trips, a high number of stops drastically increase trip time. One operational solution to reduce trip times is the introduction of Express services, which skip some stations allowing the train to achieve higher average speeds. These Express trains normally run in combination with All-Stop trains to provide service to the stops that are skipped; although Gautrain only has an Express service.

When a single train performs an All-Stop service on a portion of the line and an Express on another section of the line it is referred to as a 'Zone'-service. An All-Stop train will stop at the first couple of stations, and from a certain station continue as an Express train to the main destination, while a next train could start from that intermediate station and perform an All-stop service for the next couple of stations. Long distance passengers have the joint advantage of short walking distances, and short trip time to their final destination.

2.2 Short Waiting Time

Waiting time is dependent on the frequency of trains, which is in turn dictated by the minimum headways on the network. Two aspects play a role:

- The quality requirements would dictate a minimum level of service, for short trips a higher frequency would be required and for longer trips a lower frequency is acceptable;
- From a quantity point of view the service would need to accommodate the passenger demand (see train capacity below).

As this paper discusses the maximum capacity, the frequencies will be high and would normally suffice the quality requirements. In case of a mixed train service (All-Stop and Express trains running alternately), the frequency of each train type is reduced and a minimum frequency quality norm would apply.

2.3 Short Trip Time

Trip time is a major quality aspect and a commuter trip should be as short as possible. Trip time is determined by station spacing (see above) and maximum operational speed.

An Underground rail system, with short station spacing, would not reach a high top speed. Such systems are mostly limited to 70 - 80 km/h. Trip time could be reduced by increasing the rate of acceleration and deceleration (braking). Acceleration is mostly limited by rolling stock performance and 0.8 to 1 m/s² is technically achievable. Deceleration on the other hand is limited by the frictional area on the wheel – rail interphase and 1.5 to 2.5 m/s² is possible. The acceleration and deceleration is usually not limited by the mechanical components, as it is limited by the effect it has on passengers (Lindahl, 2001). Fast and abrupt acceleration or braking can throw passengers around in the coach and are therefore limited to a maximum of 1 m/s².

With these characteristics, average speeds of Underground systems are generally 30 - 40 km/h.

An All-Stop train service has longer station spacing 2 - 5 km, and maximum speeds are generally 100 - 120 km/h. Currently Metrorail operates with maximum speeds of 70 - 100 km/h, due to the poor state of infrastructure and rolling stock, and sometimes even lower where speeds are limited by tight curves in hilly areas. PRASA is in the process of modernising their system, with new rolling stock, improved infrastructure and signalling, and upgraded stations. The new maximum speed is set for 120 km/h (but the rolling stock is capable of 160 km/h).

Average speeds of All-Stop train systems are generally 40 - 60 km/h. Metrorail currently operates with an average speed of 30 - 40 km/h, but this will improve with the Modernisation process.

Express services can save anywhere from 1 ½ to 2 minutes per stop skipped, which could lead to 15 - 30 minutes time reduction for longer services. The average speed of Express services is generally 80 - 100 km/h. The station spacing is much longer, with an average of 10 km, resulting in maximum speeds being maintained for longer periods of time. If the maximum speed is increased to between 120 - 160 km/h shorter trip times are achievable. It is commonly stated that Cape gauge technology can operate up to 120 km/h, while 160 km/h is easily possible for Standard gauge (even in excess of 300km/h). (Plunkett, 2000). However, when Cape gauge infrastructure is designed on new corridors, it could possibly be used for 160km/h as well. The advantage of 160 over 120 km/h is some ½ to 1 minute per section between stations. Much more valuable is the subjective factor in case a rail line runs parallel to a freeway: cars will try to beat a 120 km/h train, but will be passed by a 160 km/h train, marketing train use.

Much higher speeds (up to 300 km/h) are not effective for metropolitan Express services. The overall time saving advantage is limited due to relatively close station spacing. For example on a 10 km stretch 300 km/h is hardly reached with the limited acceleration and the time saving compared to 160 km/h is less than ½ minute. In this instance the benefit of increasing speed is not directly proportional to the increased capital and operational cost required to achieve such speeds.

3 CAPACITY PER TRAIN

The passenger capacity per train is determined by the train length and the density of passengers seated and standing.

3.1 Train length

Underground stations (either underground or on viaducts) are relatively expensive in comparison to conventional stations. This is one of the reasons why Underground stations are shorter and usually limited to 100 - 120 m. Another reason lies in the fact that alighting passengers should be cleared from the platform before a next train arrives; otherwise transfer capacity (and even safety) problems might occur. With high train frequencies (see below) the walking time on the platform should not be more than 1 minute, which equates to around 60 meters. (Vuchic, 2007)

For All-Stop trains headways are generally longer (see below) and station length is limited by the possibility for passengers to spread over the full length of the platform. Passengers tend to enter the train close to the station entrance, which is normally located centrally on the station platform. For this reason the far ends of long train will be half-empty, while central parts will be overcrowded. Some 200 - 250m seems to be the maximum practical train length for All-Stop trains (Metrorail runs with 12-coach trains of 270m). Much longer trains, up to 16 or 18 coaches are not practical, as passengers would not spread over the full length of the train, walking hundreds of meters along the platform.

Express train can run a bit longer: 250 - 300 m, as passengers have more time between trains to spread themselves over the platform length. The Gautrain service however is limited to some 200 m (8 coaches), with one of the main drivers to reduce the costs of underground stations.

3.2 Double-length Trains

This is where operational ‘tricks’ can be considered to increase line capacity. One could consider running double-length trains at certain corridor sections or network bottleneck. As stated earlier, much longer trains are not efficient, as passengers will not spread over the full length of the train. But combining two full ‘normal’ trains would be possible, mitigating this problem. This service would comprise of two single services (e.g. an All-Stop and Express service), being coupled at a nodal station, run as a long double train on the busiest section of the corridor (less capacity impact compared to two normal trains), and uncouple them again close to the destination, to run the two different train parts on different distributor corridors. This type of operations is commonly scheduled in many countries, e.g. the Netherlands.

The un/coupling operation would require an electronic coupling system to be standard on all trains servicing this route, and would cost some 2 to 3 minutes additional to the stopping time at the station. Consequently on the infrastructure side some (not all) stations have to be equipped with longer platforms to accommodate two train sets. Also the ‘coupling’-stations should have more platform capacity, to accommodate the longer station times.

3.3 Seating Comfort

For short urban trips, it is acceptable for passengers to stand. The number of passengers per square meter depends on an acceptable quality level. A general quality norm is 4 passengers/m², although in Asian rail systems a density of 6 to even 10 passengers/m² occurs. For longer trips it is recommended to provide passengers with a seat, and disallow standing. Various international standards indicate that standing is acceptable for urban commuter trips, with a maximum of 15 to 20 minutes, and in designated standing areas only. In case of longer (Express) trips, the trip time is often over half an hour, and standing should not be the norm.

Furthermore, design guidelines indicate the system should cater for fluctuations in passenger numbers. Rail systems are generally designed for 80 to 90% of the maximum acceptable capacity; 'crush'-capacity is only acceptable in special circumstances.

Underground rolling stock has longitudinal seating (roughly 50 seats per coach), leaving a great part of the coach available for standing passengers (some 150 passengers per coach). Generally an Underground train has a capacity of 800 - 1 000 passengers, with an uncomfortable crush capacity of over 1 500.

All-Stop trains can have longitudinal seating or transversal seating. PRASA's new rolling stock is ordered in both versions, for shorter and longer routes respectively. The longitudinal version has a passenger crush capacity of 200 per coach, up to 2 400 per train. The acceptable design capacity is lower as one would not want to design an average service with maximum capacity; in that case half of the trains would face overcrowding. Passengers would also require a bit more comfort, with less density (passengers/m²). An acceptable maximum capacity would be 1 800 passengers per train (for longer trips one should consider 1 500). The transversal version would have a capacity of 80 seated and 20 - 40 standing per coach, equals some 1 200 passengers per train, or 1 500 in crush situation.

In Express services only limited standing capacity can be used. For most passengers the trip is long and seating is required. The seating arrangement can be further optimised to 80 - 100 passengers per coach. Mostly a 2+2 seating arrangement would be applied. Gautrain has a wider coach body allowing for 2+3. There is a little standing capacity available near the doors, roughly 20 per coach. Gautrain has shorter trains (8 coaches) and therefore less capacity per train: roughly 800. As Gautrain currently faces capacity problems, management now is considering providing more standing places; this is acceptable as a part of the passengers travel shorter distances, and also for longer trips a seat would come available after 10 or 15 minutes standing.

The normal capacity of an Express train would be 1 200 passengers per train. In case of bigger irregularities in the passenger service, additional 'crush'-capacity of 1 500 is available as standing places in the aisles can be used, but this is considered unacceptable for normal operations.

3.4 Double-decker trains

One thing that would definitely increase train capacity is the introduction of double-decker trains. A double-decker train however does not have double the capacity, as some internal space is ‘lost’ by stairs, and the area near doors and above bogies cannot be double decker. On average a double-decker train has an additional capacity of 40 - 50%, compared to normal trains. A disadvantage of double-decker trains is that the station times will increase, as passengers need more time to board and alight, walking past narrow aisles and up/down steps, as well as accommodating more passengers through less doors per coach. A 12-coach double-decker train would have a maximum capacity of some 1 500 passengers, mostly seated, or 2 000 as ‘crush’-capacity.

Introducing double-decker trains however is not possible on the current Metrorail or Gautrain systems, as these trains are too high and do not fit within the structural clearance profile. Designing new rail corridors for double-decker trains would provide optimum capacity, but would limit inter-operability as such a system could only run as stand-alone system.

4 CAPACITY PER TRACK

With a train system the braking distance is far greater than the sight distance. Therefore trains needs some kind of authorisation and signalling system to maintain safe operational distances between trains. This however reduces capacity and limits the number of trains per track per hour.

4.1 Minimal and practical headways

Generally a track is divided into blocks (at practical braking distance apart) and each block is preceded by a signal which authorises entrance to that block. There are three basic signals:

- Green light: the following blocks are empty and the train can continue;
- Yellow light: only the next block is empty, but the following one is occupied and the train should start braking, to prevent it from entering the occupied block;
- Red light: the next block is occupied, and the train should stop before the signal.

In practise trains can run 2½ to 3 times the braking distance / block length apart. This means that the headways between trains are also influenced by the train speed, as the design speed increase so does braking distance and therefore the required block length is longer.

Additionally the operations need some buffer, to be able to cater for small irregularities and practical utilisation is limited to approximately 75-80% of theoretical maximum utilisation.

Therefore following minimum headways are achievable, technical and practically:

- 1½ technical, 2 minutes practically for Underground systems with lower speeds,
- 2 technical, 2½ minutes practically for All-Stop services with 120 km/h
- 2½ technical, 3 minutes practically for Express services at 160 km/h

Line capacity is furthermore restricted by the station’s dwell time, the longer a train stands still in the station the more likely an approaching train will face a yellow or red signal, forcing it to brake. Two mitigating factors could be applied to reduce this roll-on effect of station dwell time, a short as possible dwell time, and additional signals near stations reducing block lengths.

For Underground Metro systems the short headway requires the trains to stop very short at stations. For that reason rolling stock has multiple doors (and a majority of standing space) to allow fast alighting and boarding, as well as quick door-closing procedures. Station dwell time can be reduced to between 15 - 20 seconds.

All-Stop trains' station dwell time is just a bit longer with 20 - 30 seconds. Express rolling stock normally would have less doors (to provide more seating capacity) and station dwell times are generally longer 30 - 40 seconds.

Busy stations (with longer dwell time) could have 2 platform tracks per direction, so a next train can enter the station, while the previous train is still there, or in the process of leaving.

Considering an optimum signalling lay out, short station dwell times, and additional buffer times, the practical maximum capacity of one rail track is approximately:

- 30 trains/hr for Underground Metro systems
- 20 trains/hr for All-Stop services
- 15 trains/hr for Express services

With ultra-modern signalling techniques, like 'moving blocks' even shorter headways are possible, increasing the number of trains with some 10 - 20 %.

4.2 Mixed train service

With a mix of trains (All-Stop and Express trains) the maximum number of trains is limited, as faster trains cannot overtake slower trains. Capacity of mixed-use tracks is limited to 8 - 12 trains/hour, depending on the length of single track per direction, where trains cannot overtake. Best practises in Europe however show that 12 to 16 mixed trains are possible on one track per direction. The Japanese railways perform a service with up to 20 or more mixed trains per direction, on some of their corridors. But these countries are known for their very tight planning and strict performance in operations, and optimum infrastructure lay-out (see below).

4.3 Increase track capacity

The 'easiest' way to deal with an increase of track capacity, especially with a mixed train service, is a build double track infrastructure per direction, with separate tracks for the slower All-Stop trains and for the faster Express trains. This however does drastically increase infrastructure costs.

'Cheaper' ways to increase capacity are passing stations, whereby faster Express trains can overtake slower All-Stop trains. It would however cost the slower train an additional 3 to 4 minutes waiting time. Therefore a partly double track would be preferred, where the overtaking can be planned in the timetable schedule and would take place en-route between stations, without loss of time. To reduce infra costs, this could be applied on sections with short station spacing.

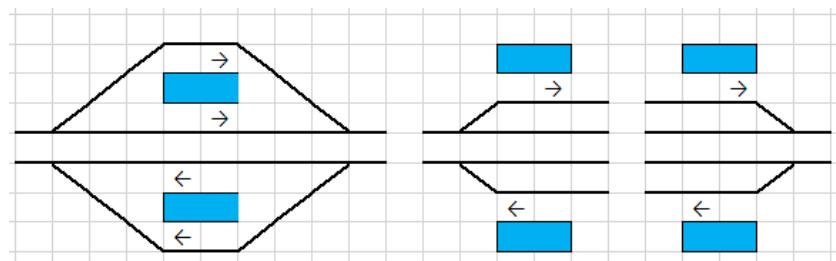


Figure 1: Layout of passing stations, and of partly 4 track passing section

Further optimisation is possible, taking into consideration that in some cases the return direction would have a limited contra-peak service with only some trains running back for another peak trip. The return direction can be designed mostly with single track. With this in mind the corridor could be designed with partly 3 tracks, making the middle track available for running in two directions (otherwise referred to as 'tidal flow').

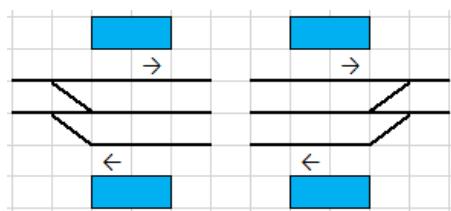


Figure 2: Lay-out of partially three track ('tidal flow') passing section

At longer section without stations, even in a mixed service, all trains will have an equal characteristic and All-Stop and Express trains can run without differences of speed with short headways on one track per direction. On the busiest section of the corridor, running double-length trains (as mentioned above) would allow the infrastructure to provide more capacity, and preventing the construction of four tracks over a greater part of the corridor. The corridor could function with mostly double track and some smaller capacity-enhancing facilities. This would reduce capital cost for rail infrastructure.

The above analysis is mainly applicable for the busiest section of the corridor. On more quiet sections further away, the number of trains can be reduced by operating short / long services. The reduced long services can run on one track per direction, as more capacity is available, even for mixed services.

With an accurately designed timetable on double / partly triple or four tracks, the maximum capacity could be close to the capacity with all-equal train characteristics, 15 - 20 trains/hr. On the other hand one should realise that South African train operations have to get used to ultra-modern techniques and high operational accuracies. Experience would need to be built up over time through personnel training and experience. It is not recommended to design and operate with these tight margins from day one. It is suggested to start designing and operating with a maximum capacity of 12 mixed trains/hour. Once such system has been adapted to, the operation could be increased.

5 ADDITIONAL MEASURES

The above analyse shows a reasonable high possible capacity in the peak hour and peak direction. This maximum capacity however is used on a small section of the corridor. There are many possibilities to increase patronage on such rail service, without burdening this busiest section.

One of these (short term) possibilities is ‘load shedding’ trying to persuade some peak travellers to travel outside the busiest peak hour or even outside the peak. This could be done by introducing higher fares in peak hour, as Gautrain is now considering. When this would be marketed as “discounts in off-peak”, it could also attract passengers with other travel motives as shopping, social, etc. and generating additional revenue at marginal costs.

Other (medium term) measure would be to introduce more flexible working and school times, to widen the peak. Additional activities could persuade some workers not to leave work in the busiest peak, but spend some time at for example the gym, coffee shops, or restaurant.

Other (long term) measures are in the field of urban planning, by introducing metropolitan areas with multiple nodes, where approaching each of these nodes would see a small peak, and seats in the train would be used by multiple passengers. It would also create a good passenger flow in contra-peak direction, where currently trains are running ‘half-empty’ to start a second peak service. Seat capacity in contra-peak is available at no costs, generating additional revenue.

6 CONCLUSION

In table 1 below a summary is given on the practical features of each metropolitan rail system (with optimised signalling). Table 2 shows the passenger capacity for a rail corridor with single track per direction (with optimised infrastructure). The numbers below are rounded (to avoid ostensible accuracy) and have taken into account a buffer to cater for fluctuations.

Table 1: Optimum / practical technical features of metropolitan rail systems

Rail system	Max speed	Station spacing	Station dwell time	Average speed	Headways tech → prac	Frequency
	Km/h	Km	Sec	Km/h	Min	Trains/hr
Underground Metro	70 - 80	1	15 - 20	30 - 40	1½ → 2	30
All-Stop trains	100 - 120	3	20 - 30	40 - 60	2 → 2½	20
Metrorail	70 - 100	3	20 - 30	30 - 40	3	15
Modernised	120	3	20 - 30	40 - 50	2½	20
Express service	120 - 160	10	30 - 40	80 - 100	2½ → 3	15
Gautrain	160	10	30 - 40	80	5	12

Table 2: Optimum / practical passenger capacity of metropolitan rail systems

Rail system	Train length	Train cap normal	Train cap crush	Frequency	Normal capacity	Crush capacity
	m	Pass	Pass	Trains/hr	Pass/hr	Pass/hr
Underground Metro	100 - 120	1 000	1 500	30	30 000	45 000
All-Stop trains	200 - 250	1 800	2 400	20	35 000	50 000
<i>Metrorail</i>	270	1 800	2 000	15	25 000	35 000
<i>Modernised</i>	270	1 800	2 400	20	35 000	50 000
Express service	250 - 300	1 200	1 500	15	20 000	25 000
<i>Gautrain</i>	200	800	1 000	12	10 000	15 000
Mix All-Stop / Express		1 500 (av)	2 000 (av)	12	20 000	25 000
<i>On four tracks</i>				35	55 000	75 000

Although Rail is said to have an almost unlimited capacity of 60 000 - 80 000 passengers per peak hour, in a practical situation the capacity of rail systems seems to be limited to some 35 000 passengers/hr on one track per direction. Only in crush situation the maximum capacity is approaching 50 000. It would need four tracks per direction over major part of a corridor to accommodate almost 60 000 passengers/hr in a mix All-Stop and Express service and 80 000 only as crush capacity.

The above results also show that current Metrorail is not capable to deliver the optimum capacity for a typical All-Stop metropolitan rail service, but with the Modernisation process ahead, it will be up to world-class. For Gautrain however design choices made (mainly the limitations of station length and headways) do limit the optimum capacity. When the Gautrain network is to be extended, these characteristics could be further optimised.

REFERENCES

- Onderwater, Emeran, 2013, Metrorail Modernisation Corridors, SATC 2013
- Emeran, Sanders, Dyer, Heyns, 2013, PRASA: Delivering the National Strategic Plan, SATC 2013
- Onderwater, Zuidgeest, 2014, Public Transport System Design and Operations Management, course at the University of Cape Town
- Esveld, C. (1989). *Modern Railway Track* (1st ed.). Duisburg: MRT-Productions.
- Lindahl, M. (2001). *Track Geometry for High-Speed Railways*. Stockholm: Royal Institute of Technology.
- Network Rail. (2011). *Guide to Station Planning and Design*. London: Network Rail.
- Plunkett, C. F. (2000). Track Infrastructure for high speed passenger operation on a metre gauge network. *Conference on Railway engineering*, 15.1 - 15.6.
- Vuchic, V. R. (2007). *Urban Transit - systems and technologies*. New Jersey: John Wiley & Sons, Inc.