

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

Rules for High Speed Line Capacity

or,

How to get a realistic capacity figure for a high speed line

by

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Summary

High speed is the new railway. Around the world, proposals for new high speed lines are booming. Many railway systems are experiencing ever increasing passenger and freight traffic and some routes are showing signs of stress, such as poor punctuality and overcrowding, often due to the capacity constraints of their systems. All this is leading to calls in various countries for new high speed routes to be built to provide more capacity and to add the benefit of a reduction in the pollution and congestion in the skies caused by air travel.



Figure 1: TGV at Grenoble, France. Photo by Rafal Tomasik.

But, a big question is just how much capacity can a high speed rail route provide? Lots of numbers have been cast about in the hope of making a case for various high speed rail projects but not many of them are accurate and some are grossly unrealistic, so this paper looks at the question of high speed railway capacity and sets out some simple rules to make sure everyone understands what's going on.

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Rule 1: Define line capacity

First, we must be sure we understand what is meant by “line capacity”. By definition, line capacity is the ability of a railway to carry a certain number of trains in one direction over a certain period. It is determined by how many trains you can run on the line in this direction in an hour and is expressed as trains per hour (tph). It can also be described in minutes or seconds as “headway” - the time interval between successive trains².

Line capacity will depend on the train’s performance, particularly its braking and acceleration, its length and how it’s controlled. How many trains you can run will also depend on the infrastructure – the power available, the maximum line speed, the station spacing, the terminal design, gradients and the train control (signalling) systems.

With a defined infrastructure and a given train design, line capacity will depend on the number of trains you can push along the track safely, one behind the other, in a given time. The actual number is then largely a function of the train performance and the train control system.

Rule 2: Define the parameters

We must first set out some basic parameters for our high speed train and its operation. Our route is flat, has a top speed limit of 300km/h and operates electric multiple units similar in general design to those well-known French, German and Japanese types.

Parameter	Data	Comment
Train top speed	300km/h	As for Eurostar. ~83.33m/s. A higher speed would consume a disproportionate level of energy compared with the benefits.
Train length	400m	This is the length of a Eurostar and also a 2-unit German-designed Velaro train.
Platform length	400m	The same as the train, naturally.
Average Acceleration	0.3m/s ²	Average over acceleration to full speed. Starts at 0.5m/s ² for first 1000m and then to 0.4 m/s ² for the next 1000m.. German ICE used as basis.
Deceleration	0.5m/s ²	This is about half the “full service brake” deceleration possible with a train but allowances are included for poor rail conditions, brake unit isolation and worn components.
Service brake distance	7200m	The actual distance is 6944m but allowances are added for command system response and brake feed up time.
Buffer zone	100m	This is the distance added in the train control system to allow a margin for safe train separation and is normally added to the braking distance.

² A formal definition of headway is, “The elapsed time at a given point between the passing of the front of one train and the passing of the front of the next.”

This table shows that to brake from 300km/h to a stop will take 7200m and to accelerate back up to full speed will take the even greater distance of 11500m. This is a total distance of 18.7kms or 11½ miles but the distance isn't what's important to us, it's the time it takes to make the stop and get away up to full speed again.

For our train, we can expect to get a deceleration rate of 0.5m/s². This will give us a braking time of 170 seconds or just 10s short of 3 minutes³. Acceleration takes longer, since the overall rate, which falls off as the train approaches its top speed, is quite low. Using the average 0.3m/s² achieved by the German ICE train, it will take 4.6 minutes to get to full speed.

So, just to slow down to a stop and restart to get back up to 300km/h takes a total of 7½ minutes and covers 11½ miles. This is twice as long as it would take the train to cover the same distance at full speed.

Just as a matter of interest, the equivalent figures for a 400km/h top speed are a brake time of 222s and an acceleration time of 370s, a total of almost 10 minutes.

Rule 3: Don't Forget the Stations

We haven't, have we? No of course not, because the time spent in stations while passengers get on and off is crucial. While we are messing about looking for a carriage we think we might get a seat on, dragging our HGV-sized bags, luxury pushchairs and screaming children up and down the platform, the next train is catching up - at 300km/h no less. So the standing time at the station (known as "dwell time") has to be limited, in our case, to two minutes⁴.

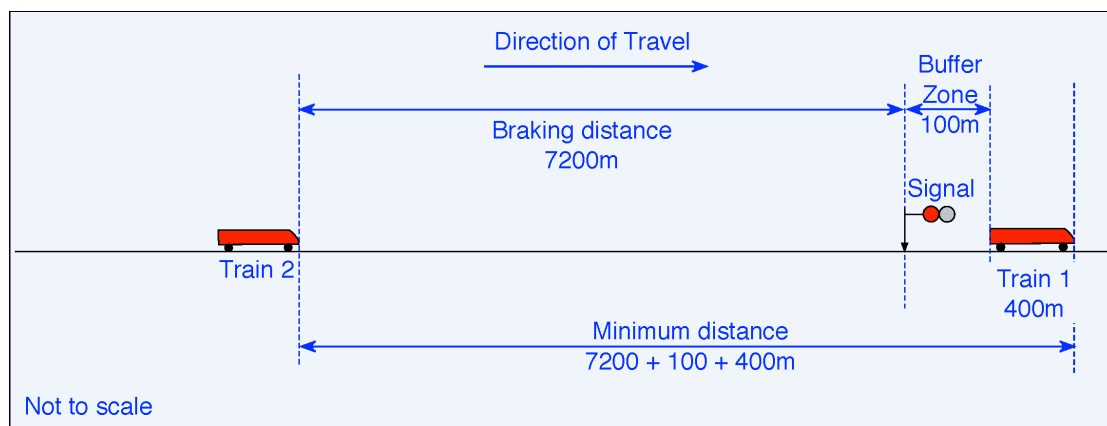


Figure 2: Diagram showing the theoretical minimum train separation distance for trains at 300km/h. The leading ends of the trains are separated by the braking distance required at 300km/h plus a 100m buffer zone and the train length. Drawing by author.

The dwell time has to be inserted into the time used by the train to brake into and accelerate out of the station. With the station stop added, we've now got 3 minutes braking, 2 minutes dwell time and 4½ minutes acceleration time - a total of 9½ minutes expended in making a station stop. This might lead us to think that we would need 9½ minutes between trains but it's not as bad as that. The next train is behind but it doesn't

³ In case you did the maths in detail, the distance required to stop a train from 300km/h with 0.5m/s² is 6944m but I've rounded it up and added time for the brake to respond to control commands and build up to the full rate. This gets us to 7200m and a time of 170s.

⁴ It should be remembered that the two minutes of a station stop is "wheel stop to wheel start time". With time needed for door opening, closing and dispatch, the actual time available for passengers boarding and alighting is about 90 seconds. It is also worth noting that the French TGV assumes a standard 3 minute station stop, with 5 minutes allowed for airport stations because of the large amount of baggage expected.

have to be that far. Thanks to modern train control technology, it can get closer. How close it can get, without being delayed by ours, will depend on the possible minimum train separation. Once we know that, we will look at stations again.

Rule 4: Understand train separation

The fundamental objective of any train control system is is safe but efficient train separation. To prevent collisions, you have to keep the trains apart and, if they are on the same track, you have to provide enough space between them to allow the second train to stop if the first train stops. This is often referred to as the “safe braking distance” and it forms a substantial part of train separation.

In our example, we already know that the train’s braking distance is 7,200m and we can assume that we have a modern train control system that monitors train speed continuously and applies the brakes if the safe distance ahead is reduced.

The stop command would be a red signal on a conventional railway but, on our brand new, modern high speed line, the trains are going so fast that a driver wouldn’t be able to see a signal long enough to respond to it, so we will have automatic train protection and automatic driving. Bearing this in mind, we can assume that it only requires an additional 100m buffer zone on top of the braking distance. To this, we must add the train length of 400m. This gives us a total separation distance between successive train fronts of 7,700m. If two trains running at 300km/h were following each other at this distance, they would be 92 seconds apart.

But this isn’t the end of it. There are other restrictions on how many trains we can run. These are usually described as “pinch points” and we need to look at these next.

Rule 5: Consider the pinch points

The first pinch point on our high speed route is the terminus at the arriving end of the trip. To maximise our capacity, we will try to provide a flow of trains arriving at the terminus one after another. Just how quickly we can do this depends on a number of factors.

The first is the braking time. An arriving train needs 170s to decelerate from 300km/h to brake to a stand at the terminus. This means that the following train has to be at least that far behind it if it is to get a clear run in. To this we must add 10s for route changing between trains at the terminus entrance fan, so now we get 180s (3 minutes exactly) between trains.

We also have to provide some time for conflicting moves at the terminus. Each train using the terminus will have to cross the path of another train for at least one of its moves, either on the way in or on the way out. Trains will be accelerating or braking during these moves over the terminus entrance fan, so this will cause it to block the entrance for up to 75s⁵. Adding this time to our 3-minute headway will put a limit of 4.5 minutes on the headway for trains we can get into the terminus.

There are other pinch points, as we will see, but this is the most obvious, and strangely, the most often forgotten. While we’re thinking about the terminus, it is useful to remember that a single terminal platform cannot handle more than three trains per hour. We have to allow time to unload passengers and their baggage, clean the interior, replenish water, restock victuals, change the crew and load the passengers for the outgoing trip. Thus, for a 4.5 minute service, you would need a minimum of 5 platforms.

⁵ Of course, this delay will not occur for every train. It could be reduced to 50% of arrivals and this would give an average operating headway of 3.62 minutes. I prefer the worst case.

You should really have a spare too, so that you've got room for changeovers and service disruptions, so that's six please. Seven would be even better.

Before leaving the terminus we should note see what other restrictions it causes. For example, just getting two trains away one behind the other takes time. Let's see what happens.

Let's say Train 1 leaves at 00m:00s past the hour and initially accelerates out of the terminus at 0.5m/s^2 . It needs 500m (its length plus its buffer zone) before it is sufficiently clear to allow anything else to happen. It will also need to be clear of any routes covering the fan at the end of the platforms - probably another 200m. To cover this 700m will take 53s.

Now the next route can be set up for the departure of Train 2. This will take a minimum of 10s. However, Train 2 can't leave until there's a safe braking distance between it and Train 1. Because neither train is running at full speed yet, the distance will be shorter than the full speed distance of 7,200m but it is not likely to be less than 1500m. We've already covered some of it but we should add another 25s before we can expect Train 2 to get the green light. However, as we've already seen, there are likely to be conflicts caused by arriving trains and we have to allow 75s for that. This gives us a total of 163s since the previous train started moving.

If we get the green light now, we must allow at least 30s for the station staff to get everything closed up and the train dispatched and this means it's now 193s - that's 3 minutes plus of anyone's money. All this shows us that we can only get trains away from the terminus at $3\frac{1}{4}$ -minute intervals. And we've assumed that everything is running to the second.

Rule 6: Junctions won't save you

We could overcome the terminal's pinch point problems, and reduce its footprint on the ground, by splitting the destinations and sending half the trains somewhere else. If we did this, we would need a junction. A junction has turnouts and turnouts, even the best of them, have speed limits. For high speed operation, simple engineering constraints limit turnout design speed to around 160km/h for a diverging train. This means that a train has to reduce its speed by almost half in order to take the diverging route at a junction.

A speed reduction of 50% to go through a junction will add almost 16s to the train's time on the main line, something we must add to the 180s we already have for terminal braking and route setting time. This pushes our headway out to 196s. Junctions however, are the Achilles heel of railway operations.

Rule 7: Add the operating margin

Junction operation relies on accurate timing. So does everything else we've considered in this paper. So far, we've assumed that everything will work according to plan and that train timing will be to the second but, as we know only too well, life on the railway isn't like that. Even with the best designed system, including grade separated junctions, reliable trains and control systems, well-behaved passengers and fine weather, trains cannot be expected to approach at the exact second. You will always get minor variations for such things as gradients, curves, temporary speed restrictions and extended departures.

Most passengers will know from their experience that "within a minute or so" is more like it, even on the best run lines. Battle-hardened railway operators know this too and the UIC (the French initials of the International Union of Railways) recommends a 25% margin on train timings when compiling a timetable. So, if we are setting a headway for

our high speed railway, we must take the 196 seconds “signalling” headway and convert it into an “operating” headway of 245s or 4 minutes.

Rule 8: Reconsider the effect of stations

Now we understand the effect of some of the pinch points and the need for an operating margin, we need to look at stations in a little more detail to see their effects on throughput. To protect the train standing in the station, we must show the train behind a stop command at least 7200m to the rear of the station, plus our buffer zone of 100m (Figure 3). However, if we can get our train moving within the allotted two minutes and we time the following train sensibly, we can prevent it being delayed.

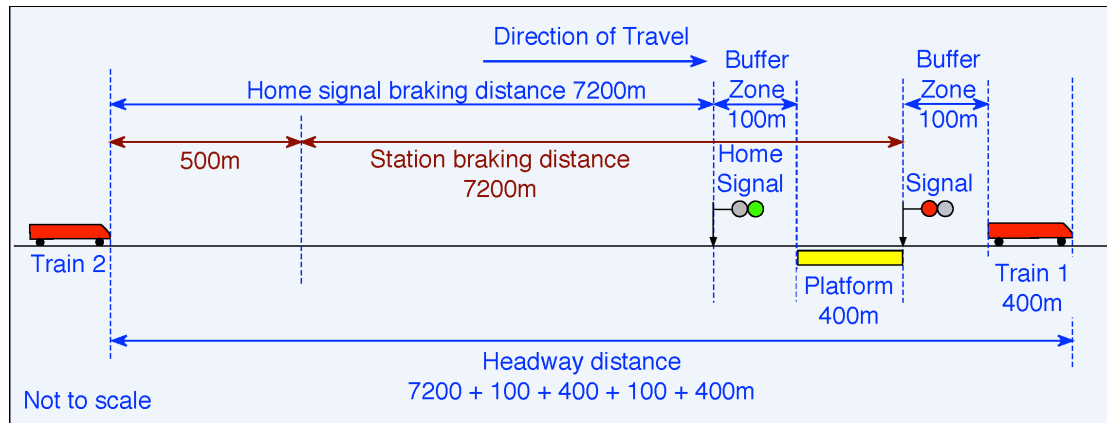


Figure 3: Diagram of factors incorporated in station stop time. A buffer zone is inserted into the train control allowances for safety purposes. The station braking distance is also shown. From this, the time required for station stops can be generated. Drawing by author.

Once the platform work is complete and our train is despatched, it can start to move. The rear of the train must be clear of the platform and the buffer zone before we can allow the following train in. There must also be a safe braking distance between the two trains at all times.

If we assume that the following train is also going to stop at the station, it will have to get a stop command when it’s 7200m from the front end of our station platform⁶. All we’ve had to do is create a safety buffer between the two trains and allow for the train and platform lengths and we’ve got the two trains quite close together in perfect safety.

In our example, the train is 400m long, so the platform will also be 400m and we have 100m buffer zones. Figure 3 shows how these are arranged around the station. Now we can calculate the headway that results from two successive trains stopping at a station.

Rule 9: Do some simple maths

The total distance between the leading cabs of two successive trains stopping at a station is $7200 + 100 + 400 + 100 + 400 = 8200\text{m}$. The time taken to cover this distance is the “station headway” and it is calculated as follows:

- 500m at the full speed of 83.33m/s = 6s
- 7200m at -0.5m/s^2 for braking = 170s
- 500m at 0.5m/s^2 acceleration = 45s

⁶ It should be remembered that, if the station is clear, an approaching train will brake at 7,200m on the approach side of the leading end of the platform. This means it will travel at full speed for the first 500m of the home signal braking distance. I have allowed for this in my calculations.

- Dwell time = 120s

This gives us the total time required for a train to clear a station platform and allow the following train to approach without being offered a restrictive speed command. It adds up to 341 seconds or 5 minutes 41 seconds. In capacity terms, this equates to 10.5 trains per hour.

And don't forget, we must add our operating margin to this. Now our capacity drops to 8.5 trains per hour. This doesn't seem a lot but we can improve on it by using passing loops at stations.

Rule 10: Build 4-track stations

The obvious solution to the problem of the delays caused by station stops is to divert stopping trains off the main line into a loop track built specially for the platform. One of these loops on each side of the line will give a 4-track station layout. It's a common solution on high speed lines and it's used on conventional routes too. Let's see what happens to the throughput if we try it.

The best approach would be the one where the stopping train diverges from the through line at full speed but this is unlikely to be viable. No one has managed to engineer a turnout to take a speed higher than 200km/h and even that was very expensive. As we mentioned in our discussion on junctions (Rule 6), the operational maximum is generally reckoned to be 160km/h, just over half our line speed of 300km/h.

If we assume a possible headway of 180s (from Rule 5), a train slowing for a diverging route will increase our time by 16s to 196s. Effectively, this is the additional run-in time for the station. If a non stop train is following, the closest it could get is 196s.

The run out time will also be limited by the converging turnout. If we assume an average acceleration of 0.3m/s^2 , a speed of 160km/h is reached 3300m beyond the station. This leaves 8200m to get to full speed and it will take 130s to do it. This is 32s more than it would take to cover this distance at full speed. It's double the time required for the run in, so we can discount the run in as far as the overall headway is concerned but we have to add the run out time to the 180s full speed headway, and this will give us just over 3½ minutes. Add the operating margin and we get 4½ minutes. Our capacity is now just over 13 trains per hour.

Just for the record, to get the maximum benefit of a 4-track station, the section between the entry turnout and the exit turnout must be at least 2000m long on the run in side and 3300m on the run out side.

Results

Looking at the results we've got from our survey of possible throughputs for a new high speed railway, we can wrap up the deal for what we need for optimum performance as follows:

- A 400m train with a 300km/h top speed;
- 5,500m long 4-track sections at intermediate stations;
- Six platforms at each terminus;
- Grade separated junctions;

We can expect no more than a 13 trains per hour capacity. It doesn't mean high speed rail isn't worth the cost but at least we should know what we'll get.

If you were wise, you would take the advice offered by both the German ICE high speed operator and the French TGV consultants Systra and assume that, if you can operate 12 trains per hour on a high speed line, you are doing as well as anyone.

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