High Speed Railway Capacity

Understanding the factors affecting capacity limits for a high speed railway

by

Piers Connor[1]

Abstract

High Speed Rail is the new railway. Around the world, proposals for new high speed lines are booming. Many existing 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. This is leading to calls in various countries for new high speed routes to be built to provide more railway capacity, with the added benefits of reduction in the pollution and congestion caused by cars on the roads and planes in the skies.

These are laudable objectives 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 simply unrealistic. In this paper I look at the question of high speed railway capacity, with the case of the British HS2 project as an example and analyse the factors affecting capacity, including terminals, junctions, stations and rolling stock performance.

High Cost Transport

Railways are high investment systems. In the UK, a new double track railway, like HS2, will cost around £76million per km. (HS2, 2011). A modern train will use up to £1.5million per vehicle. Signalling systems will be up to £3million/km. Power supplies and communications will fall into similar price ranges. These systems represent a significant investment and this investment must be seen to be used to its fullest potential. For this reason, a railway and its systems must be planned and engineered to allow the maximum capacity to be realised, if not at opening, then for a future date. In this paper, I examine the issues surrounding the potential capacity that might be achieved on a high speed railway.

Line Capacity

First, what is meant by railway capacity? Railway capacity can be described in a number of ways but, in this paper, I use the term "line capacity" as the ability of a railway to carry a certain number of trains in one direction on one track over a certain period. It is determined by how many trains you can run on a track in this direction in an hour and is expressed as trains per hour (tph). It can also be described as "headway" - the time interval between successive trains. I offer a formal definition of headway as, "For a single direction, 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."

Line capacity will depend on train performance, particularly braking and acceleration, length and how trains are controlled. How many trains can be run will also depend on the infrastructure – the power available, the maximum line speed, the station spacing, the terminal design, gradients and the railway control (signalling) systems. On top of that, the operating conditions - dwell times at stations, terminal operations, allowances for speed restrictions and recovery margins will also affect throughput. Although we are looking at high speed lines, these conditions apply to all railways, regardless of the top speed of the fastest train.

Looking at capacity for existing high speed routes, we can see published ranges of between 12 and 15 trains per hour. The UK's HS2 is proposing an eventual total of 18 tph. This is at least a 20% increase over the established norms. Could this be done? If so, how? What factors have to be considered? In this paper, I examine the major issues

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[1] University of Birmingham (Part Time)

Published Information

Publications (referenced as appropriate throughout this paper) include a number of papers published by or on behalf of the HS2 project. Interestingly, these papers suggest that 18 tph is possible but they follow different paths on the route to their conclusions. The list of the main differences is as follows:

- Variations in the top speed proposed;

- Variations in acceleration and braking rates and

- Variations in train control allowance times.

There is, also, minimal reference to terminal operations and only passing references to automation vs. manual control. From this, it seems that more needs to be done to consider the whole of the operation of a high speed route, its interfaces and its pinch points, in order to get a realistic view of its capacity and the reliability of that capacity. In this respect, I offer some discussion in the following paragraphs.

Defining the Parameters

Parameter	Data	Comment
Train top speed	360km/h	~100m/s.
Train length	400m	
Average Acceleration	0.3m/s^2	Straight line calculation
Deceleration	0.5m/s^2	Straight line, 50% "full service brake".
Service brake distance	10000m	
Buffer zone	300m	For ATP
Driver reaction	8s	Manual operation
ATP response (Tx/Rx)	8s	Including interlocking
Turnout operation	10s	Lock to lock time

We must first set out some basic parameters for a train and its operation (Table 1). For the sake of this discussion, I assume that the route is flat, has a top speed limit of 360km/h and operates electric multiple units similar in general design to those well-known French, German and Japanese high speed types. I have chosen 360km/h (100m/s) since this the UK's HS2 chosen speed for the start-up timetable but below its 400km/h civil design limit. I doubt the latter figure will be reached as it is not energy efficient for the distances between the planned HS2 stations. Indeed, I might suggest that it is not energy efficient at 360km/h. A top speed of 300km/h might be more suited to the comparatively short distances of full speed running on HS2.

Acceleration

Being constrained at the upper end of the speed range by the power available, modern electric train acceleration shows a broadly parabolic curve that, generally, starts to fall most significantly from its maximum at about 30% of the top speed. The published HS2 documentation does not offer acceleration rates (apparently it is from the Alstom model and they refuse to let it be published) but it is inferred in figures supplied on the operation of junctions by HS2 (McNaughton, 2011). This suggests that up to 165km/h, the acceleration will average 0.21m/s^2 and above this level it will fall to 0.14m/s^2.

These acceleration figures are rather low. The latest Japanese Shinkansen train, type N700, is reported to have an initial acceleration of 0.72m/s^2 (Ueno et al, 2008) but the equivalent straight line acceleration to 300km/h shows a rate of 0.31m/s^2 (Harding, 2012). This is in keeping with some other high speed railways, e.g. the German Velaro design (Siemens, 2011) but is better than the French TGV-A (McNaughton, 2011). I have chosen an average rate of 0.3m/s^2. This means our reference train will take 333s (5.55min) over 16.67km to reach its top speed of 360km/h.

Braking

Like acceleration, a train's deceleration curve forms a parabolic shape but one that steepens at the lower end of the range. Again, a straight line approach is necessary to obtain a simple view of the effect on capacity (Figure 1). The braking rate adopted by HS2 (0.7%g or 0.687m/s^2) is not, based on data currently available, sustainable at the higher speed end of the speed range. A more realistic

approach is by Hunyadi (2011), who proposes a series of braking rates that vary with speed as follows:

360-300km/h: 0.49m/s^2

300-230km/h: 0.52m/s^2

230-0km/h: 0.60m/s^2

This gives a braking distance from full speed to zero of 9270m. Further, MVA/Systra (2011) shows an average braking rate of 0.42m/s^2 for the TVM 430 signalling system under normal conditions. A plot of a Chinese high speed run from Tianjin to Beijing (Appendix 1) shows an average deceleration of 0.4m/s^2.
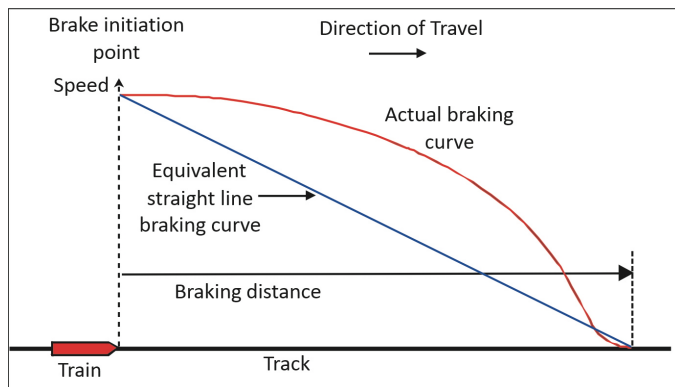

Figure 1: Simple diagram demonstrating the principle of the straight line braking curve. The approach to the stopping point is characterised by a reduction of brake effort for positioning and comfort purposes. Graphics: Author.

In considering train braking, it should be remembered that it is the most difficult part of a train's operation. At any speed over 100km/h (and often at lower speeds), the driver must commence braking for a stop at a point from where the final stopping location is not visible. If lineside or cab indications of the braking commencement points are not provided, the driver has to learn them during training. The braking commencement points will usually be conservative, with allowances for variations in weather and visibility conditions, individual train performance and individual driver performance. Many railways in the UK, nowadays insist on a "defensive" driving approach to reduce the risk of signal overruns and some operators advise a platform entry speed of under 32 km/h (20 mi/h). This is not conducive to efficient capacity but is does reduce the overrun risk during poor adhesion conditions[2].

Another point to consider for train braking is the need to reduce the rate at the lower end of the speed range (Figure 1), in order to allow for accurate positioning and to create a comfortable station stop for passengers, many of whom could be on their feet preparing to alight. This is not taken into account in Hunyadi's calculations (2011), which have an average braking rate of 0.54m/s^2, so I have adopted a rate of (0.5m/s^2), which shows that to brake from 360km/h to a stop will take 200s (3.33min) and cover 10km. This provides an allowance of 730m for comfort and positioning.

Consideration of capacity values therefore, must include variable train braking skills, conditions of reduced adhesion and the adoption (or not) of a "defensive" driving policy. Automation to some degree might assist in this consideration and this is discussed later in this paper.-
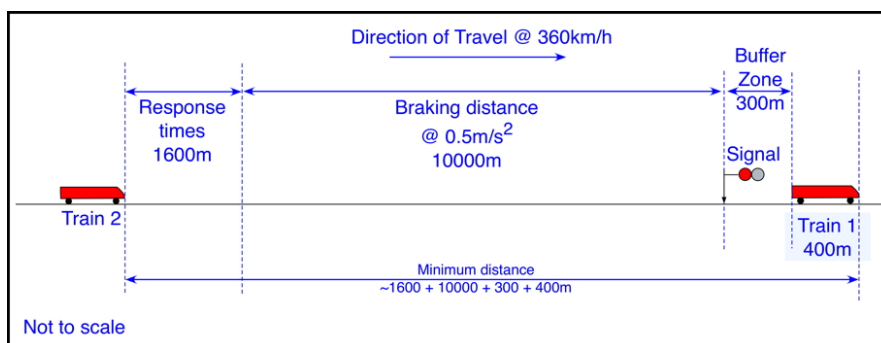

Figure 2: Simple diagram demonstrating the distances required for safe train separation. The data used is discussed in the text. Graphics: Author.

Train Separation

The fundamental objective of any train control system is safe but efficient train separation. To prevent collisions, trains must be kept apart and, if they are moving on the same track in the same direction, there

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[2] In my view, with such expensive infrastructure, equipment and staff, a defensive driving policy is a waste of resources. It decreases capacity. Drivers should, in the case of braking, be taught to use the full service brake rate on the approach to station stops unless rail conditions require otherwise.

must be enough space between them to allow the second train to stop when the first train stops. This is often referred to as the "safe braking distance" and it forms a substantial part of train separation, which increases with speed.

From our example above, we already know that the train's full speed braking distance is 10,000m and we can assume that there will be a modern train control system like the European Train Control System (ETCS) that monitors train speed continuously and which will apply the brakes if the driver fails to when safe distance ahead is reduced. Appropriate indications will be provided in the cab.

For safe train separation at line speed, the signalling system requires the braking distance (10000m) plus a contingency of a buffer zone between two trains moving at full speed. The buffer zone has been suggested as 300m (HS2, 2011). Perhaps this could be regarded as excessive but at 360km/h it's only 3s. There is also the consideration of a train being stopped in a tunnel and the effect on the smoke control airflow if trains are positioned too close together.

There must also be an allowance for both driver reaction and signalling equipment response. These figures vary from source to source but I offer 8s for driver reaction and a further 8s for equipment response under the plain line case, including train detection functions, transmission time and train response time. This adds a further 1600m to the train separation distance. An additional time of 10s should be added where turnout operation is included.

We must include the train length of 400m. This gives us a total separation distance between successive train fronts of 12300m (Figure 2). If two trains, both running at 360km/h were following each other at this distance, they would be 123s apart. This may be defined as the full speed, signalled headway, sometimes referred to as the "technical headway". Thus, if all trains ran along the line at this speed and separation, the line could be said to have a capacity of 29.27 trains per hour. However, there are a number of issues that will reduce this number and I consider these next.

Diverging Routes

Figure 3: High speed turnout designed for 200km/h operation. The turnout is 164m long with 65m switch rails and 8 motors, plus an additional 3 motors for the movable crossing angles. Photo: Georg Trüb of Railpictures.net.

Where routes diverge, there is a need for turnouts (points). Diverging or merging routes off the main line at turnouts must be negotiated at reduced speed, the actual speed depending on the turnout design. A maximum diverging speed of 230km/h is now possible (Vossloh Cogifer SA, 2012) but I would suggest that the maintenance of such necessarily highly machined switch rails and the large number of point motors needs to be carefully considered (Figure 3).

Imposing a speed reduction for a diverging train from 360km/h to 230km/h will affect the following train if this is to pass the junction on the main route at 360km/h. If it continues to run at full speed, it will violate its safe braking distance as it will close in on the slowing train ahead. To avoid this, the distance between it and the slowing train must be increased. Allowances for the speed reduction and for the turnout change after the diverging train has cleared the route must be included. This amounts to 22s, which will increase the headway to 145s. This is equivalent to a theoretical capacity of 24.8 tph. A comparison with the calculations offered by McNaughton (2011) shows a very similar 141s headway for a $0.5m/s^2$ braking rate.

Braking Management

It should be noted that the choice of brake rate has a significant effect on the results for

capacity calculation. If the braking rate is increased to the 0.687m/s^2 suggested for HS2, the full speed headway is reduced to 96s @ 360km/h, to give 37.5 tph or a 22% improvement over the 123s full speed headway. The diverging headway becomes 121s.

For a driver, the ability to vary braking between 0.5m/s^2 and 0.687m/s^2 is very slight in terms of control capability and therefore, left without additional technical support, the throughput for the railway will rely largely on driver skills. This is not an efficient solution and it points to the need for some degree of automation. In addition, this level of variation is less than that required by bad weather, which may induce adhesion values as low as 0.3m/s^2 without a robust technical solution.

Intermediate Stations

Not unnaturally, trains require to stop at stations. If station stops were inserted on the same track as the non-stop trains, the technical headway would be reduced to something like 8 tph. To avoid this, loop tracks must be provided for intermediate stations. The critical point for the headway then becomes the location of the turnout for the loop track. Ideally, from a headway perspective, this will be at the highest speed possible or 230km/h. This would locate the turnout some 4132m in rear of the station (3402m + 730m for comfort and positioning) in order for the train to follow a natural braking curve from full speed to a stop in the correct position in the platform berth.

Acceleration after leaving the platform berth at the average of 0.3m/s^2 requires that the converging turnout for the 230km/h maximum speed possible when joining the main line is located some 6800m beyond the station. The better acceleration actually available at the lower speed will reduce this but even if the train arrives at the converging turnout at the exact time allowed by the movement authority of the train control system, it will require a further 120s, covering 9864m to reach full speed. This will add another 21s to the headway. However, McNaughton (2011) suggests that the acceleration will have fallen to an average of 1.14m/s^2 over this section, causing an increase in headway of 46s. These times will only be achieved if the departure of the stopping train is timed to match the minimum converging moment allowed by the train control system. However, battle-hardened operators will know that station stop timings are notoriously difficult to predict and a prudent operational strategy would allow for this by including a significant margin.

Unfortunately, a converging scenario is not considered by Hunyadi (2011) but Arup (2011) examines the operation of station stops and starts with both diverging and converging turnouts and offers a detailed series of parameters for two types of train. The result is broadly similar to other studies since it assumes the same or similar train accelerating and braking performance.

What does arise from these variations is a need for a whole system model that takes into account the whole range of the dynamic speed curves, allowances for train positioning and comfort when stopping, the distances between stations and turnouts and the relationship between station dwell times, train starting times and the passing of non-stop trains.

Mitigation

A station loop layout with 230km/h turnouts at each end would require a 4-track section of at least 11.5 km in length. This will be expensive. However, Hunyadi (2011) has shown that it may be reduced by a stepping technique of speed reduction that requires trains to reduce speed earlier, thereby bringing the turnout closer to the station and thus reducing the length of the 4-track section but this includes a requirement for reducing the speeds of all trains on the approach. Such a technique has been common on metros for many years, where it was known as speed control.

Speed control will require block lengths to be designed accordingly. MVA/Systra (2011) suggest that 1600m blocks should be the standard since longer blocks would reduce capacity. In my view, shorter blocks will be required for speed control purposes in a number of locations.

The speed control technique does reduce the headway and both Hunyadi (2011) and Systra (2011) show that it can be used to help maintain the 18 tph service suggested by HS2 but it does increase journey time and the requirement of the system designer at this stage is to consider the impact of both. The question he has to answer is whether the system will attract more passengers by offering an increased frequency but with an increased journey time or the inverse, providing a shorter journey time with fewer trains per hour. The answer is not simple, since is has to be considered within the context of the increased life cost of the infrastructure and facilities required for shorter journey time. In my view, the slightly longer journey time will be a small sacrifice in comparison to the benefits of cost reduction and frequency increases.

MVA/Systra (2011) implies a similar conclusion and suggests that station stops should have turnouts with a speed of no more than 170km/h. This imposes constraints on journey time but their suggestion is that, using the fixed block TVM340 train control system with 1600m blocks, a technical headway of 143.2s is possible. To this they add a "driving allowance" of 20s. Their introduction of a driving allowance leads me to consideration of operational headways.

Operational Headways

So far, this discussion has been limited to technical headways. The technical headway is the theoretical headway offered by the train and its control system. It is never achieved in practice. Since it cannot be expected that a train will arrive at the exact point allowed by the control system at the moment it becomes available, a system designer must recognise that a margin for operational variances must be allowed for. This margin is additional to those already included above, like driver sighting, data transmission and equipment response times. This margin covers such things as variable dwell times, varying train performance, variable traction voltages, variable driver performance, weather, temporary speed restrictions and some sort of recovery margin.

The UIC recommends that 75% of technical headway is as good as can be obtained for operational throughput. In our example, this would give an operational headway of 16 trains per hour, assuming the most restrictive technical headway at the converging junction as offered by McNaughton (2011). This is close to the MVA/Systra model (2011) where 16.6 tph is proposed at 350km/h. This model includes the 20s "driving allowance", which could be reduced with some level of automation. Nevertheless, the conclusion here is that 16 tph is a sensible capacity for a high speed rail system of the type proposed by HS2.

Dwell Times

A large part of operational variability in high capacity rail systems is caused at stations. Dwell times at stations are notoriously difficult to control, particularly under European conditions, where passenger discipline is not as good as it is in, say, Japan. While we are wandering about looking for the carriage where we think our allocated seat might be, dragging our HGV-sized bags, luxury pushchairs and screaming children up and down the platform, the next train is catching up - at 360km/h. So the dwell time at an intermediate station has to be limited, in this case I would suggest, to three minutes[3]. Systra note that the dwell time at airport stations is fixed at 5 minutes on TGV routes to allow for the additional baggage carried by passengers. This would almost certainly have to be considered for HS2 at Old Oak Common and Birmingham Interchange.

Luggage Facilities

It is perhaps worth considering the location of luggage storage facilities on trains. A feature of trains in the UK at least, is to provide luggage storage at the ends of cars near the vestibules. This requires passengers to stack luggage before entering the saloon seating area. When several passengers attempt this process a queue forms through the entrance doorway and on to the platform. The prompt departure of trains is often delayed in this way. Some consideration should be given to alternative storage locations inside the cars. A central position might be more appropriate.

Terminals

The operation of terminals must not be forgotten in any assessment of railway capacity. In London, the operation of the whole of the Victoria Line was constrained to 28.5 tph by the terminus at Brixton, while the rest of the line was capable of supporting 30 tph. This situation lasted for 40 years until the original train control system was replaced in 2012.

A critical area will be the location of the turnouts and the permitted approach speed. It is instructive to watch the Eurostar trains run into St Pancras International at 50km/h while the East Midlands trains are restricted to 22km/h in the same terminus. The difference is simply in the train control system provided.

The location of the turnouts needs to be carefully selected so that the speed limit through the turnout matches, as closely as possible, the braking curve of the train approaching the terminal. This will not always be possible but some degree of integration in this area is most desirable. The terminal itself

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[3] 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 2.5 minutes.

will also need to be designed so that the train protection system includes a buffer zone for the speed limit of the final block.

It is, perhaps, worth noting here that platform capacity at the terminals is another constraint that must not be ignored. A single terminal platform cannot normally handle more than two intercity trains per hour. An allowance of at least 20 minutes has to be made for time to unload passengers and their baggage, clean the interior, replenish water, restock victuals, change the crew and load the passengers and their baggage for the outgoing trip. To this must be added the incoming route setup time, the run in time, the run out time and the route clearance plus a margin.

Thus for, say, a 5-minute service (12 tph), a minimum of 7 platform tracks is required, six plus a spare for late running. For future proofing, the 18 tph ultimate capacity would require a 10 platform terminus.

Automation

Considerable benefits can be achieved through automation. In a study I completed a few years ago (Connor, 2008), I found that automation of driving on a given fixed block metro gave a 14.7% increase in throughput over manual operation. The two principal factors behind this improvement were in the train braking profile and the elimination of the driver sighting time, although a percentage of the latter is re-imposed as the replacement ATO equipment response time.

In the case of a high speed railway, a degree of automation may offer similar benefits. The braking performance offers the highest level of improvement but this must be tempered with the reduction of adhesion capability under bad weather conditions. Compensation for this may be found in automatic sanding equipment or eddy current braking solutions.

The introduction of automation will bring its own problems, the most significant being driver inattention and the need to maintain competency. Manual driving on conventional lines will have to be retained. If automation over the high speed line is not considered viable, an automated driver advisory system may be considered as a sensible alternative.

System Model

Each of the factors discussed in this paper will have an effect on the overall performance of the system and there are plenty of other issues that time does not allow me to consider here. Most importantly in my view, it is essential to adopt a system model that would be able to simulate the effects of the issues discussed here and their relationship with other factors such as station spacing and location, energy use, power supply, degrees of automation and their effects on drivers and performance, dwell time management, the location of luggage facilities on trains and the design of terminals, to name but a few. I am sure there are others.

Concluding Comments

In this paper, the basic issues affecting train operations and throughput over a high speed railway have been discussed, using HS2 in the UK as an example. Various published papers have been reviewed in an attempt to understand the arguments behind the capacity estimates offered and some conclusions have been reached as follows:

- Line capacity is very sensitive to train acceleration and braking rates and these need further consideration;
- Practical braking rates proposed for HS2 are too high;
- Even with intermediate stations on separate loop tracks, station stops have a significant affect on throughput;
- Turnout speed and location have a significant effect on capacity;
- Weather conditions will impact capacity;
- Manual driving will have a further impact on capacity;
- Terminal capacity must be included in the assessment of capacity;
- Train interior design should be considered in respect of dwell time management;
- There will be a trade off between journey time and train frequency and
- A comprehensive system model should be used to provide the optimum design and capacity.

The discussion in this paper suggests that, under perfect conditions, 16 trains per hour capacity could be obtained, without including recovery time. If Automatic Train Operation was provided, 1-2 more trains per hour is possible by taking the driver out of the performance loop.

If wisdom was needed, perhaps we would take the advice offered by both the German ICE and the French TGV operators and assume that, if you can operate 12 trains per hour reliably on a high speed line, you are doing as well as anyone. But, can HS2 do better?

End.

Appendix 1
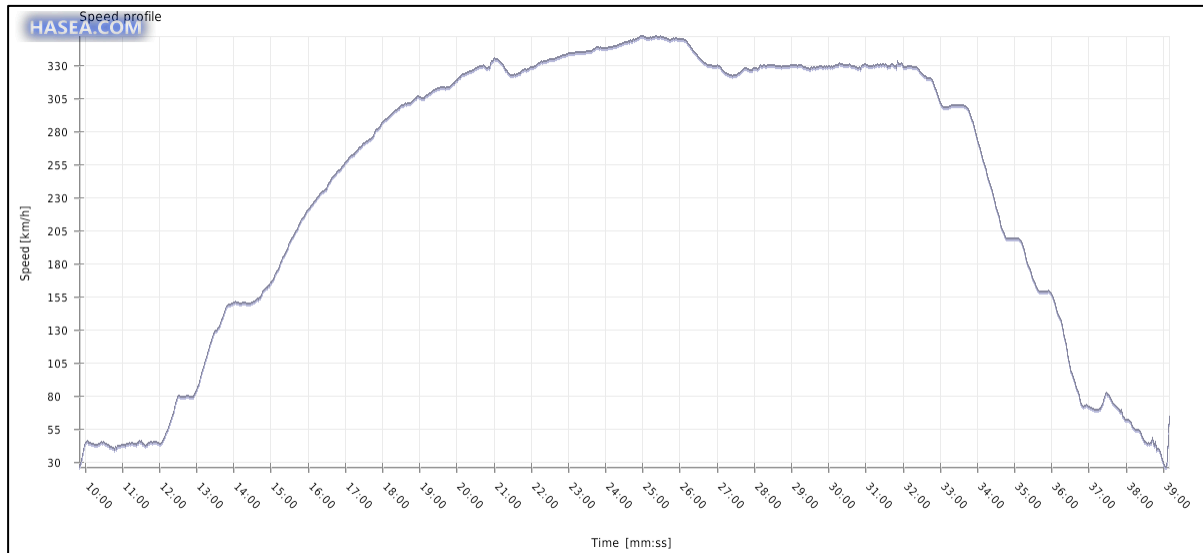
Plot of high speed train run between Tianjin and Beijing on 30 June 2011 using GPS tracking. It shows an average acceleration of 0.46 m/s^2 up to 150km/h and 0.13m/s^2 up to 330km/h. Braking averages at 0.4 m/s^2.
Source: YaoHua at Hasea.com.

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