Operational Concept Study

Technical Note: HS2 Capacity and Reliability

Report for High Speed Two (Ltd)

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Executive Summary

1.1 Purpose

HS2 has ambitious expectations in terms of passenger capacity and quality of service, so train capacity on the new infrastructure and reliability are subjects of particular interest. This technical note provides an in-depth study of these questions, with a level of detail that would not be appropriate for the primary Operations Concept report.

1.2 Operating margins and journey times

Accepting that it is necessary to incorporate some margin into journey time calculations, to accommodate minor delays, we have made some recommendations about margin distribution within the train journey, based on good practise and experience of operating high-speed train services. In the case of HS2, brisk braking and acceleration will be able to maximise capacity. Because of the relatively few intermediate stops, it will make sense for drivers and operators to plan trips on a timetable with a slightly lower operating speed than the line speed permits, which can then be used, if required, to recover lost time.

1.3 Placing train paths and UIC guidance

There is underlying logic in the UIC guidance, which may appear excessively prudent by suggesting that 75% of available technical capacity is used for timetabled train paths, but it should be remembered that the application of this advice is the responsibility of each operator, taking local circumstances into account.

We advise that northbound services use 3 min headway with 2 spare paths per hour and that southbound services use 2.5 min headway with either 2 x 7.5 minute spare paths per hour or 3 x 5 minute spare paths per hour. We also recognise that the emerging service patterns for HS2 will develop their own logical pathway distribution, which complies with the UIC guidance as appropriate.

1.4 Headway calculations and comparison with HS2 work

We have reviewed the headway work undertaken by HS2 and recognise that there are some detailed timing figures that are different between the two analyses. We advise addition of 1.5 sec to account for train speed uncertainty and a movement authority update time of 12.5 sec, rather than 2 sec. However, this is a field of railway engineering that is rapidly changing and these variations are hard to conclude with certainty for a project that will produce signalling systems several years hence. We have carried both figures forward into the analysis

Open route - we have undertaken first-principles calculations of headway and, for the minimum open time headway of 126 sec, this leads to a theoretical capacity of 21 trains per hour (tph).

Diverging trains - we have assessed the impact on capacity of alternating diverging trains, using these same headways parameters and 139 sec minimum initial headway leads to a theoretical capacity of 20 trains per hour. The actual capacity impact of divergence will depend on the service pattern used.

Converging trains - we have assessed the impact on capacity of alternating converging trains, using these same alternative headways parameters and a combined headway of 257 sec leads to a theoretical capacity of 20 trains per hour. Again, the actual capacity impact of convergence will depend on the service pattern used.

1.5 Speed Reductions

The important consideration of the impact on capacity of speed reductions, for station stopping, permanent or temporary restrictions has to be assessed carefully, because braking can have a significant impact on capacity. We have tabulated the influence of various speed reductions on capacity. Whilst there is a further loss of trip time if stepped braking is used, compared with simple braking, capacity is safeguarded. We look at Old Oak Common in further detail and at temporary speed restrictions. A direct reduction from 360 kph to 200 kph reduces capacity from 23 tph to 14 tph. We have recommended a mechanism of stepped reductions to safeguard capacity so that a stepped reduction from 360 kph to 200 kph reduces capacity from 23 tph to 21 tph.

1.6 West Midlands Junction

We have also looked in detail at the West Midlands Junction layout and made an alternative layout proposal for this junction which permits 14 parallel movements from a 28 movement operational scenario.

1.7 Reliability

We have undertaken a reliability assessment of high speed rail and made recommendations, using Network Rail data. We have not made an assessment specific to HS2, but recommend that such an assessment is made for proposed services from the classic network. This will feed into the service patterns and junction movement assumptions.

1.8 Suggestions for further work

If asked to do so, the logical next step for the capacity assessment is to undertake a simulation with the current proposed service pattern.

2 Introduction

2.1 SYSTRA

SYSTRA is an international engineering consultant specialising in rail transportation. Founded in 1995 by the merger of two engineering companies, Sofrerail owned by SNCF and Sofretu owned by RATP, Systra has subsequently grown through its participation in many of the world's best-known high-speed rail and metro projects. Today, Systra employs more than 2500 staff throughout the world, advising governments, national authorities and rail operators on the development and implementation of their transport projects.

2.2 Purpose of this Technical Note

Systra has been retained by HS2 Limited to undertake a study of the operations of the proposed railway called the 'The Operational Concept', which addresses some of the priorities for the future development of the line.

Given the ambitious expectations that have been established for HS2 in terms of capacity and quality of service (discussed in the paragraphs below), line capacity and reliability are subjects of particular interest. This technical note provides an in-depth study of these questions, with a level of detail that would not be appropriate for the Operational Concept report.

SYSTRA has been given access to published work of HS2 and to some of the working documents being used by the technical teams. All external documents are listed in the bibliography and referenced with a number in brackets [].

SYSTRA has been invited to comment on the work that the HS2 team has undertaken so far in relation to line capacity. This includes the working assumptions that the maximum future capacity of the Y-shaped network will be able to accommodate a growing demand for services, including the aspiration to run up to 18 trains per hour in each direction on the track section between north of Heathrow and Birmingham Interchange. HS2 have specified and designed the proposed route to allow speeds up to 360km/h and have designed the route alignment itself to allow an increase in top speed up to 400km/h in the future.[1] The objectives of HS2 have been set out in further detail below.

2.3 Structure of this document

We have taken the following approach to the structure of this report in order to review work already undertaken by HS2, inform the reader and signpost areas for further analysis.

Firstly, we discuss the historical development of HSR and the growing demand for services, which has led to the development of signalling systems and operating procedures that are able to accommodate increasingly frequent services, maintaining the same high passenger expectations in terms of reliability and punctuality.

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[1] London to the West Midlands and Beyond, in Exec. Summary, p. 3, bullet 5, page 11 [4]; in chapter 2.3.10; in chapter 3.10.20; in Technical Appendix 1 (3.1.d, 3.2.d) [5], in Appendix 4 (2.2, 2.4, 2.5, 3.1) [6]

Secondly, we have looked at the calculations affecting trip times and the need to accommodate some operational margin in these calculations.

Then we look at the ways in which minor and more significant delays can be managed, commenting on the application of UIC guidance for train planning. We look at ways in which these recommendations can be accommodated into trip time and how recovery time can be placed within the timetable.

Next we review the HS2 documents in relation to train headway and related subjects that have a bearing on line capacity. We consider alternative methods of calculation, to enable a comparison to be made with the HS2 conclusions.

Finally, we look at the way in which various operational requirements can have an impact of line capacity, including the need to slow for junctions, terminus stations and speed restrictions. We also look at the impact of converging and diverging tracks on line capacity.

We draw conclusions and make recommendations for further work to be undertaken in the development and detailed design stages.

2.4 HS2 Objectives

HS2 Ltd has published the high-level objectives of the new high speed rail network in its Technical Specification (2011) [13]:

- *"HS2 rail services would serve long distance, city-to-city journeys rather than shorter distance trips;*
- *only high speed trains would use HS2: running slower trains on the line would reduce the numbers of trains that could run per hour;*
- *in the early stages of developing a network we would extend benefits to cities further north by running trains off HS2 onto the existing national network;*
- *over time, as the high speed network expanded it would become more separated from the existing network so as to maximise reliability and capacity benefits; and*
- *we must design our stations to integrate HS2 with connecting public transport and road networks to make people's overall door to door journey as fast and convenient as possible."*

HS2 also summarises some of its main technical, operational requirements, within the overall context of providing a safe and reliable railway by using proven European standards, technology and practice:

HS2 Objective - Speed

> *To deliver quicker journeys we would need to maintain high speeds wherever possible. That is why we have specified and designed our proposed route to allow speeds up to 225 miles per hour* [360 km/h] *initially and computed journey times on this basis. This maximum speed is similar to that on high speed lines being opened now in Europe and Asia.*
>
> *We have designed the route alignment itself to allow an increase in top speed up to 250mph* [400km/h] *in the future. This would be permitted only on the condition that there would be no unacceptable increase in noise levels.*

In built up areas approaching stations we have designed the route for lower speeds.

HS2 Objective – Capacity

In order to carry the highest possible number of customers we would maximise the number of trains that can run per hour. We would also run long trains that can seat up to 1,100 passengers. As a two-track railway (one track running towards and one track running away from London), HS2 (London to West Midlands) could run up to 14 trains per hour in each direction. We believe that, as the railway develops, we could run up to 18 trains per hour.

Trains would operate throughout the day and evening, seven days a week though frequencies would be lower at off-peak times. No HS2 trains would leave their origin before 05.00 (08.00 on Sundays) and last trains would complete their journeys by midnight. Between 00.00 – 05.00 hours (08.00 hours on a Sunday), we would use this time for maintenance of the line."

As one part of the HS2 Operations Concept study, Systra has been asked to write a technical note concerning the constraints and considerations in relation to train capacity and to comment on the related subject of reliability.

2.5 Description of the planned high-speed rail network

The future high-speed rail network includes the following infrastructure, to be built in two phases:

- Phase 1 infrastructure:
  - Significant re-development of London Euston terminus
  - A new single-track tunnelled link to HS1 (including a link from HS1 to Old Oak Common via the North London Line)
  - High speed line linking London Euston to the West Midlands
  - New stations at Old Oak Common (Crossrail interchange), Birmingham Interchange and Birmingham Curzon Street
  - A connection to the West Coast Main Line
- Phase 2 infrastructure:
  - 2 new branches of high speed line linking the West Midlands with (1) Manchester and (2) Leeds
  - New stations (allowing for 400-m high speed trainsets) serving Manchester, East Midlands, South Yorkshire, Leeds
  - Spur link to Heathrow Airport
  - Connections to the West Coast Main Line and East Coast Main Line

The government's proposed high speed network (source: Consultation [12])

2.6 Future services

HS2 will be a significant capital investment in additional transport infrastructure. Future train operators will wish to offer services that meet the demands of passengers. The infrastructure owner will wish to ensure that facilities that are constructed are able to meet the needs of all future operators. These demands will change over the long operating life of the line, so at the preliminary design stage it is important to consider the likely configuration of train services in general terms and to look at the anticipated stopping patterns and services.

The work carried out is based on a set of service assumptions set out in Appendix 1. Nonetheless, the services that will actually be run on HS2 will most certainly differ from these assumptions. It is crucial that the system that is actually built not be a "custom-fit" for an assumed service pattern, but rather a system that allows enough flexibility to allow for a great variety of possible service patterns.

2.7 Future Reliability

It is also worth noting that there is an important relationship on any intensively used railway between the number of operation services and the service reliability.

A longer journey, and particularly one that runs partially on the classic rail network, will have a higher chance of an event leading to a delay. The more trains that run, the greater the likelihood that a train service will be affected by an event that leads to a delay. It is also the case that, as the intensity of the service grows; the relationship ceases to be linear. Train delays compound and, ultimately the level of disruption is excessive, severe delays result and operators cannot recover the timetable without cancellations.

Cancellations are clearly undesirable for any railway, but for a long-distance, intercity, or international railway, on which individual trains carry a high number of passengers, the logistical and reputational consequences of cancellation are serious. This will be particularly relevant to Britain's high-speed lines, as it is already for Eurostar services on HS1.

Thus, we need to call upon a combination of science, judgement and experience to ensure that the HS2 forecast service patterns are realistic against system capabilities and that all aspects of their operations are considered when reaching a conclusion as to the acceptable intensity of offered services.

The service assumptions taken into account in the current document stem from those laid out in previous HS2 documents, in particular the HS2 Consultation [12] and the Technical Appendices to the document "High Speed Rail - London to the West Midlands and Beyond" [4]. Though indeed the definition of exact service patterns will be a matter for train operators, it is necessary for the purposes of the Operational Concept to establish assumptions regarding future services and stopping patterns. The presumed service patterns were provided by HS2 Ltd:

- Phase 1 services: On- and off-peak service patterns as presented in the document "Economic Case for HS2" [14]
- Phase 2 services: On-peak service pattern variation "Y52" as provided by HS2 Ltd

These service patterns are presented in Appendix 1.

3 Historical Context and Common Practice

3.1 The design approach

The design approach taken for the HS2 lines needs to be seen in the context of a high-speed rail environment that is changing: both as technological solutions emerge in response to growing demand for high-speed train infrastructure and also as there is an ever-increasing amount of experience in operating high-speed trains.

It would be inappropriate to adopt either the extreme view that today's technology and experience was the only guide, or to design assuming unrealistic future developments in technology.

3.2 History

During the initial development phase of high-speed rail projects in Europe, in the 1980s, when France, Germany and Italy launched their first high-speed services, railway companies were national entities that managed rail infrastructure, rolling stock and train operations. They needed to determine a safe and effective high-speed train signalling system and each developed a proprietary system that relied on effective communication between infrastructure and rolling stock. The ability to function safely and effectively at speed was paramount. Line capacity was not the primary design consideration at the time, as nobody anticipated the very heavy demand for high-speed passenger traffic that became apparent in the 1990s.

At this time a signalling system based on discrete block-sections that would allow 10 trains per direction per hour was considered largely sufficient. Various proprietary signalling systems were developed in partnership with industrial suppliers, which easily provided the required capacity.

In the early 1990s, however, the level of traffic drove engineers to develop systems that would provide reduced train spacing (headway) and thus present higher line capacity. Compatibility with the existing national systems needed to be assured. This new generation of signalling culminated in the operation of 280 trains per day on France's first high-speed line (Paris – Lyon), where the line speed is 300 km/h. Here the daily peak service runs 12 trains per direction per hour (and there is nominal additional capacity for 15 trains per direction per hour). This signalling system can be considered as the 'conventional technology'. It was specified on Britain's HS1, which entered passenger service in 2007.

3.3 ETCS

More recently, changes in technology have been indirectly driven by the European Commission decisions in favour of a new organizational structure for the rail industries in member states. Infrastructure Managers are now responsible for track and associated systems. Railway Operators provide transport solutions to customers, following similar models to those adopted in the air transport sector. To support these changes, and to encourage competition, the European Commission has mandated that new lines should be built with a train spacing system called ETCS (European Train Control System), which, together with the GSM-R radio system, forms the European Rail Traffic Management System (ERTMS). New high-speed rolling stock should accommodate this requirement, with an appropriate capability to run on existing lines not yet equipped with ETCS technology.

The experience of this technology in Europe is mixed. ETCS is still effectively in its development stage. The technical issues underlying implementation on each line are complex. Some difficulties have been encountered with the ETCS system on the Eastern High-Speed Line in France, which is operating at 320 km/h, where it would appear that there are some difficulties in the train equipment being able to read the track beacons at 320 km/h. This problem has remained unresolved over an extended period. Elsewhere in the world, a Chinese ETCS 1 system appears to work well on the Beijin - Tianjin high-speed line.

3.4 Headway

The headway is the safe time interval at which two trains on one line may follow one another without a speed constraint being imposed on the following train. Conventionally this is quoted for straight and level track.

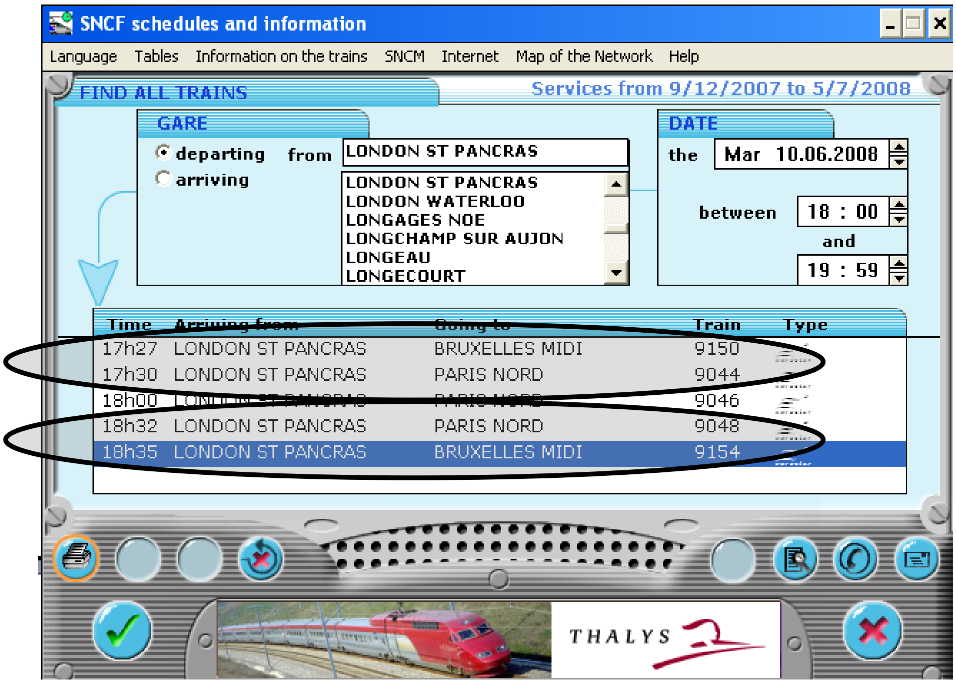
In current train operations, the European high-speed rail control systems, including the conventional systems and the new ETCS technology, provide a theoretical 3-minute headway:

- 3 minutes in France on the North TGV (with a proprietary system TVM 430)
- 3 minutes in Belgium on lines 3 and 4 (ETCS 2.3 by Alstom)
- 3 minutes in the Netherlands, HSL Zuid (ETCS 2 by Siemens)

There are practical examples of such headways being used in operational passenger timetables on a 300 km/h high-speed line.

The figure below, a screenshot of the SNCF RIHO timetable software, shows two occasions where trains leaving London St. Pancras International are bound for the Continent with a 3-minute interval.

This interval is maintained on HS1 to the Channel Tunnel, and is then is still retained on France's North HSL to the Frethun connection, where one train diverts to Brussels and the other continues to Paris. Both HSL sections are run at a speed of 300 km/h and are mainly on level terrain. The signalling system not only allows two trains to be dispatched with a 3-minute interval between them, but the operating margin is still sufficient to permit the trains to slow for the Channel Tunnel and for the first train to reduce its speed to 230 km/h in order to be diverted at a high-speed junction without affecting the timing of the following train.



Continent-bound Eurostar trains scheduled with a 3-minute interval between trains

3.5 ETCS / TVM comparisons

It can be noted that the ETCS system does not provide significantly better capacity than the 'conventional systems', but that this is largely a consequence of differences in the systems' objectives. ETCS has been developed with the twin objectives of matching the best performance of the existing systems (otherwise the owner of the legacy systems would not change to ETCS) as well as offering interoperability across a European HSR network, boosting competition, encouraging new entrants and ensuring operators are not imprisoned by national legacy systems. Furthermore, ETCS should be better suited for heterogeneous traffic (ie rolling stock with different braking capacity).

The ETCS system is based on a combination of a train's target speed and target distance with continuous monitoring of train position. In theory, this should provide a shorter headway than a conventional system, based on finite block sections and track circuits[2], with manual train control by a human driver, but both systems are inherently limited by the approach to train speed monitoring during the braking process.

The conventional systems apply emergency braking if the speed exceeds a certain value (for example 15 km/h over the requested speed at a given point). The braking profile is designed in function of the fixed track sections. The driver is expected to use skill and experience to manage the braking process in an efficient way, which includes operation in all weather (temperature, humidity, wind) and line conditions (such as gradients). The driver has to reduce train speed from 320 to 300 km/h, then to 270, 230, 170 and finally to stop within the final block section (a final deceleration rate of up to 0.75 m/s^2). Indeed, it is possible to maintain a more permissive braking curve in the case of TVM, as an entire track section length of buffer is provided (about 1500m). The braking curve must be more restrictive in ETCS because the buffer is smaller (assumed only 300 m in the current document).

[2] The establishment of braking curves based on fixed block lengths, such as in the TVM signalling system, makes it impossible to take advantage of new improved train characteristics.

ETCS (or equivalent systems), based on continuously updated braking instructions to the driver, needs to be extremely prudent and to keep some braking power to stop the train in case the driver exceeds the required given target speed. Therefore, the design philosophy of this system has to be based, not on cumulative experience of collective drivers' skill in braking, but on deceleration curves guaranteed by the train manufacturer, including adverse climatic and physical conditions that the system cannot detect. Therefore the guaranteed deceleration, mindful of risk transfer in a litigious industry, is lower than what can be expected from a human driver.

ETCS systems also have to cope with their own imprecision on speed and space measurements, which are normally taken into account by the driver or the technology in the case of conventional cab-signalling systems.

On the French East HSL, both systems have been implemented. The mandatory ETCS and the more conventional TVM 430 system (with which the French and German rolling stock was already equipped) offer identical headway and line capacity.

ETCS and TVM 430 (the system in operation on HS1, in the Channel Tunnel and in France) were compared as candidates to replace the older TVM 300 system on the Paris to Lyon line. The design maximum line capacity were equal (the block sections into which the line was divided were optimized in both cases), with a capacity of 15 to 16 tph depending on track sectioning. However, ETCS had the advantage of being interoperable, and offered the possibility of an eventual upgrade to ETCS 3, thus providing an additional capacity increase.

We conclude that, at present, high-speed rail headway and capacity have not been significantly improved by the arrival of ETCS technology. The subject has been dealt with extensively by others, but this is the conclusion we draw at this stage of the development process.

3.6 Looking ahead

It is reasonable to assume that the current European high-speed rail control systems could be improved, over time and at a development cost, in order to optimise capacity.

In relation to conventional high-speed rail systems, the development objective is the reduction in the length of block sections[3]: saving a proportion of headway length and thereby a proportion of headway measured in time. These reductions are likely to come through improved train braking capabilities and by project design optimisation around this leading parameter.

However, on a cautionary note, the cost of a block-section signalling system increases as the number of those sections increases. HS1 in the UK, the high speed line in Korea, or the Channel Tunnel, are examples where block sections are shorter. The Channel Tunnel is a mixed traffic railway where sections are only 500 meters long, allowing for a headway of 2 minutes 30 seconds between trains, but the maximum permitted speed is 160km/h.[4]

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[3] A block section is a section of track that must not be occupied by more than one train.

[4] Channel Tunnel sections are 500 m, but the line is not to run at 300 km/h (the maximum permitted speed is 200 km/h, and Eurostar are actually operated at 160 km/h). This copes with many different operating speeds (freight, car shuttles, lorry shuttles, Eurostartrains). HS1 has 950 m sections on the London to Ebbsfleet section, running at 225 km/h with a combination of Javelin and Eurostar trains.

So, it has been explained that optimisation of capacity has not, specifically, been the expressed objective for ETCS system development, which has rather placed an emphasis on interoperability. There is therefore some logic in assuming that ETCS system developments can bring improvements in this area, addressing the points made in the short comparative section above, especially given the increase in market demand that we referred to earlier.

However, it must be kept in mind that whatever the choice of high-speed rail signalling system, the higher the speed, the greater the necessary headway, in distance and in time.[5]

We conclude that reduction of headway below 3 minutes (for example to 2 minutes 30 seconds) will necessitate significant technological and engineering progress to work effectively at speeds of 360 km/h. However, with the continued growth in high-speed rail infrastructure projects, and a buoyant market in the relevant technologies, there are grounds for optimism.

Headway is addressed in further detail later in this document.

[5] This is because the headway takes into acount the braking distance and other technical distances (train length, the location of the safe protection point) and provision for certain times (information transmission times, driver's reaction times, brake full action time). Some of the times are fixed, but others increase with the speed, and the largest, which lies with the braking process itself, increases faster than the speed, since it is related to the train's kinetic energy.

4 Operating Margins and Journey Times

4.1 Introduction

High-speed lines throughout the world have a reputation for a high quality of service. Customers expect and deserve reliability and punctuality.

Journey times may be calculated with precision, but train operators know that there must be an allowance for variables such as weather conditions and human behaviour before a robust passenger timetable can be finalised.

In this section we start to look at some of the reasons for differences between theoretical and published journey times. It should be borne in mind that design emphasis, which may bring an increased cost, may be able to reduce the time provisions that might otherwise prudently be made. On the other hand, achieving precision and operating performance are often related to behaviour as well as to investment.

4.2 Base time computation

Whilst minimisation of lost time is a design objective and a daily imperative for the operational staff, in railway trip time calculations some account must be taken of the realistic operating conditions.

Calculations must also include some time allowances, or operating margins, to cope with various, virtually inevitable, low-level time losses: caused by operational imperfections, minor rolling stock and infrastructure limitations. A number of parameters, such as the available power from the electrical catenary system, the wind force and direction, the driver's reactions time, the loading of the train, the state of wheel wear and its diameter, presence of neutral sections in the catenary system, rotating mass inertia, etc, must all be taken into account at some point.

The first step is to calculate a 'base' trip time: the best achievable time with fully-powered rolling stock and no speed restrictions beyond the nominal infrastructure capability (in other words only permanent infrastructure-related restrictions, rather than short term maintenance or emergency-imposed restrictions).

This 'base' trip time therefore depends on:

- General or published rolling stock characteristics
- Physical line characteristics (gradients, curves, permanent speed limits and restrictions, electrical infrastructure constraints)
- Acceleration and braking times for commercial train stops

The train's force-speed curve is normally calculated with 22.5 kV power for a nominal 25 kV electrical system (-10%). This measured reduction takes into account the fact that a train is rarely alone in an electrical section (fed by a single sub-station) and the available voltage decreases in proportion to the distance from the sub-station. Clearly investment can reduce these provisions, but this is our current recommended approach.

4.3 Margin and operational time

To this base time is added a 'recovery margin', which includes two different elements:

- An operational margin, whose value is related to the line and its operational conditions, but generally would lie between 5 and 8 % in France and Germany, but may be more than 10 % in Spain[6]. This margin is intended to make it possible to recover the normal schedule after a small operational delay, or unexpected speed restrictions.
- Provision of a 'normal' time margin for engineering works, to compensate for the loss of time due to planned speed restrictions following infrastructure works. This provision has to be determined on a case-by-case basis.

In France, a second calculation is made for TGVs: it is not uncommon that one out of the 4 motors of a TGV has to be isolated for technical reasons (such as minor insulation defects, or false positives by automatic detection systems[7]). A TGV with 3 motors can still reach 300 km/h on a level section, but accelerations and speeds on rising gradients are lower. In order to keep the trainset in normal service until its working plan enables it to reach the maintenance depot, the base trip time with 3 motors is calculated, and compared to the trip time with the operational margin above. The longer of these two time values is retained. [8]

The addition of the base time and the recovery margin gives the operational trip time.

In the case of HS2, an analysis of this margin can be made with due consideration of the actual geography, service patterns and an asset reliability risk assessment.

4.4 Application of the operational margin

Several important questions arise from the operational margin calculations at this stage:

- Should the margin (as a percentage), be the same for all trips (or vary for the length of each trip, or for particular routes)?
- Should the margin be the same in both directions?
- How should the margin be distributed along the route?

These questions are addressed in further detail below.

<u>Margin and route</u>

It is obvious that an approach that takes a given percentage of the total trip time will provide large margins for long trips and small margins for short trips. Since a part of the margin is in order to compensate for delays in stations (caused by crowded platforms, groups of passengers with luggage, time for disabled passengers to board, etc.), which are not directly linked to the trip length, it would be wise to increase the margin percentage for short trips.

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[6] RENFE (Spanish train operator) reimburses passenger tickets if the train arrives with a delay greater than 5 minutes. This very commercially attractive proposal drives high recovery margins into the working timetable, even for a high-speed system largely segregated from classic services due to the physical differences in track gauge that exist in Spain.

[7] For example, an automatic system may believe that all train doors are not closed, although they are in reality.

[8] Distributed power high-speed rolling stock solutions with more, smaller motors may lead to variation of this rule, but are unlikely to eliminate it altogether. Any justification would be based on detailed reliability and performance calculations.

For example, routes such as Paris - Lille, Paris - Le Mans or Paris - Tours, which last less than one hour, have a margin time of less than 3 minutes (5 % of an hour). Any longer delay in departure will delay arrival at the destination, reducing turnaround time. A larger margin would avoid this, but may not be justifiable.

It has to be remembered that those short distance trains are not the only trains on the line. Slowing them down through the addition of a larger percentage would also slow down the other trains running behind them, which may be longer distance trains.

10h22	PARIS NORD	VALENCIENNES	7113	TGV
10h25	PARIS NORD	AMSTERDAM CENTRAL ST	9323	THALYS
15h58	PARIS NORD	LILLE FLANDRES	7059	TGV
16h01	PARIS NORD	KOLN HBF	9445	THALYS
17h58	PARIS NORD	TOURCOING	7277	TGV
18h01	PARIS NORD	BRUXELLES MIDI	9353	THALYS
18h01	PARIS NORD	KOLN HBF	9453	THALYS

Short distance TGVs followed by long distance Thalys services

So, some assessment needs to be made. Simply adding a higher percentage margin to trip time for short distance trains is not an option on very busy lines, where trains follow one another at minimal distances apart.

Margin and direction

At a converging junction, a slightly delayed train on one branch may force the following train on the other branch to slow down or stop, to yield to the first. This source of delay can be compensated for by applying a slightly higher margin, on both sides, to all trains, in the direction of converging traffic.

This explains partly why, in general, trains terminating in a dead-end station take a little longer than outbound trains; another reason being the limited speed permitted approaching the buffers.

Margin distribution

There are several ways in which to distribute the operating margin along the train trip. These may be put into effect by giving instructions to drivers and to operating staff, so that, in the event of a delay, recovery is possible without excessive impact on neighbouring services.

For example:

- A constant reduction applied to planned train speed (including acceleration and braking rates) throughout. (This is the simplest approach.)
- Planning maximum acceleration and braking rates, with a planned lower speed along the line (corresponding to energy savings, but increasing brake wear).
- A concentration of the operating margin in the last part of the trip, so that the train keeps its full margin for as long as possible. (Passengers may wonder why the last leg of the journey is artificially slow. Also, this may create potential conflicts with late-running following trains).

- A distribution of the margins between station dwell times.

Acceleration and braking on the Atlantic TGV.

A 10% time margin is achieved by pre-planning a 19% reduction compared to maximum speed. This offers a 32 % energy saving compared to maximum speed running

4.5 Recommendations

The evaluation of trip time and margin has to be made with care. Good practice would be to document the assumptions made, so that they can be regularly re-visited as line-specific information becomes available and design develops.

The particular geography and proposed stopping patterns of HS2 will result in a risk profile that will change with direction of the service, origin and destination. The anticipated rolling stock characteristics and infrastructure will also feature in an assessment of the likely operating margin. This will also change as the HS2-dedicated infrastructure extends.

All these various solutions for attributing margin to journey time have their virtues, and lead to different operational behaviour from station staff as well as from drivers.

On a very busy line, such as HS2, we will see that brisk braking and acceleration are the keys to maximising line capacity, and that the most difficult situations to manage will occur at the extremities of the line, not in the middle where the vertical profile is relatively smooth and there are no intermediate stations.

To keep a sufficiently large operating margin until late on in the trip, full acceleration and braking are to be recommended, and a planned reduction in the maximum operating speed to achieve the desired margin, which can be recovered in cases where the operational margin is required to be used, seems to be a good compromise.

5 Placing Train Paths

5.1 Introduction

We have looked at the computation of journey times and allocation of operating margin. Here we look at the allocation of train paths within the time available, in order to optimise passenger services: maximising line capacity and providing recovery time within the timetable for more significant train disruption than can be accommodated within the trip time.

5.2 UIC guidance

It is not generally considered wise and prudent to use the full theoretical line capacity. A 'rule of thumb', based on wide experience is recommended by the UIC[9]. This states that the maximum scheduled line capacity should not be more than 75 % of that theoretically available during peak hours: 60 % taken as an average over the operating day. The UIC guidance is not specific in terms of the nature of the delays to be attributed, preferring to refer to infrastructure and rolling stock reliability in general terms. It also cites the service frequency as well as local mitigation measures that might justify a variation from this recommended value.

Whilst this requirement appears to be a broad imposition on top of an otherwise apparently exact science, the reason for this requirement is that train operators are historically and inevitably faced with various kinds of events from which they have to recover. We have previously discussed this in relation to minor delays, accommodated within the trip time. For example, temporary speed restrictions may be imposed on part of the line for infrastructure defects or following engineering works, there may particularly difficult weather conditions, local or general problems with passenger behaviour.

Whilst a full analysis would ensure that no duplication of assumptions were being made, in principle the guidance here is aimed at longer or more systemic delays. These would be delays from which a train cannot recover within the trip and which may affect the times of neighbouring services, or which may affect all of the services on a particular route, or those calling at a particular station. The UIC objective is to ensure that a cascade of service cancellations is not initiated. The recommended values are specific to high-speed services.

Another way to express the UIC advice is to ensure that the timetable includes a certain number of theoretical paths, but that only 75 % of paths are actually used to run trains. Accepting higher numbers of train services increases the probability of significant disruptions and the size of their impact, or reduces the ability of the operator to recover normal services in the case of disruption.

[9] International Union of Railways' (UIC) studies on capacity - notably leaflet 406 R, p. 19, 2004 [1]

5.3 UIC guidance application

In practice, application of this UIC advice varies with the line and the type of traffic to be operated. An isolated line, without a mix of services running on high-speed and conventional infrastructure, is less subject to operations disruption. Examples are the Japanese Shinkansen service, the Taiwanese HSL from Taipei to Kaohsiung, or the Spanish HSL services. High-speed services in France or Germany run on conventional lines, sometimes for extended periods. They share tracks with freight trains, regional and other passenger trains before or after their journey on the high-speed infrastructure. The future network in Great Britain will include some dedicated high-speed infrastructure, increasing as the HS2 line is extended, but will broadly fall into this second category.

There are different ways to put this UIC recommendation into practice when planning train times, the two generally in use being:

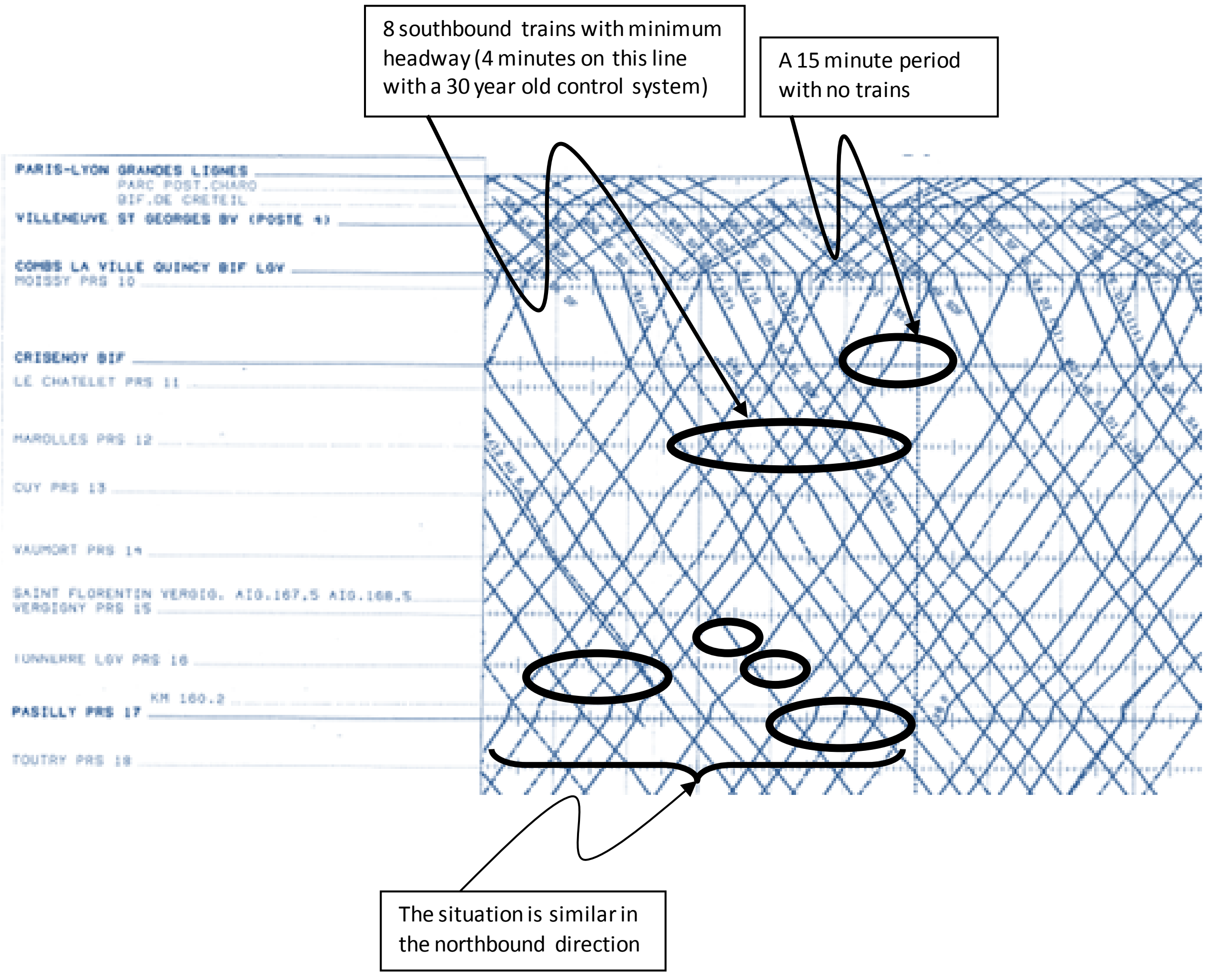
- Make use of the theoretical headway during a certain period, and then maintain a period without trains
- Use a slightly longer headway (say 4 minutes instead of 3) for all train intervals, effectively spreading the recovery time

One can understand that, if the operator only fears small delays, such as occasional late departure from a station for door closing problems, the second solution is perfectly adapted, offering a small operating margin and an extension of the logic that was described in the chapter above in relation to operating margin and journey times. By contrast, the first solution, with trains packed one behind the other, will see the delay passed from one train to the next until the blank period without trains allows for full recovery.

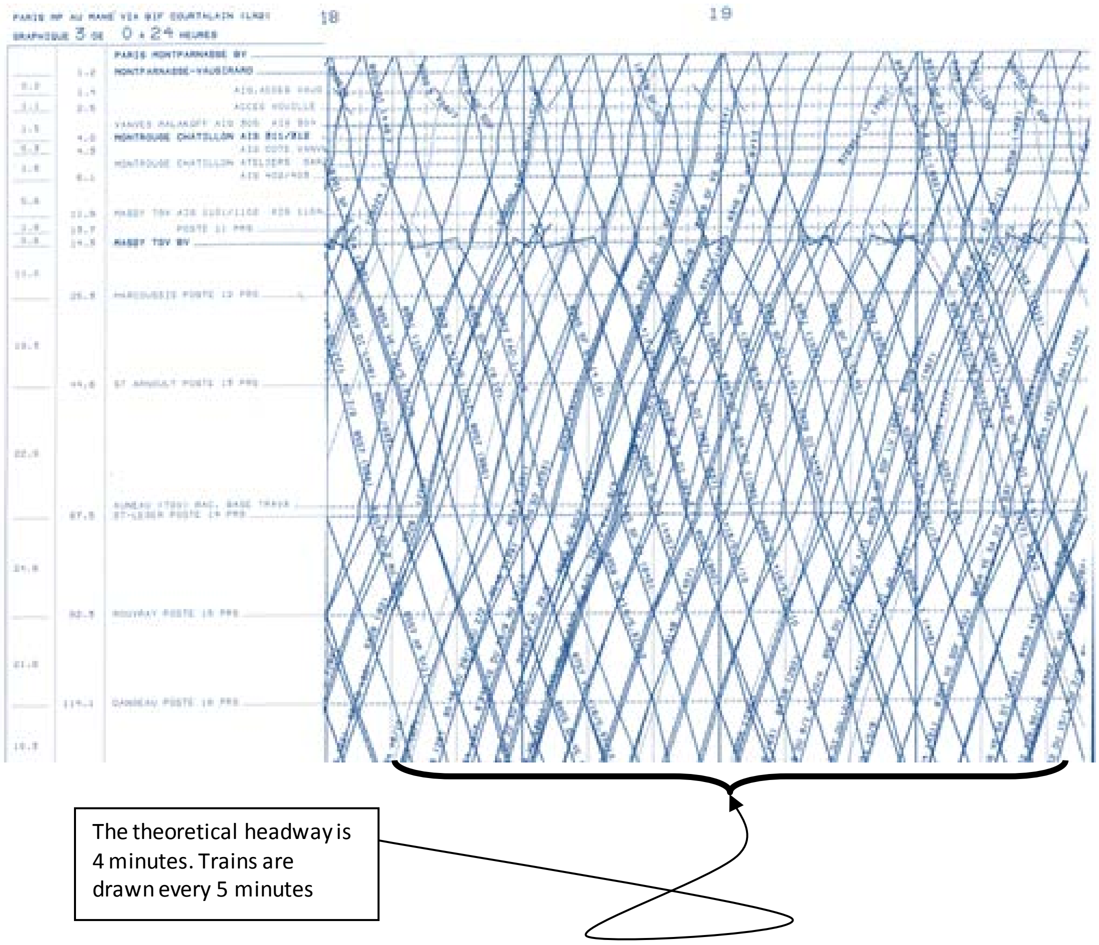
On the other hand, if a more serious delay occurs, such as a train coming from a remote origin with a 10 minute delay, or a 10 minute interruption of power, it will be nearly impossible to recover a normal situation with the first approach, whilst the second arrangement permits a full recovery after less than one hour.

The use of the spare capacity is thus a question of judgment and must be based on an analysis of the context (that can vary during the day, week or year).

The two graphs below show the two different solutions applied on two different high-speed lines in France, because local conditions are different on each line, justifying the different approach.



On the Paris-Lyon high speed line, extended periods of time are preserved in the timetable for recovery from longer train delays



On Paris to Bordeaux High Speed Line, spare capacity is spread between all scheduled trains for immediate recovery from small train delays

5.4 Characteristics of HS2

Turning to the application of this logic to HS2, during both phase 1 and phase 2, the Euston – West Midlands segment is the most important from the perspective of this capacity analysis.

The significant operating characteristics are:

- There is only one intermediate-type station on the line for the purpose of this analysis[10]: Birmingham Interchange.
- That station is served by 6 trains each hour, including 2 trains that will divide in the northbound direction and join in the southbound direction.
- There are at least 2 different rolling stock types to be operated (captive high-speed trains and classic compatible trains, (and potentially Eurotunnel compatible trainsets).
- There is a complicated series of operations north of Birmingham, with the high-speed line dividing into successive branches - a total of 9 separate branches serving

[10]) Old Oak Common is also an intermediate station, but served by all trains to or from London. As such, from the perspective of this analysis, no special operating process is going to occur in this station, such as skip-stopping or trainset (un)coupling, so therefore it can be considered more as the origin of the line, rather than as an intermediate station.

Birmingham, Manchester, Liverpool, Glasgow, Edinburgh, Nottingham, Sheffield, Leeds and Newcastle.

- In phase 2, there are 3 non-terminal stations on the high-speed infrastructure - Manchester Interchange on the west branch, and East Midlands Interchange and South Yorkshire Interchange on the east branch.
- There are many stations to serve on the conventional line extensions beyond the new HS2 infrastructure.
- Services come from relatively well-equipped branch lines (with no single track sections, modern signalling systems, centralised train control, etc).

So, following UIC guidance, in order to operate 18 trains per hour under acceptable conditions, the signalling system must allow a minimum of 24 trains per hour, which means a maximum headway of 2 minutes 30 seconds (3600 seconds per hour/24 trains per hour = 150 seconds headway).

5.5 Recommendations for HS2

This network has many similarities with the French Atlantic high speed lines from Paris to the west.

Our preliminary analysis concludes that it would be prudent for HS2 to build a train service line diagram as follows:

- In the northbound direction, plan services using a 3-minute headway, and include 2 spare paths per hour, since, for trains coming from the south delays are likely to be minor. This effectively creates a regular spacing of the delay margin (by planning around train headway of 3 minutes instead of 2 minutes 30 seconds). This will make it possible to quickly recover small delays and return to a normal service.
- In the southbound direction, plan services with 2 minute 30 second headway and allow two 7.5 minutes gaps in the timetable to accommodate late trains from remote branch lines (or three 5 minutes gaps). As discussed above, in this direction there is more potential for major delays for trains coming from the classic network. Although these delays will necessarily be propagated to closely following trains, the timetabled gaps make it possible to swiftly return to normal service.

The source of delay and appropriate mitigation strategy can be analysed in detail for each line and service pattern, with the aid of statistical analysis tools as appropriate. Such an analysis for HS2 might ensure that there was no duplication in the assumptions made between the estimated operational margin included in trip time calculations and the application of the UIC guidance. It would enable a timetable to be drawn up that minimised trip time and optimised capacity with specific application to HS2.

6 Headway: Stopping Time and Distance

Currently, the French TGV operators claim to be able to run up to 15 to 16 trains per hour on their northern line between Lille and Paris (though current schedules are actually made up of 13 trains per hour), with a maximum speed of 300 km/h.

Current plans for HS2, however, plan for 18 trains per hour and per direction at 360 km/h, feat that has not yet been attempted on any existing railway.

Headway (the minimal interval between trains) is of course paramount to the question of line capacity. If a sufficiently low headway cannot be maintained in all circumstances, running 18 trains per hour will not be feasible.

In this section we calculate needed headway in various situations (open line running, at a diverging turnout, with slowdowns on the line, etc). We also review the approach to headway estimation in various situations that has been taken by HS2 in the document *Signalling Headways and Maximal Operational Capacity on High Speed Two London to West Midlands Route, version 3,* dated 1 August, 2011 [21].

For each situation, we proceed as follows:

- Summary of the calculation (if one was carried out) appearing in the HS2 headway document [21]
- If necessary, comments on the approach, as well as the values of the parameters used, in the HS2 headway document calculation
- Presentation of our own approach to the corresponding headway calculation
- Comparison of the results

6.1 Open line minimum headway

This section concerns calculations of **minimum headway between two consecutive trains travelling in open line at 360 km/h without slowdowns, diverging or converging crossovers, or station stops to impede their progress.**

6.1.1 Summary of the HS2 calculation of open line headway

In order to calculate open line headway, the HS2 document [21] presents a set of technical parameters (pages 3-4), and then goes on to sum a series of numbers to estimate open line minimum headway (page 5).

In the table below we attempt to present the calculation undertaken; nonetheless, a certain amount of guesswork had to be carried out, as in the HS2 document there is not a clear indication which numbers in the sum correspond to which parameters.[11]

[11] Concerning open line headway, the document states « *.. signalling headway is (20+5+2+1+8+1+3+3+73)=116 seconds* » ([20], page 5).

Time in seconds	
Clear 1600-m track section (plus 400-m train length) at 360 km/h	20
Train detection (TD) system reporting delay time	5
Movement authority (MA) update transmission time	2
Train On Board ETCS reaction time	1
Worst case driver response time	8
Automatic Train Operation (ATO) response time	0[12]
Odometry error	1
Time to clear buffer between Supervised Location (SvL) and End of Authority (EoA)	3
Brake actuation time	3
Braking time 360 => 0 km/h at deceleration of 0.687 m/s^2	73
Total headway needed for in-line train circulation	**116**

In addition to the assumptions that appear above, the HS2 headway document makes the working assumptions that:

- The alignment is perfectly gradient-free in areas where trains travel at 360 km/h
- Braking provides a constant deceleration of 7%g (0.687 m^2/s)

The document concludes that the maximum number of signalling paths per hour (with a headway of 116 seconds) is 3600 /116 = 31.

With the UIC recommended usage of 75% of signalling paths during the peak hours, this leads to the conclusion that 23 paths (75% x 31) could be included in the schedule.

Globally, the approach is correct, though the treatment of some elements may seem to be optimistic, and others may have been left out. We discuss these issues below.

6.1.2 *Comments on the HS2 open line headway calculation*

Measuring uncertainties

As explained in the HS2 Headway text, odometry error of 4% for a 1600-m track circuit would actually only account for 0.64 seconds at 360 km/h, thus the 1 second figure used in the above table. But we note that uncertainty regarding train speed assessment is not mentioned. If the uncertainty regarding train speed is 2%, then the speed can be 2% higher (than 360 km/h), which means that the braking time at a constant deceleration rate is also 2% higher, and 2% of 73 seconds is 1.5 seconds.

We advise that an additional 1.5 seconds be added to the open line headway calculation in order to take into account train speed uncertainty.

[12] See comments in following section.

Braking curve

The braking curve to be applied for the future operation of HS2 requires some consideration of the future developments of braking capability, in order to determine the braking rate, and also an assessment of the best method of applying the braking calculations.

To offer a comparison with the proposed 7%g braking (0.687 m/s^2), we note the following tabulation of current braking capacities for a German ICE 3 train at a range of speeds. German rail operations allow for relatively strong braking, compared to other high-speed rail systems.

SBD	
v [km/h]	a [m/s²]
0 – 160	1,1
160 – 165	1,025
165 – 175	0,875
175 – 180	0,8
180 – 210	0,7
210 – 300	0,6625
> 300	0,65

Deceleration of the ICE 3 (SBD = Service Brake Deceleration)

Above 300 km/h, the deceleration is 0.65 m/s^2. It seems reasonable to conclude that in the future high-speed rail service braking may be slightly stronger than today. So, the assumptions taken by HS2 would appear reasonable.

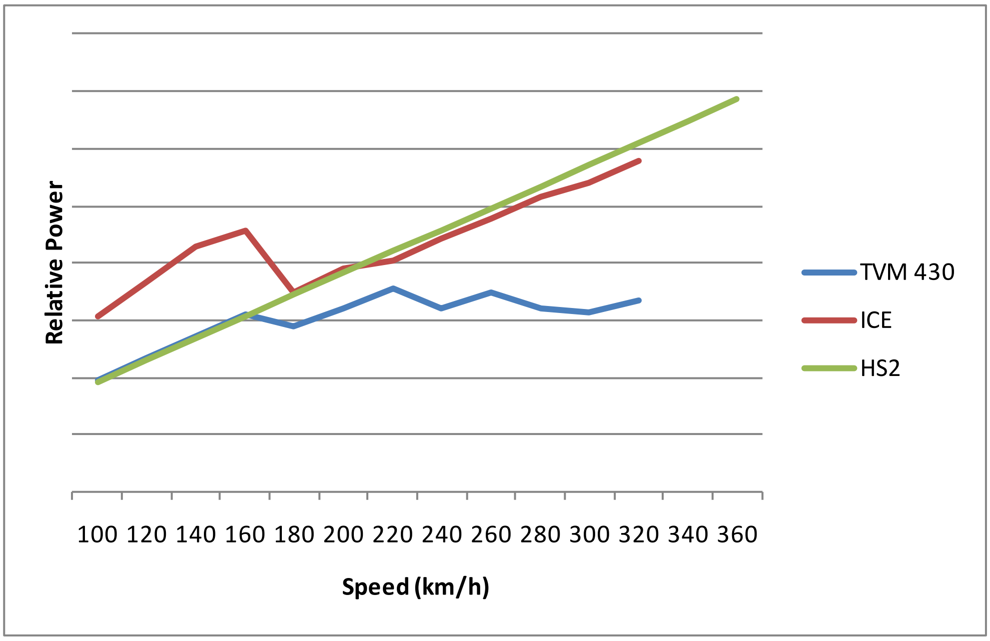
Another way of thinking about deceleration is in terms of the necessary braking power. If train mass is assumed to be constant, braking power is proportional to *speed x deceleration.* The graph below shows relative braking power as a function of speed for three cases:

(1) HS2's assumption, with constant deceleration of 0.687 m/s^2

(2) The ICE 3 case, according to the braking rates shown in the table above[13]

(3) A train decelerating according to the TVM 430 braking steps - 320km/h, 300 km/h, 270 km/h, 230 km/h, 170 km/h, (considering a track section of 1600 m)

[13] It is generally true that German trains brake harder than French. Thalys on German conventional lines has its speed limited to 140 where the German local trains can run at 160, because their braking power is not sufficient. TGV train designs have not prioritised braking - the position of the brake disks has been chosen to have a low aerodynamic resistance, but the penalty is that the rate of cooling is slow.



Relative braking power in function of speed

In the case of a train decelerating with the TVM 430 curve, braking power remains relatively constant, even at high speeds. In the case taken by HS2, constant deceleration necessarily means that braking power required increases linearly as a function of speed. The need for a great deal of braking power at high speeds may lead to problems with brake heating. Nonetheless, we see that in the case of the ICE 3, braking power also increases nearly linearly with speed starting at about 180 km/h.

This raises the question of whether the way in which braking applications are to be made, as well as the rate of deceleration, should be taken into account in the future assessment of the braking rate.

<u>ETCS delay times</u>

The UIC document *Influence of ETCS on line capacity* [3] considers the following values for ETCS level 2:

	mean value for ETCS level 2 [sec]
interlocking to RBC	0,05
RBC	1,5
RBC to train	1,1
EVC + DMI	1
Summation	3,65

Mean ETCS reaction times [3]

Where:

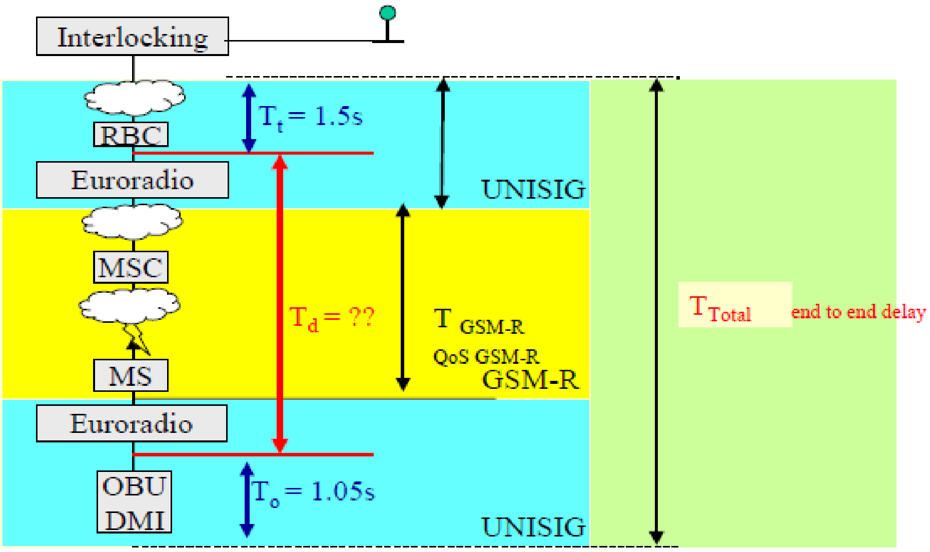
RBC = Radio Block Centre

EVC = European Vital Computer

DMI = Driver-Machine-Interface

In the HS2 Headway document, these elements (which total 3.65 seconds) correspond to the 3 seconds estimation allocated to “Movement authority (MA) update transmission time” (1 second) and “Train onboard ETCS reaction time” (2 seconds, [21], page 4).

The *ERTMS/GSM-R Quality of Service – Operational Analysis* [2] illustrates the chain of interfaces and actions included in the process of a movement authority (MA) update - as follows:



ETCS MA update transmission path [2]

Indeed, there is some deal of uncertainty surrounding the GSM-R transmission time. It is worth noting that the mean (average) transmission time cannot be used to calculate headway, but rather an allowance must be made for the maximum transmission time in normal operating conditions.

This (above quoted) document defines the following performance requirements:

“*The signalling system shall be designed for an MA update time of 12.5s assuming a data transmission rate of 4800 Baud, BER of 10E-4 and a 750 octet MA. Where smaller values are required in time-critical locations, e.g. stations and junctions, this must be achieved by optimisation of MA size, data transmission rate and BER.*” ([2], page 32)

This implies that the MA update time of 12.5s, rather than 2 seconds, would be appropriate,so we take this value, together with the 2 second values assumed by HS2, forward into our forthcoming comparative analysis.

Automatic Train Operation (ATO) delay time

The text in the HS2 document [21] leading up to the open line headway calculation takes note of 3 different factors that would each contribute 3 seconds to the headway: *(a)* Time to clear buffer between Supervised Location (SvL) and End of Authority (EoA), that is 300 m to be crossed at 360 km/h (page 3), *(b)* Automatic Train Operation (ATO) response time (page 4), and *(c)* Brake actuation time (page 4). In the calculation (page 5), the value 3 only appears twice. In the table we guess that the factor that is left out is (b).

1. There exist two possible scenarios regarding ATO response time :The train is running in manual driving mode. In this case, if after 8 seconds there is no driver response, ATO kicks in, but this process takes an additional 3 seconds.
2. The train is running in automatic driving mode. In this case, the 8 seconds for driver response time are eliminated, and the 3 seconds for ATO response time must be taken into account.

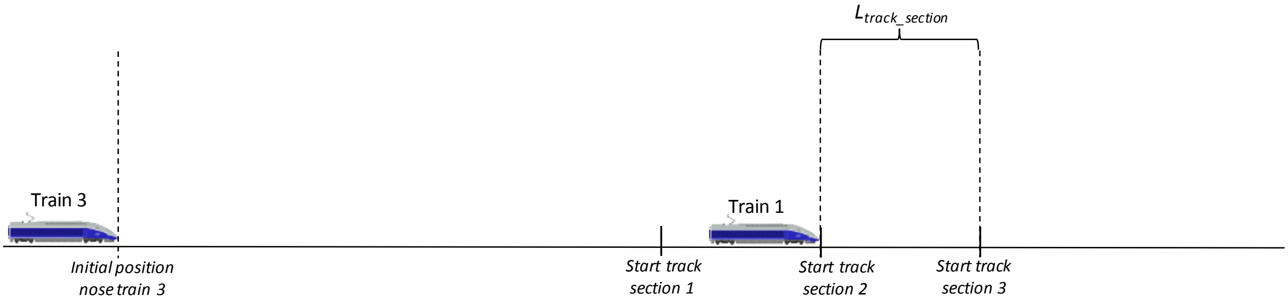
It appears that the HS2 open line headway calculation is based on the first case. Furthermore, the ETCS Guidance for Great Britain [4] indicates that the "*ETCS onboard equipment calculates the point at which the brakes need to be applied to ensure that the EOA is not exceeded. If the driver fails to control the train correctly (such that the EOA would be exceeded) the ETCS onboard equipment automatically applies the brakes*" (paragraph 4.6.2.2). As such, it appears to us that both driver and ATO response times should be counted.

6.1.3 *Alternative open line headway calculation*

To ensure common ground and enable us to draw common conclusions we consider that it might be helpful to evaluate open line headway calculations through a step by step analysis, which is presented in the following diagrams. Readers may wish to skip to the resulting formulation for headway on page 32.

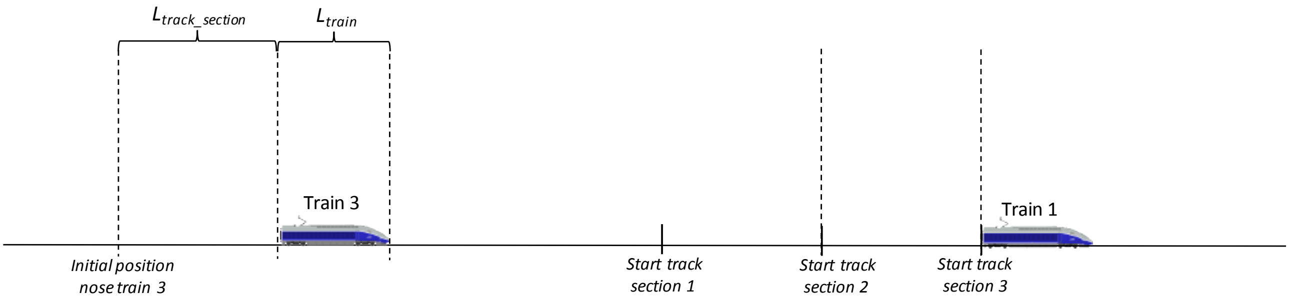
Calculation of headway needed between trains at a speed V, open line
Needed headway = H_v seconds, needed safety distance = S_v meters

(0) Train 1 and train 3 are travelling at ***V*** *m/s. The nose of train 1 has reached the end of track section 1 (the start of track section 2).*



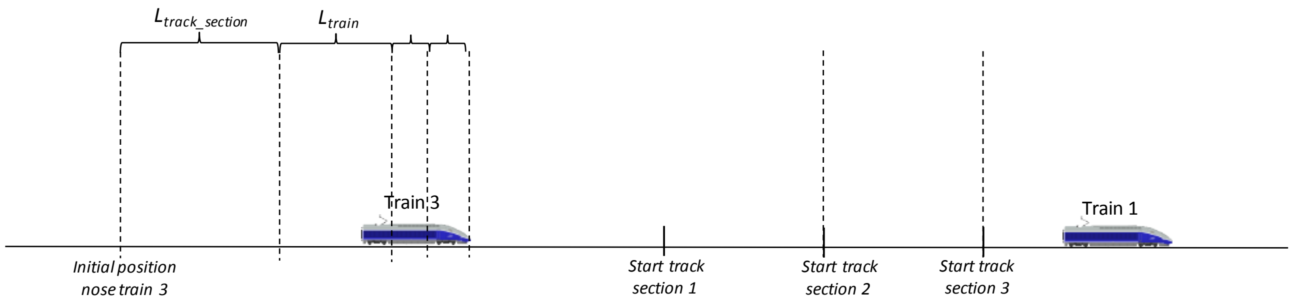
Open line headway calculation: instant 0

(1) Train 1 has cleared track section 2. Both train 1 and train 3 have covered $L_{track\_section} + L_{train}$ *meters, in* $(L_{track\_section} + L_{train})/V$ *seconds since (0). The process of updating the movement authority (MA) can begin.*



Open line headway calculation: instant 1

*(2a) The MA has been updated in T_{MA} seconds, and the ETCS on-board system of train 3 has been updated in T_{ETCS} seconds. Both train 1 and train 3 have covered **(T_{MA} + T_{ETCS}) * V** meters, in **T_{MA} + T_{ETCS}** seconds since (1).*

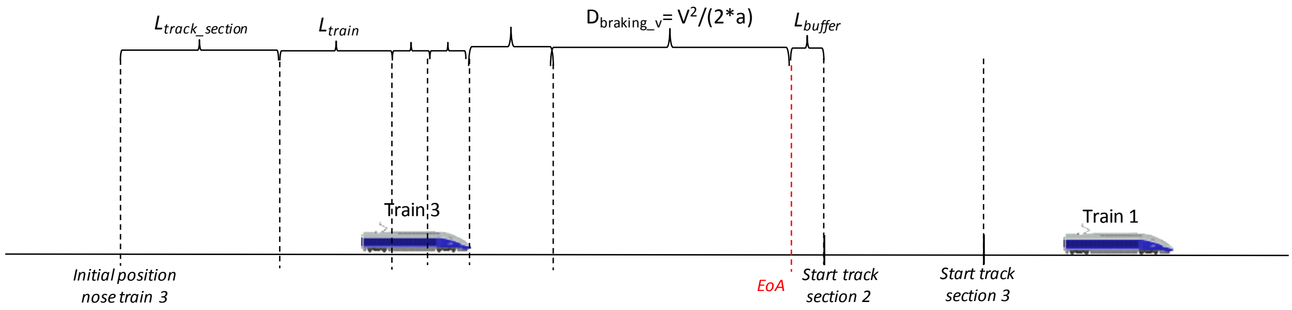


(2b) When Train 3 learns that track section 2 is clear, it must still be <u>at least</u> at a distance from the start of track 2 that would have provided sufficient time for complete braking <u>if track section 2 had not been cleared</u>:

- Distance for driver and brake reaction: $\boldsymbol{T_{reaction}*V}$

- Braking distance: $\mathbf{D_{braking\_v} = V^2/(2*a)}$

- Buffer between the End of Authority (EoA) and the Supervised Location (in this case the start of track section 2): $\boldsymbol{L_{buffer}}$



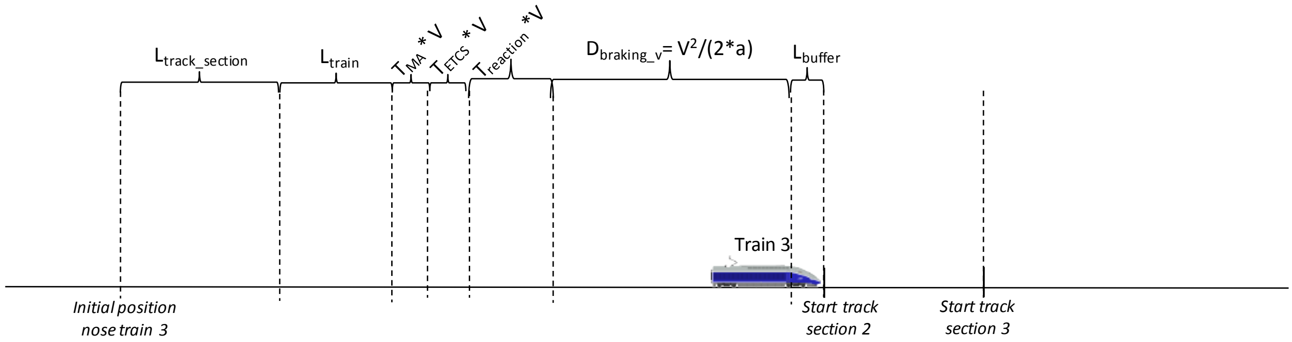
Open line headway calculation: Instant 2

(3) Train 3 has covered the distance that separates it from train 1 (nose to nose). If both trains travel at speed V, the distance between them (nose to nose) must be <u>at least:</u>

$$\boldsymbol{S_v = L_{track\_section} + L_{train} + L_{buffer} + (T_{MA} + T_{ETCS} + T_{reaction})*V + V^2/2a}$$

Their minimum headway is <u>at least:</u>

$$\boldsymbol{H_v = (L_{track\_section} + L_{train} + L_{buffer})/V + (T_{MA} + T_{ETCS} + T_{reaction}) + V/2a}$$



Open line headway calculation: instant 3

Thus, we consider that line headway can be expressed as:

$$\boldsymbol{H = \frac{L_{track\ section} + L_{train} + L_{buffer}}{V} + (T_{MA} + T_{ETCS} + T_{Reaction}) + \frac{V}{2a}}$$

If we are to derive the parameters from the HS2 Headway document [21], their values would be the following:

a: Deceleration braking	0.687	m/s^2
L_{buffer}: Buffer between EoA and SvL	300	m
L_{train}: train length	400	m
$L_{track\_section}$: track section length	1,600	m

Train detection (TD) system reporting delay time	*5*	*s*
Movement authority (MA) update transmission time	*2*	*s*
T_{MA}: Update delay	**7**	**s**

Train on board ETCS reaction time	*1*	*s*
Odometry error	*1*	*s*
T_{ETCS}: On-board delay	**2**	**s**

Worst case driver response time	*8*	*s*
Brake actuation time	*3*	*s*
Automatic Train Operation (ATO) response time	*0*	*S*
$T_{reaction}$: Reaction time	**11**	**S**

Open line headway parameters according to HS2 headway document

In general, in all of the headway calculations that follow, we will rely on these values, *unless otherwise specified.*

In particular, we consistently calculate headway for two different values for the Movement authority (MA) update transmission time:

- 2 seconds (in accordance with the HS2 headway document [21])
- 12.5 seconds (in accordance with the maximum value indicated in the Quality of Service document [2])

The retention of the higher number is a cautionary measure; we feel that it is important to look at what the impact on headway would be if this (or some other) parameter were a bit too optimistic.

Thus, using the open line headway formula presented above, the open line headway between two trains travelling at 360 km/h) is presented in the table below:

Speed (km/h)	360	360
Mouvement authority (MA) update transmission time (s)	2	12.5
Minimum open line headway (s)	116	126
Paths per hour (75% of theoretical)	23	21

Minimum open line headway between trains travelling at 360 km/h

6.1.4 Comparison of the open line headway calculations and conclusions

The resulting headway at 360 km/h, using the HS2 parameters, is 116 s. This is the same result as that obtained in the HS2 headway document.

As we saw above, the formula for open line headway at a speed V is the following:

$$H = \frac{L_{track\,section} + L_{train} + L_{buffer}}{V} + (T_{MA} + T_{ETCS} + T_{Reaction}) + \frac{V}{2a}$$

Logically, a second of reduction in any one of T_{MA}, T_{ETCS} or $T_{Reaction}$ will amount to a second of reduction of the open line headway.

Likewise, if V=100 m/s (360 km/h), then a reduction by 100m of any one of

- Track section ($L_{track\_section}$)
- Train length (L_{train})
- Buffer length between the end of authority and the supervised location (L_{buffer})

would lead to a reduction of the open line headway by one second. For example, if the track section were taken to be 1000 m instead of 1600, open line headway would be 110 seconds instead of 116.

Assuming that the parameters supplied by HS2 are correct, we agree that the theoretical open line capacity, ***ignoring junctions, slowdowns, etc.,*** would be 75% * 3600 / 116 = 23 paths per hour.

If headway is lengthened by 10 and a half seconds (corresponding to an MA update transmission time of 12.5 seconds, for example), the theoretical **open line capacity** would be 75% * 3600 / 126.5 = 21 paths per hour.

Theoretical open line headway thus clearly allows for 18 trains per hour, even if slightly less optimist parameters are taken.

6.2 Headway approaching a diverging turnout

The current section concerns the headway needed for two trains approaching a diverging turnout.

6.2.1 Summary of the HS2 calculation of headway approaching a diverging turnout

The table below presents the headway calculation between a first diverging train and a following non-diverging train, as carried out in the HS2 Headway document[14] on pages 6 and 7. The assumption is made that open line speed is 360 km/h, but that a train taking the diverging turnout must slow to 225 km/h

[14] As in the case of the open line headway calculation, this is an attempt to clarify the headway document, but the interpretation may not be totally correct.

Time in seconds	HS2 Document
Headway lost between first train and following train during braking (360 to 225 km/h at 0.687 m/s2)	10
Headway lost while first train crosses the 300-m EOA - SvL buffer.	2
Time for first train to pass over the turnout track section (300m plus 400m train length)	11
Turnout operation time	9
Train detection (TD) system reporting delay time	5
Movement authority (MA) update transmission time	2
Train On Board ETCS reaction time	1
Worst case driver response time	8
Automatic Train Operation (ATO) response time	0
Odometry error	1
Brake actuation time	3
Breaking time 360 => 0 km/h at deceleration of 0.687 m/s2	73
Total headway approaching a diverging turnout	125

Summary of the calculation of headway approaching a diverging turnout, according to the HS2 headway document [21]

The HS2 headway document concludes that the combined signalling headway of two trains would be 116 + 125 = 241 seconds, which would lead to 22 paths per hour, with a 75% occupation rate.

6.2.2 *Comments on the HS2 calculation of headway approaching a diverging turnout*

The comments regarding ATO response time, train speed error, etc., are the same as in section 6.1.2. Furthermore, we do not agree with the approach to calculating headway related to the EOA – SvL buffer. This point is explained in section 6.2.4

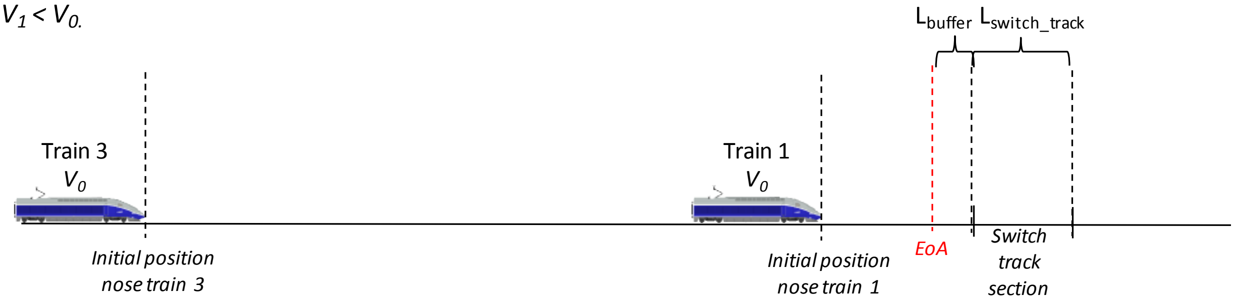
6.2.3 *Alternative calculation of headway approaching a diverging turnout*

Once again, in order to verify this calculation, we find it helpful to imagine what goes on in a number of discrete steps, illustrated in the figures below. The resulting equation for headway approaching a diverging turnout is presented page 38.

Calculation of headway needed between trains travelling at speed V_0, if the first train must take a turnout at speed V_1

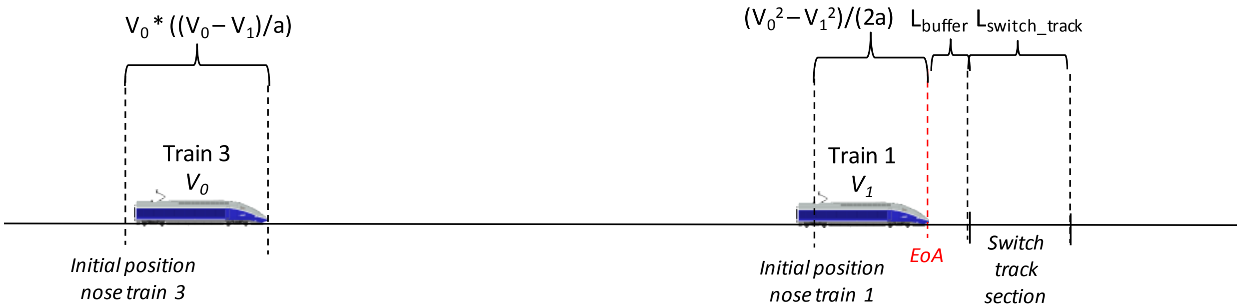
Needed initial headway = H_n seconds, needed initial distance = S_n meters

(0) Train 1 and train 3 travel at speed V_0. At this moment train 1 begins braking to reach speed V_1, where $V_1 < V_0$.



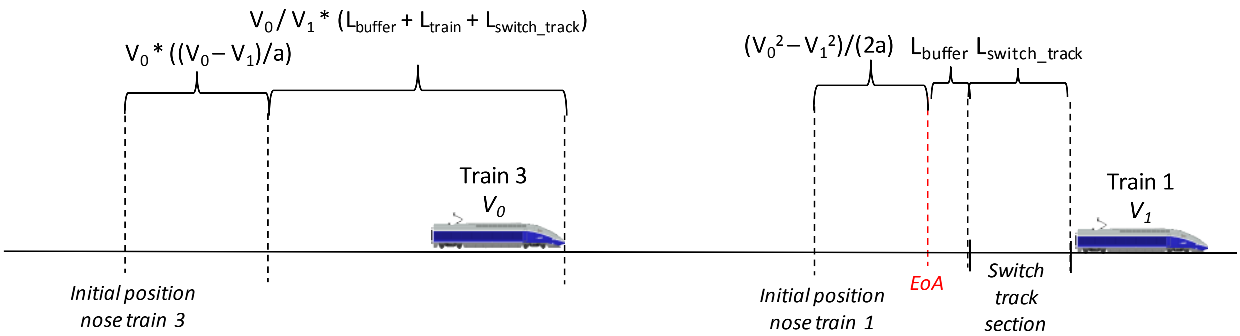
Diverging turnout headway calculation: instant 0

(1)Train 1 is travelling at V_1 m/s.



Diverging turnout headway calculation: instant 1

(2) Train 1 has liberated the switch track section.



Diverging turnout headway calculation: instant 2

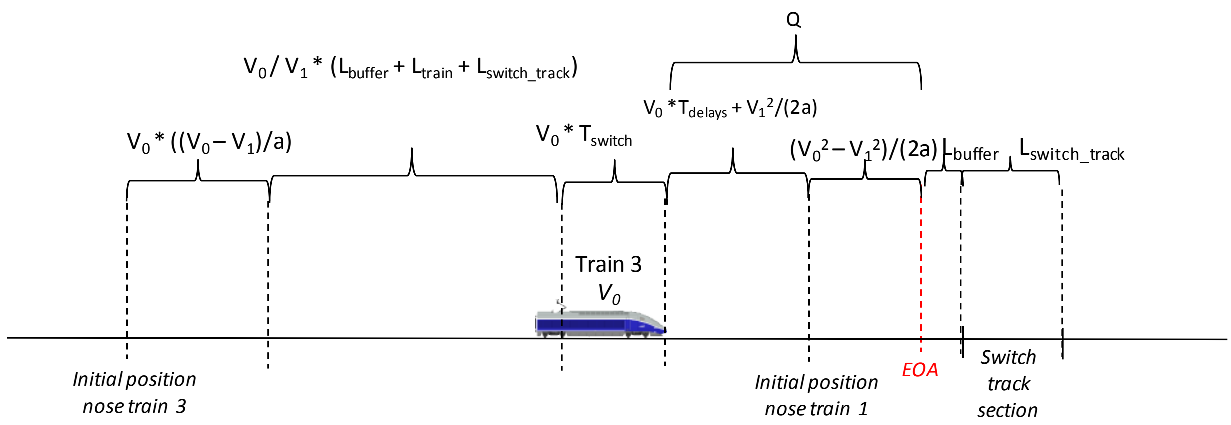
(3) Switch has finished turning in T_{switch} seconds.

*Train 3 must be at a distance **Q** from the EOA associated with the turnout:*

$$Q = \underbrace{V_0 * T_{delays}}_{\text{Dist. covered at } V_0 \text{ during system delays}} + \underbrace{V_0^2/2a}_{\text{Stopping time at } V_0} \qquad \text{where } T_{delays} = T_{MA} + T_{ETCS} + T_{reaction}$$

This means that the minimal distance from train 1's initial position, such that train 3 does not begin a braking sequence before receiving an updated MA is

$$V_0 * T_{delays} + V_0^2/2a - (V_0^2 - V_1^2)/(2a) = \mathbf{V_0 * T_{sdelays} + V_1^2/(2a)}$$

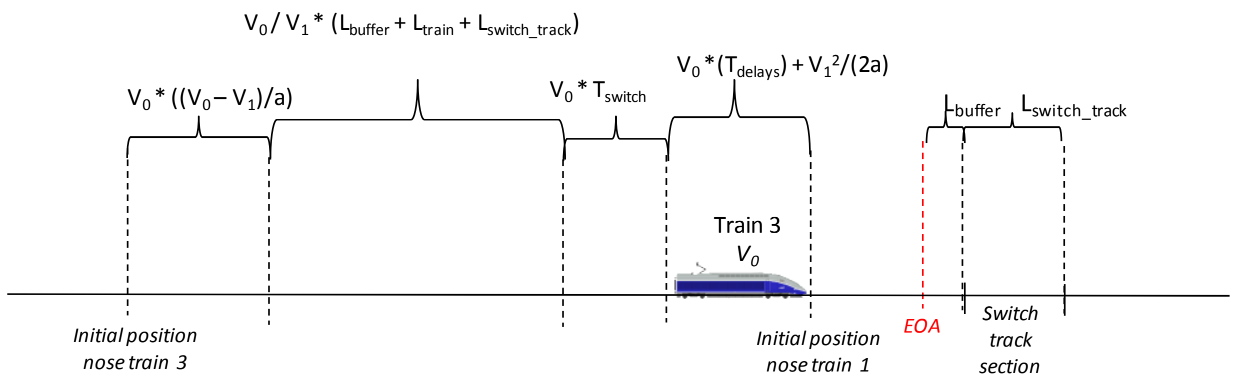


Diverging turnout headway calculation: instant 3

(4) Train 3 has reached the initial position of train 1 (at the moment when train 1 began braking)

$$S_n = \underbrace{V_0*(V_0-V_1)/a}_{\text{Dist. covered at } V_0 \text{ while preceding train brakes from } V_0 \text{ to } V_1} + \underbrace{V_0/V_1*(L_{buffer} + L_{train} + L_{switch\_track})}_{\text{Dist. lost between train 3 and EOA while train 1 cleared switch}} + \underbrace{V_0*T_{switch}}_{\text{Dist. lost while switch turned}} + \underbrace{V_0*T_{delays}}_{\text{Dist. covered at } V_0 \text{ during system delays}} + \underbrace{V_1^2/(2a)}_{\text{Stopping distance at } V_1}$$

$$H_n = \underbrace{(V_0-V_1)/a}_{\text{Time to brake from } V_0 \text{ to } V_1} + \underbrace{(L_{buffer} + L_{train} + L_{switch\_track})/V_1}_{\text{Time lost between train 3 and EoA while train 1 cleared switch}} + \underbrace{T_{switch}}_{\text{Time for switch to turn}} + \underbrace{T_{delays}}_{\text{System delays}} + \underbrace{V_1^2/(2aV_0)}_{\text{Time to cover } V_1 \text{ stopping dist. at } V_0}$$



Diverging turnout headway calculation: instant 4

Headway approaching a diverging turnout can be expressed as follows:

$$H_n = \frac{V_0 - V_1}{a} + \frac{L_{switch\_track} + L_{train} + L_{buffer}}{V_1} + T_{switch} + T_{delays} + \frac{V_1^2}{2aV_0}$$

As before, using the assumed parameters of HS2, we can draw conclusions.

According to these calculations, and again using the parameters provided by HS2 (section 6.1.1) the minimum initial headway between the two trains if the first train (but not the second) takes a diverging turnout at 225 km/h would be:

Speed on-line (km/h)	360	360
Movement authority (MA) update transmission time	2	12.5
Minimum initial headway (s)	128	139
Paths per hour if every other train diverges (75% of theoretical)	22	20

Headway and capacity in the case of alternating diverging train/through train (SYSTRA calculation)

6.2.4 Comparison of the calculations of headway approaching a diverging turnout

It is to be noted that we do not find the same headway at diverging turnouts (128 s according to SYSTRA, and 125 seconds according to the HS2 headway document [21]), even if the same values (speed, delay times, etc.) are used.

The table below compares the HS2 diverging turnout headway calculation carried out previously (see section 6.2.1) with that described in the diagrams and formulas in section 6.2.3:

Time in seconds	***HS2 Document***	***SYSTRA***
Headway lost between first train and following train during braking (360 to 225 km/h at 0.687 m/s2)	10	10
Headway lost while first train crosses the 300-m EoA - SvL buffer.	2	5
Time for first train to pass over the turnout track section (300m plus 400m train length)	11	11
Turnout operation time	9	9
Train detection (TD) system reporting delay time	5	5
Movement authority (MA) update transmission time	2	2
Train On Board ETCS reaction time	1	1
Worst case driver response time	8	8
Automatic Train Operation (ATO) response time	0	0
Odometry error	1	1
Brake actuation time	3	3
Breaking time 360 => 0 km/h at deceleration of 0.687 m/s2	73	73
Total headway approaching a diverging turnout	**125**	**128**

Comparison of HS2 and SYSTRA calculation of headway at diverging turnout

We see that the disagreement is in the way in which to take into account the 300-m EOA-SvL buffer.

Whereas HS2 considers that the value to be calculated is the *spacing lost* between train 1 and train 3 while 1 crosses the buffer, we consider that the factor to be calculated is simply the *time* that it takes for train 1 to clear the buffer. The same logic (in the HS2 document as well as in our calculation) is applied for the switch section and the train lengths: the time expressed as *distance/V1* is taken into account.

Assuming that the parameters supplied by HS2 are correct, we agree that the theoretical capacity if trains alternate between heading straight on the main line and taking a diverging junction, would be 22 trains per hour.

If headway is lengthened by 10 and a half seconds (corresponding to an MA update transmission time of 12.5 seconds, for exemple), the theoretical capacity if trains alternate between heading straight on the main line and taking a diverging junction, would be 20 trains per hour.

If trains were to alternately diverge and not diverge on a junction requiring a maximum speed of 225 km/h, even with slightly less optimistic parameters than those provide by HS2, 18 trains per hour would thus be largely achievable.

6.3 Headway between converging trains

6.3.1 Summary of the HS2 calculation of headway between converging trains

The HS2 Headway document also discusses the case in which a train (train 1) travels at 350 km/h along the main track, and another train (train 3) converges onto the main line after train 1. The headway calculations are based on the assumption that train 3 is at a complete stop in a station, and that it starts accelerating before it has been passed by train 1 in order to obtain a minimum headway between the two.

6.3.2 Comments on the HS2 calculation of headway between converging trains

In order to effectively carry out the operation described above, train 3 would have to "know" with precision:

- Where train 1 is
- At what speed train 1 is travelling

In reality all that train 3 can "see" (unless we conjecture a safety-critical system that enables a driver to have access to additional traffic information) is the movement authority ahead of it, based on:

- The position of the converging set of points
- The position of the nearest train "after" the converging points

If train operations were perfect, train 1 would be exactly on time (down to the second) and train 3 would leave the station at its precisely scheduled time. In reality, train 1 might have a slight delay (say 30 seconds), so train 3 will have to wait ahead of the points, and the precise train scheduling, designed to maintain high line capacity, would be lost.

6.3.3 Alternative calculation of headway between converging trains

We do consider that it would be possible for the driver of train 3 to start when train 1 passes.

Assuming that 5 seconds pass between the moment when train 1 passes and train 3 starts accelerating, the final headway between trains 1 and 3 would be 141[15] s (if both have a maximum speed of 350 km/h).

Thus if converging and through services alternate, the combined headway would be (116[16] + 141) = 257 seconds. The operational capacity would be 3600 x 2 / 257 x 0.75 = 21 paths per hour. Based on the less optimistic value for movement authority update time, the operational capacity would be 20 paths per hour.

As such, the case of converging trains coming from intermediate stations would still allow for 18 trains per hour.

6.3.4 Comparison of estimated headway between converging trains

[15] Assumes 5 + 136, derived from HS2 reference train acceleration curve [19] for a train starting at 5 seconds after it is overtaken by a passing train at 350km/h, then accelerating at full speed. At full speed it will be 136 seconds behind.

[16] According to the HS2 Headway document

The HS2 document concludes that if converging and through services alternate, the combined headway would be 239 seconds (page 8); we argue that it would be 257 seconds.

6.4 The effect of speed reductions on headway

The problem posed by speed reduction is an issue that has not yet been discussed, but that is essential for the calculation of line capacity.

Speed reductions can come from several sources, both permanent and temporary. For example, reduction in speed for tunnel or curvature restrictions are permanent, whilst reductions for track speed restrictions following maintenance are temporary. First we will discuss the temporary case, which is analogous to that which mystifies motorway drivers, who encounter traffic congestion for no apparent reason.

The theoretical open line headway of 116 s, as calculated above, is possible if trains infinitely maintain a speed of 360 km/h. This is clearly a theoretical case. Not only will the London – West Midlands line have permanent speed restrictions below 360 km/h, but indeed, according to the assumed Y52 service pattern (presented in Appendix 1), in the southbound direction 16 trains per hour will slow to a stop at Old Oak Common.

If a train follows another train with a time interval equal to the minimum headway open line headway, it should not be disturbed by the first train, and ETCS (or other signalling system) will show a movement authority that allows the train to run at full speed. Indeed, by definition, the minimal headway is precisely the time interval that allows that full speed.

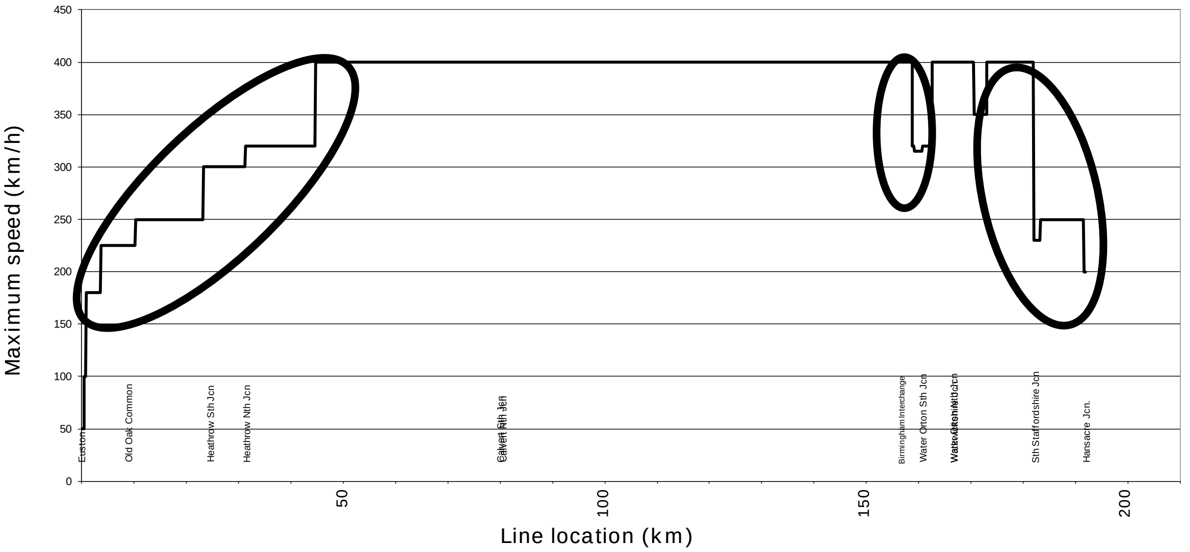
However, if the first train reduces its speed, even by a small amount, the following train will have to brake immediately in order to maintain a safe braking distance from the first train.

If trains run at 360 km/h (100 m/s), with a control system allowing a minimum headway of 120 seconds, the distance between running trains is 12,000 m. This means that, if the first train brakes at km post 100, the second train begins braking 12 km before the point of braking of the first train, thus at km post 88. If there is a flight of trains following one another at the same headway, the point where the nth train will start braking is km post 100 – 12*n. Practically, this would mean that the 9th train cannot start from the origin station at km post 0, and the line is blocked by this simple (and maybe very limited) speed reduction by the first train.

Due to the reaction time of the control system, if the first train reduces its speed for example by 10 km/h, and reaccelerates to top speed immediately, the second train will have to brake harder, and for a longer time, until its computer allows it to resume its normal route. This ripple effect will increase with each successive train, until services are severely disrupted, just in the same way as on a motorway, when all cars run at the maximum permitted speed and a driver suddenly brakes - reducing speed for a brief moment before resuming normal speed. The following driver brakes harder or for longer, and this continues until a point and a time where all cars stop, only to then proceed without any apparent cause for the delay.

What this means in practice is that the minimal headway must not only take the line characteristics into account (curves, gradients, block section length) and the control system transmission and computation times, but also the speed profile of the line, in order to compute the minimal headway approaching the deceleration point(s) so that a following train is not troubled by the braking of the previous train.

The second train must start braking at the same point where the first train did, and for the same reason, not because it is approaching the first train too closely.



HS2 speed profile and the speed reduction in both directions

In the discussion that follows, we undertake a detailed investigation of the dynamics of slowdowns in order to find a solution that minimises both headway and journey time.

The results obtained are applied to HS2 in section 6.5, page 49.

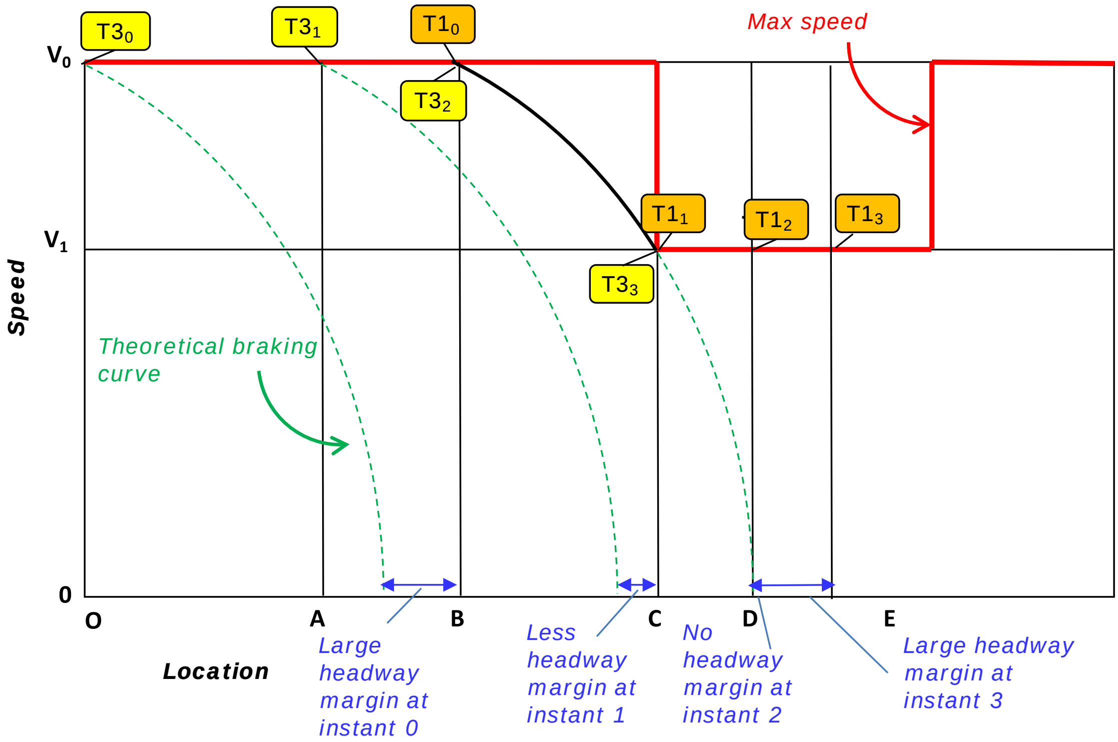
The diagram below presents the movements of a train (T1) and the train following it (T3) approaching a speed reduction zone.

To make things simpler in the diagram, we consider that trains have no length and are represented as a point, and no reaction/transmission/computation time is considered, but the formulae we use for the calculations take into account all the real parameters.

The train T1 is followed by the train T3, on a line whose maximum speed is V_0 until a point C where it drops to V_1.

Four critical instants are considered, named 0, 1, 2 and 3.

Train position is indicated as follows: {Train Name}$_{\{instant\}}$. For example, $T3_2$ shows the position of train T3 at instant 2.



Movement of trains 1 and 3 approaching a speed reduction zone

The following events are illustrated:

- At instant 0, train T1 reaches position B (T1$_0$), where it is necessary to start braking to comply with the speed limitation V_1. T3 is at position O (T3$_0$), travelling normally at V_0.
- At instant 1, train T1, after having reduced its speed, is at position C (T1$_1$), beginning of the speed reduction zone, and its speed is V_1. Train T3 is at position A (T3$_1$), still travelling at V_0.
- At instant 2, train T3 arrives at B (T3$_2$), where it starts braking. Train T1 has moved at speed V_1 and is now at D (T1$_2$).
- At instant 3, train T3 is at C (T3$_3$), beginning of the speed reduction zone, and its speed is V_1. Train T1 has reached E (T1$_3$), travelling at V_1.

During the time when train T1 was braking, and then travelling at V_1, while train T3 was still moving at V_0, T3 was catching up on T1. It was of course necessary that the safe distance be kept between the two trains, especially at the most critical moment, when T3 starts braking at B (T3$_2$). After that moment, train T3 is braking, and able to stop at D, while train T1 is still travelling away from this point D. Therefore, the safety distance is sufficient and minimal at instant 2.

On the graph above, one can see that the critical instant is when T3 reaches the braking point B (instant 2). Until this moment, it was travelling at speed V_0, while train T1 was either reducing its speed from V_0 to V_1, or travelling itself at V_1.

At that point, two conditions must be met by train T3:

- It must start braking to comply with the speed reduction
- It must start braking because it reaches the safety distance from train T1

This means that the braking curve for train T3 at $T3_2$, virtually extended to the stopping point, must end in D ($T1_2$), where train T1 is presently located.

Before that instant, the trains were separated by an interval that was greater than the safety distance. This extra margin, indicated by the double arrow, was shrinking down to 0 from instant 0 to instant 2.

After instant 2, train T3 is catching up train T1, but the distance between T3 and T1 decreases slower than the safety distance is itself decreasing due to the deceleration of T3.Therefore a new extra margin appears, which is at its maximum at instant 3, and will remain constant while both trains travel at speed V_1.

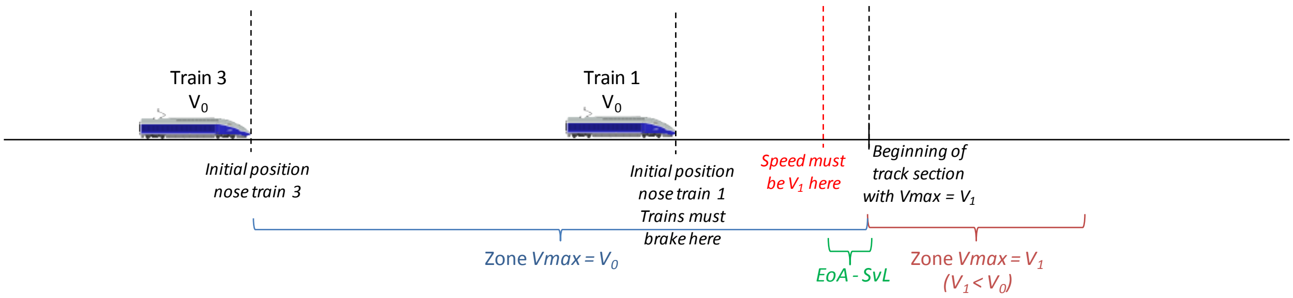
We will now determine the formulas to compute the headway necessary in case of a slowdown from V_0 to V_1, keeping the same notation as in the previous calculation.

In particular, the normal headway between trains at a speed V_0 on line is called H_{V0}, and the headway for V_1 is H_{V1}.

Calculation of headway needed between trains travelling at speed V_0, if the first train slows to speed V_1

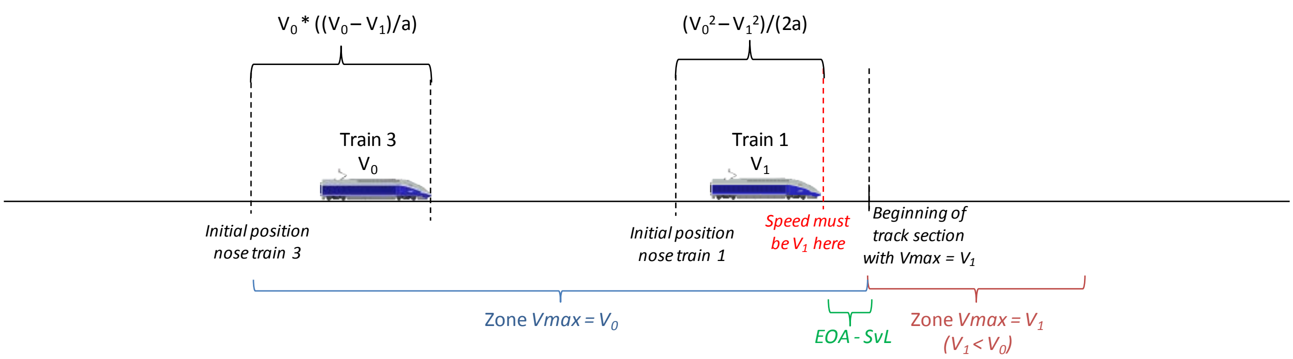
Needed headway = $H_{0,1}$ seconds

(0) Train 1 and train 3 travel at speed V_0. At this moment train 1 begins braking to reach speed V_1, where $V_1 < V_0$.



Effect of speed reduction: Instant 0

(1) Train 1 has braked to speed $\boldsymbol{V_1}$*. Train 3 has covered* $\boldsymbol{V_0 * ((V_0 - V_1)/a)}$ *meters.*



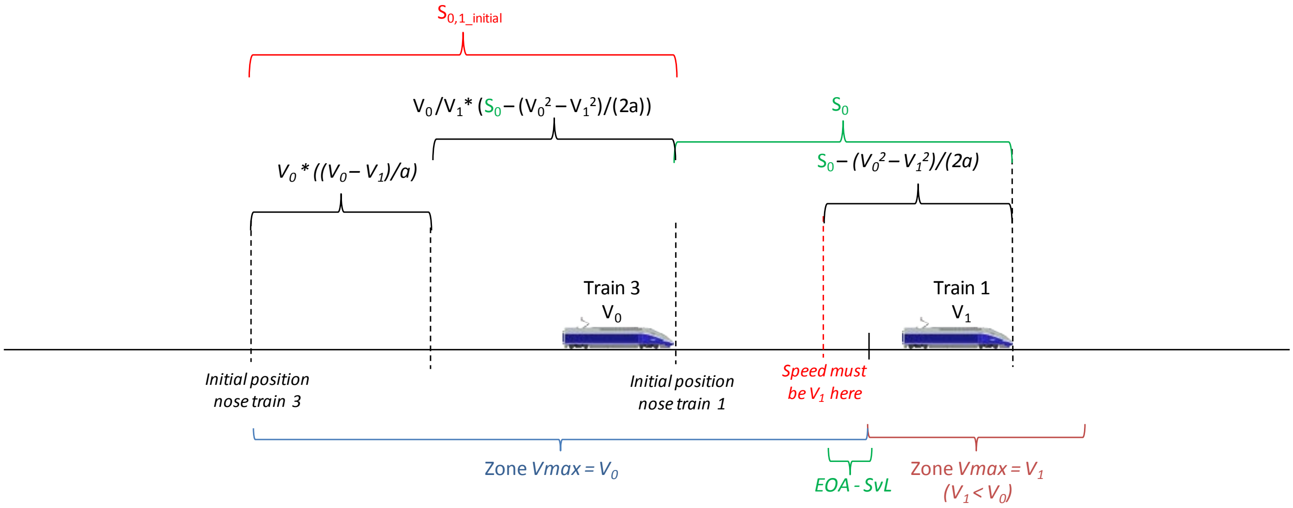
Effect of speed reduction: Instant 1

(2) *Train 3 has covered the distance that* initially *separated it from train 1 (nose to nose). It must now be at least* S_0 *meters from the nose of train 1. The initial distance must be* <u>*at least*</u>

$S_{0,1\_initial} = V_0 * (V_0 - V_1)/a + V_0/V_1 * (S_v - (V_0^2 - V_1^2)/(2a)) = V_0/V_1 * S_0 - V_0(V_0-V_1)^2/(V_1 2a)$

The headway must be at least

$\boldsymbol{H_{0,1} = V_0/V_1 * H_O - (V_0-V_1)^2/(V_1 2a)}$



Effect of speed reduction: Instant 2

The headway that must be used to calculate line capacity will be the worst case depending on the line profile and the speed reduction(s) imposed on the line (the highest value of H_{V0} along the line, depending on the vertical profile of the line and the various $H_{0,1}$ according to the various V_1).

In order to understand the influence of the slowdown factor, the table below indicates various values of the required headway as a function of various speed reductions. The open line headway at 360 km/h has been taken as 116 seconds, as in version 3.0, dated August 1st, 2011, of the HS2 document “Signalling headway and maximum operational capacity”, and detailed in section 6.1.

V_1 (km/h)	360	320	300	260	230	200	100
Headway (s)	116	129	137	153	166	183	280
Increase (s)	0	13	21	37	50	67	164
Number of paths	31	28	26	23,5	21,5	19,5	12,5
Loss of capacity	0 %	10 %	15 %	24 %	30 %	37 %	59 %
Operational paths	**23**	**21**	**19**	**17**	**16**	**14**	**9**

As we saw in the figures above, the formula giving the required headway for a speed reduction from V_0 to V_1, that we will call $\boldsymbol{H_{0,1}}$ is:

$$H_{0,1} = \frac{V_0}{V_1} H_0 - \frac{(V_0 - V_1)^2}{2aV_1}$$

This formula is useful for calculation purposes, but not so easy to decrypt. We can write it differently so that its consequences appear clearly.

As we saw in section 6.1.3, the formula for open line headway H_0 is:

$$H_0 = \frac{L_{track\ section} + L_{train} + L_{buffer}}{V_0} + (T_{MA} + T_{ETCS} + T_{Reaction}) + \frac{V_0}{2a}$$

Among the three terms building H_0, one is half the braking time from V_0 to 0 ($V_0/2a$), and the two others are “system” times, linked to ETCS, the rolling stock, the infrastructure or the operators.

If we note T_{B0} the braking time from V_0 to 0 and T_{s0} the system time at V_0, we can then write:

$$H_0 = \frac{V_0}{2a} + T_{s0} = \frac{1}{2} T_{B0} + T_{s0}$$

Basing the calculation on the input parameters provided by High Speed 2 Ltd (and presented in section 6.1.3), the braking time from 360 to 0 km/h with a deceleration of 0.687 m/s² is 145.6 seconds, and $T_{B0}/2$ is thus 73 seconds, and the system time is 43 seconds, for a total of 116 seconds.

If we introduce that value of H_0 in the formula for $H_{0,1}$, and if we note $T_{B0,1}$ the time for braking from V_0 to V_1, we can come to the following expression:

$$H_{0,1} = H_0 + \frac{1}{2} T_{B0,1} + \frac{V_0 - V_1}{V_1} T_{s0}$$

This formula expresses that the loss of capacity is the sum of:

- Half the braking time for reducing speed
- The percentage of speed reduction (with respect to the target speed) applied to the system time

So, in conclusion, each of the terms is important, and can be used to minimize the loss of capacity.

The first term indicates that the loss is half the braking time.

The drivers must be instructed to brake at the last moment and strongly (respecting ETCS instructions, of course). Coasting, or attempts to reduce brake wear by reducing the rate of deceleration, must be avoided, as they would prolong braking time and thus increase necessary headway. This may have to be taken on a case by case basis, but is an important conclusion, nonetheless.

The second term in the formula has a different consequence. The loss is proportional to the percentage of speed reduction (with respect to the target speed), and therefore this speed reduction must be as small as possible. We have seen that after the speed reduction, when both trains are travelling at the reduced speed, the final headway is longer than necessary. This means that a new speed reduction can now be implemented with no consequence on the capacity, if it is kept in the appropriate limits. After this second speed reduction and stabilisation, a third and possibly a fourth reduction can be imposed, until the required speed has been obtained.

For example, a direct deceleration from 360 km/h to 200 km/h in order to connect with the WCML would lead to a headway of 183 seconds (and thus the addition of 67 extra seconds to the basic line headway), reducing the number of operational paths from 23[17] to 14 per hour.

If the speed reduction is implemented in 4 steps:

- 360 km/h to 330 km/h
- 330 km/h to 290 km/h
- 290 km/h to 245 km/h
- 245 km/h to 200 km/h

with a stabilisation length of 8 block sections at 330 km/h, 7 at 290 km/h and 6 at 245 km/h, the loss of headway is limited to 10 seconds (the required headway is 126 seconds).

	Slowdown from 360 to 200 km/h				
	Direct	With 4 intermediary steps			
Initial speed (km/h)	360	360	330	290	245
Final speed (km/h)	200	330	290	245	200
$L_{track\_section}$ (m)	1,600	1,600	1,600	1,600	1,600
Movement authority (MA) update transmission time	2.0	2.0	2.0	2.0	2.0
Minimum headway (s)	183	126	126	125	125
Paths per hour (75% of theoretical)	14	21	21	21	21
Time lost for steps		*12*	*17*	*22*	
Paths per hour with steps	**21 (instead of 14 without steps)**				
Time lost for steps (as compared to direct deceleration)	**50 seconds**				

Braking in four steps only consumes 2 paths rather than 9 for a one step braking (track section length=1600 m, MA update transmission time=2 s)

[17] With track sections of 1600 m, a speed of 360 km/h, and an MA update transmission time of 2 seconds, the headway is 116 s (see section 6.1). The number of theoretical paths in this case is 75% * 3600 / 116 = 23 paths per hour.

The consequence is of course a slightly more complicated driving process (the decelerations steps have to be integrated in the ETCS system), and there is of course a loss of trip time, but still limited as it can be seen in the above example, where it reaches only 50 seconds – in other words it does not reach 1 minute, but has the significant consequence of saving 7 train paths.

If track sections were brought down to only 800 m in known critical locations, there would be no loss of capacity (with regards to an open line capacity of 23 trains at 360 km/h with track sections of 1600 m) for a 360 to 200 km/h slowdown if the slowdown were accomplished in 4 steps:

	Slowdown from 360 to 200 km/h				
	Direct	With 4 intermediary steps			
Initial speed (km/h)	360	360	330	290	245
Final speed (km/h)	200	330	290	245	200
$L_{track\_section}$ (m)	800	800	800	800	800
Movement authority (MA) update transmission time	2.0	2.0	2.0	2.0	2.0
Minimum headway (s)	168	117	116	113	110
Paths per hour (75% of theoretical)	16	23	23	23	24
Time lost for steps		*10*	*14*	*18*	
Paths per hour with steps	**23 (instead of 16 without steps)**				
Time lost for steps (as compared to direct deceleration)	**43 seconds**				

Braking in four steps only consumes 2 paths rather than 9 for a one step braking (track section length=400 m, MA update transmission time=2 s)

It must be kept in mind, however, that this would mean doubling the number of track sections over more than 28 km, which would of course increase costs. Furthermore, the installation of shorter track sections at critical points would not solve the problem of provisory (non-permanent) slowdowns due to track works or some other reason. **For the remainder of this document we assume that track sections are 1600 m long.**

If we consider that the movement authority (MA) update transmission time is 12.5 seconds instead of 2 (see section 6.1.2 for a discussion of appropriate values for this parameter), capacity is as follows with a 4-step slowdown from 360 to 200 km/h:

	Slowdown from 360 to 200 km/h				
	Direct	With 4 intermediary steps			
Initial speed (km/h)	360	360	330	290	245
Final speed (km/h)	200	330	290	245	200
$L_{track\_section}$ (m)	1,600	1,600	1,600	1,600	1,600
Movement authority (MA) update transmission time	12.5	12.5	12.5	12.5	12.5
Minimum headway (s)	201	137	138	138	137
Paths per hour (75% of theoretical)	13	19	19	19	19
Time lost for steps		*12*	*17*	*22*	
Paths per hour with steps	**19 (instead of 13 without steps)**				
Time lost for steps (as compared to direct deceleration)	**50 seconds**				

Braking in four steps only consumes 2 paths rather than 9 for a one step braking (track section length=1600 m, MA update transmission time=12.5 s)

If track section length is 1600 m and MA update transmission time is 12.5 s, then a slowdown from 360 to 200 km/h in 4 steps would reduce theoretical capacity to 19 paths per hour.

Nonethless, pending a detailed discuss with HS2 on this topic, for the remainder of this document we assume that the MA update transmission time is 2 s, consistent with prior HS2 technical assumptions.

A 3 step process (315 km/h, 260 km/h, 200 km/h) would save less than 10 seconds in trip time with 1600-m track sections (compared to 4-step braking with 1600-m track sections), but at the expense of one path loss (only 20 compared to 21 with 4-step braking) because the required headway increases to 131 seconds, as shown in the table below.

A single intermediate step at 280 km/h would save only 4 additional seconds (compared to 3-step braking) but would cost 2 paths, reducing the operational line capacity to 18 paths per hour.

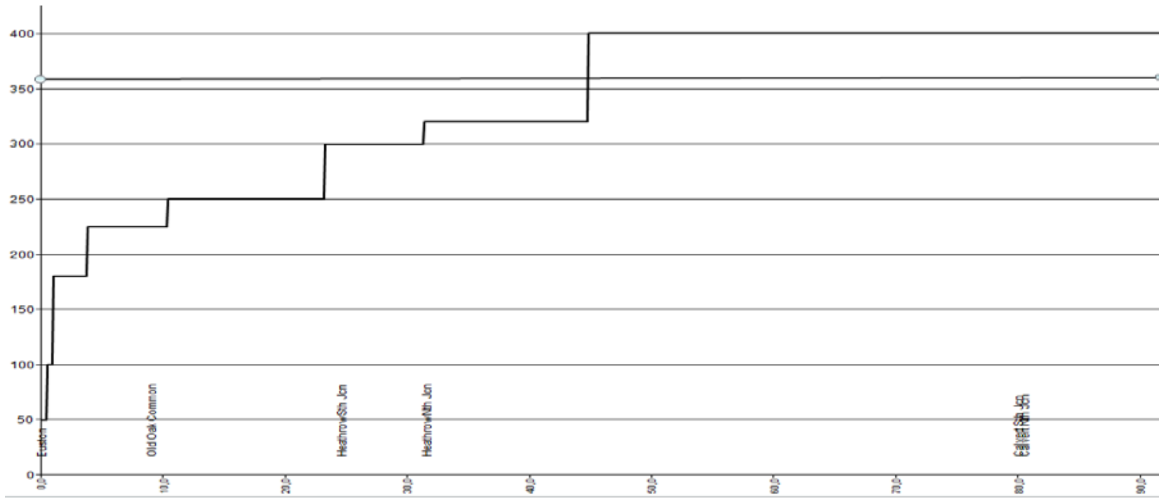
	Slowdown from 360 to 200 km/h				Slowdown from 360 to 200 km/h		
	Direct	With intermediary steps			Direct	With intermediary	
Initial speed (km/h)	360	360	315	260	360	360	280
Final speed (km/h)	200	315	260	200	200	280	200
$L_{track\_section}$ (m)	1 600	1 600	1 600	1 600	1 600	1 600	1 600
Transmission time	2,0	2,0	2,0	2,0	2,0	2,0	2,0
Minimum headway (s)	183	131	131	132	183	144	142
Paths per hour (75% of theoretical)	14	20	20	20	14	18	18
Time lost for steps		*18*	*23*			*37*	
Paths per hour with steps	20 (instead of 14 without steps)				18 (instead of 14 without steps)		
Time lost for steps (as compared to direct deceleration)	41 seconds				37 seconds		

Less steps, little time saved, much capacity lost (3 and 2 steps, with 1600 m block sections)

6.5 Application to HS2

Speed reduction on HS2 occurs mainly at the extremities of the line, at junctions, and in the vicinity of Birmingham where the design speed drops from 360 km/h down to 320 km/h, then 315 km/h. Another source of speed reduction is the service of Birmingham Interchange, where several successive trains serve the station.

In the table below, we have concentrated on the southbound direction, approaching Old Oak Common from about km post 60.

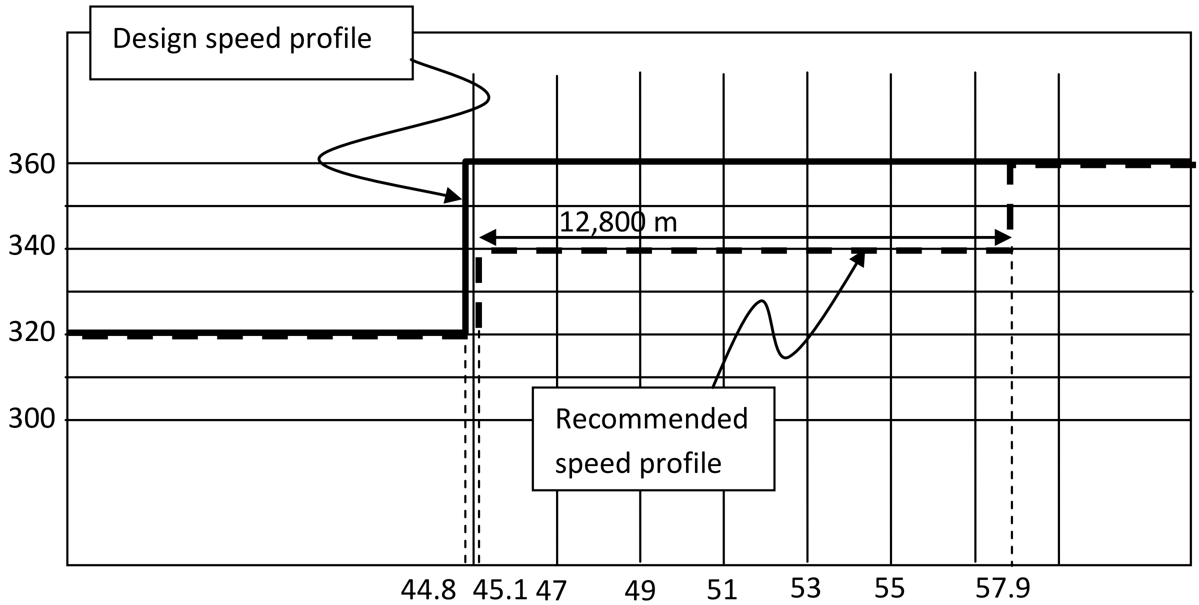


The speed profile approaching London

The permitted speed decreases from 360 to 320 km/h at km 45, due to the Little Missenden, then Amersham, tunnels. If the reduction is made in one single step (and assuming that track section is 1600 m), the headway has to be increased by 13 seconds, and the capacity is reduced from 23 to 21 trains per hour.

To minimise the loss of capacity, SYSTRA suggests that the speed reduction consist of 2 steps: the first one from 360 km/h to 340 km/h, lasting 12,800 m (8 block sections), and the second one from 340 km/h to 320 km/h.

The loss in trip time is limited to 8 seconds, the required headway is 122 seconds (+ 6 seconds) and the loss of capacity to 1 train per hour (22 trains per hour compared to a theoretical 23 for open line operation).



Suggested southbound speed profile around km 50

The second difficult section is approaching Old Oak Common, where all trains will call using the two faces of an island platform. The design speed is 250 km/h from km 23.300 to km 10.400, the station entrance turnouts being at km 9.500, and the end of platforms at about km 8.850. The distance is therefore very short between the clearance point of the turnout and the platform, which means that the tail of a given train will pass the turnout at no more than 40 km/h (with not much more than 200 m to stop the train and adjust the stopping position).

The situation requires two different phases:

- Slowing down from 250 km/h to a certain speed (headway on slowdowns)
- From that speed, entering the station and stopping, every other train using each face of the platform (headway on diverging turnout).
- The intermediate speed has to be carefully chosen so that the capacity remains the same during all segments of the two phases.

With the same parameters on ETCS system times, we came to the conclusion that, if 1600-m track sections are maintained:

- A four step deceleration is required from 250 to 90 km/h (170 km/h, 115 km/h, 90 km/h), safeguarding a capacity of 18 trains per hour,
- With a final speed of 40 km/h of the tail of the train when clearing the turnout to each platform face, this speed of 90 km/h also provides a capacity of 18 trains per hour.
- The corresponding loss of trip time is 103 seconds.

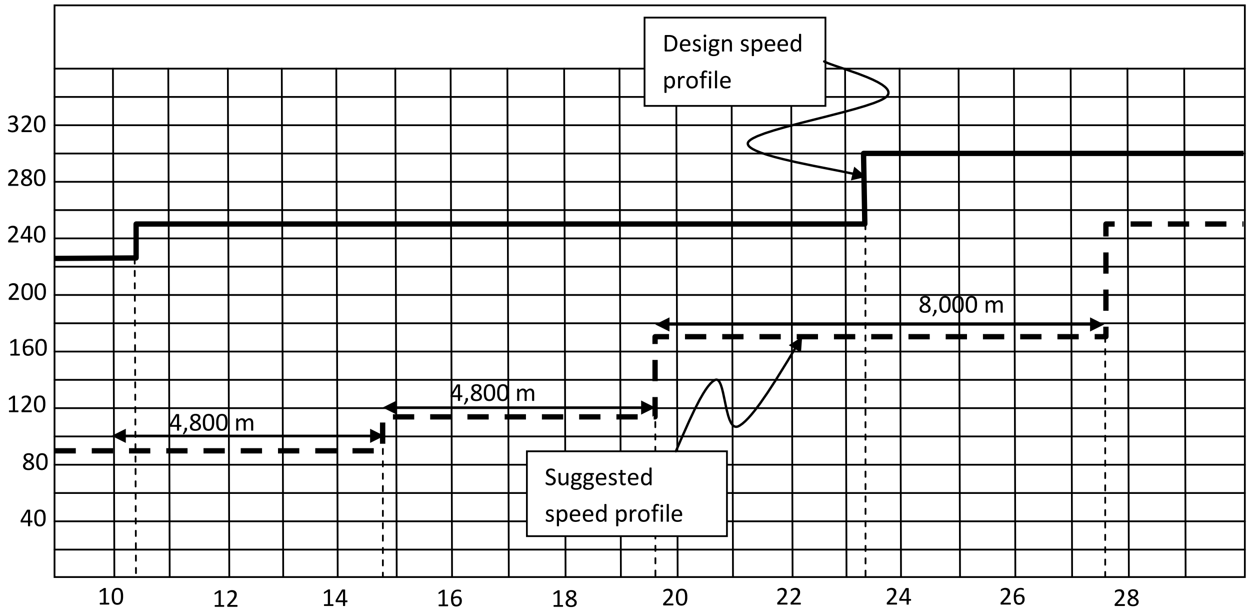
Since this loss is significant, our recommendation would be that the deceleration steps should not be included in the ETCS speed profile itself, because it would prevent late trains from recovering time, especially during off-peak periods, when the full capacity is not needed. Therefore, it should be implemented through drivers' training and behaviour. Here, paradoxically, drivers must also be instructed not to try to recover time when they are late during peak hours, but only to drive at the required speed, to safeguard capacity.[18]

	Slowdown from 250 to 90 km/h			
	Direct	With intermediary steps		
Initial speed (km/h)	250	250	170	115
Final speed (km/h)	90	170	115	90
$L_{track\_section}$ (m)	1 600	1 600	1 600	1 600
Transmission time	2,0	2,0	2,0	2,0
Minimum headway (s)	230	145	147	146
Paths per hour (75% of theoretical)	11	18	18	18
Time lost for steps		*54*	*49*	
Paths per hour with steps	18 (instead of 11 without steps)			
Time lost for steps (as compared to direct deceleration)	103 seconds			

Three steps from 250 km/h to 90 km/h with a minimal loss of capacity (track sections of 1600 m)

[18] It is possible for a driver to brake at a higher rate than the ETCS curve, since ETCS is based on a guaranteed brake rate in "adverse conditions". So braking at a higher rate is possible in normal conditions.

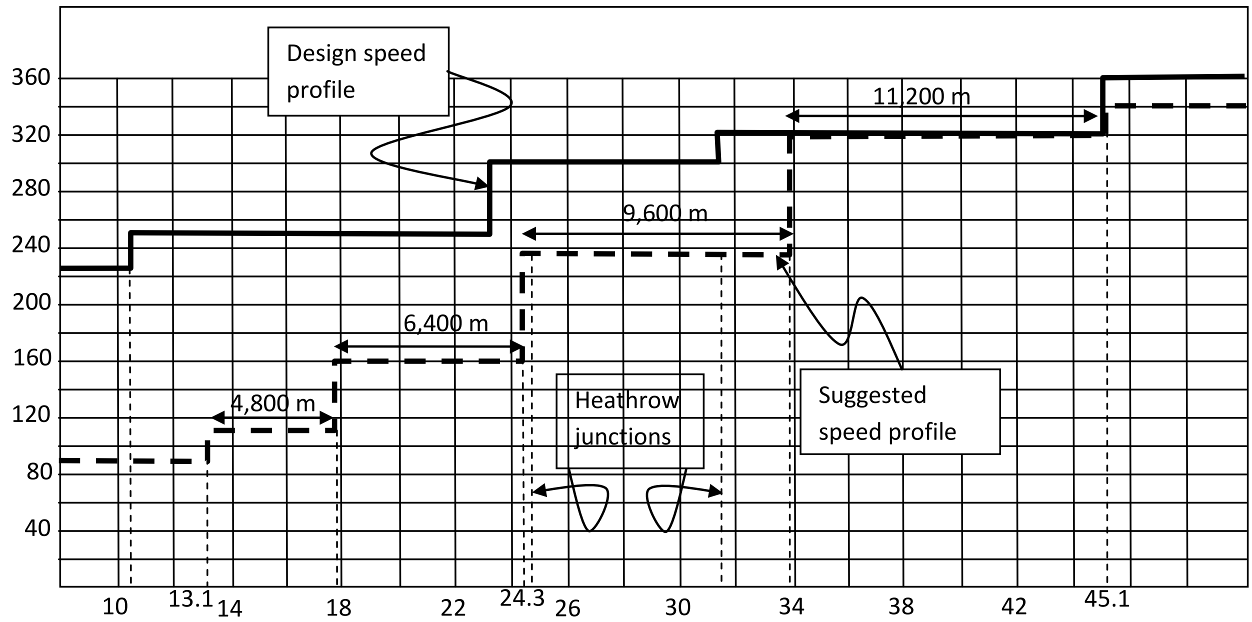
The step lengths are respectively 8,000 m at 170 km/h, 4,800 m at 115 km/h and 4,800 m at 90km/h. Therefore, the speed profile of the trains in normal circumstances and preserving full line capacity could be as below:



Possible southbound speed profile approaching Old Oak Common

However, compared to the designed speed profile, the suggested speed profile remains very low, which explains the loss of nearly 2 minutes in trip time. On top of that, we see that there may be a detrimental effect on the operations of the Heathrow north (km 31.5) and south (km 24.6) junctions.

It is thus necessary to consider the whole southbound sequence approaching Old Oak Common. SYSTRA has made a short study of the question, and the results suggest that a speed profile such as below, though reducing the speed from km 33.9, could provide a suitable solution for: maintaining high capacity, avoiding an excessive increase in journey times, serving Old Oak Common in good conditions, and avoiding a detrimental effect on Heathrow junctions.



An improved speed profile approaching Old Oak Common

The suggested profile starts from the 340 km/h step determined above, and the maximum speed decreases then to 300 for 11,200 m, then 235 for 9,600 m, 160 for 6,400 m, 110 for 4,800 m and finally 90 km/h at km 13.1.

The loss of journey time is 141 seconds (7+39+46+49), and the headway is kept in all cases under 150 seconds (120, 144, 144, 147, 143), allowing an operational capacity of 18 trains per hour.

All the above calculations will have to be reconsidered when the exact positions of the various critical points (turnouts, junctions, speed transition points) and parameters (speed on turnouts, detailed system times of ETCS) are finalised.

However, the principle will remain one of successive speed reductions and long sections of stabilised, lower, speed.

Of course, the same principles would apply in the case of temporary speed restriction for engineering purposes, in order to maintain the line capacity, at the expense of journey time if necessary. Though it has to be remembered that short turnaround times may lead to train cancellation for rolling stock availability reasons if there is insufficient recovery time.

The table below indicates, for a horizontal profile, the steps, length and loss of journey time incurred by various speed restrictions, if the normal line speed is 360 km/h and track sections are 1600 m long.

Speed restriction (km/h)	170	130	100	80	80
Steps (km/h)	300 230 170	275 190 130	280 200 135 100	250 155 100 80	270 190 130 95 80
Length (km)	28.8	25.6	32.0	28.8	35.2
Additional loss of time due to braking in discrete steps (s)	61	82	133	181	187
Remaining paths	19	18	18	17	18

Braking steps, increase in journey time and overall number of paths per hour with various slowdowns from 360 km/h (MA update time of 2 s, track sections 1600m)

6.6 Conclusions regarding headway

In conclusion, timetables with 18 trains per hour and per direction, with trains running at a maximum speed of 360 km/h, appear to be feasible, even if we take input parameters that are less optimistic than those of HS2 Ltd (effectively increasing minimum headway in most cases by 10 seconds).

The most critical situation is that of slowdowns on line. Capacity losses due to slowdowns can be minimised by dividing the braking sequence into a series of discrete steps, although this approach leads to some increase in overall journey time (generally between 1 and 3 minutes, depending on the initial and target speed). In the case of permanent slowdowns, both capacity loss and journey time increase can be significantly reduced by the installation of shorter track sections (for a greater financial cost, of course).

However, even with somewhat less optimistic parameters, and rather significant temporary slowdowns (where track section length cannot be adapted), solutions can be found to maintain 18 trains per hour.

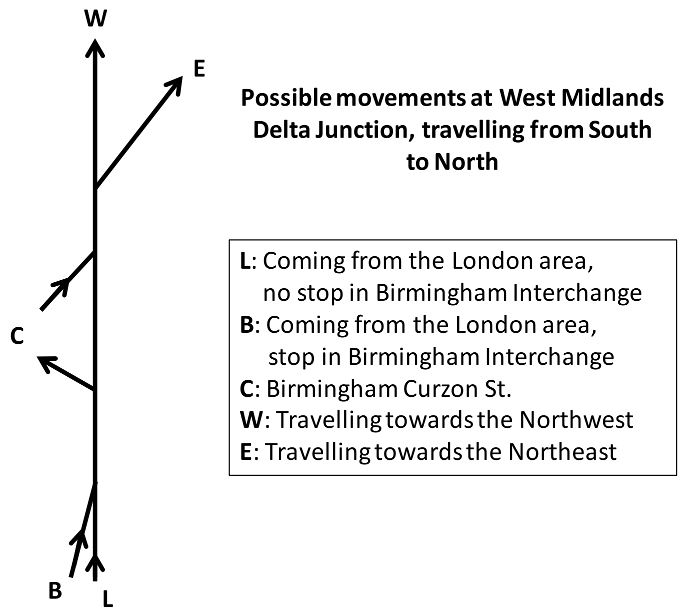
7 West Midlands Delta Junction

The West Midlands Delta Junction is the area, beginning at Birmingham Interchange (BI), that, in Phase 2 of HS2, must accommodate movements from and to the London area, BI, Birmingham Curzon Street, the Northwest and the Northeast.

According to the assumed service pattern, 28 trains per hour and per direction will need to pass through this junction. As such, the track layout must absolutely be such not only that it provides a feasible solution to permit the operation of the assumed service pattern, but it must also offer a sufficient degree of flexibility such that alternative timetables and a minimum of operational flexibility can be provided for.

We thus dedicate the current chapter to the track layout of West Midlands Delta Junction.

To simplify the problem, we only consider train movements in the South -> North direction. The figure below presents the possible movements at the Delta Junction.

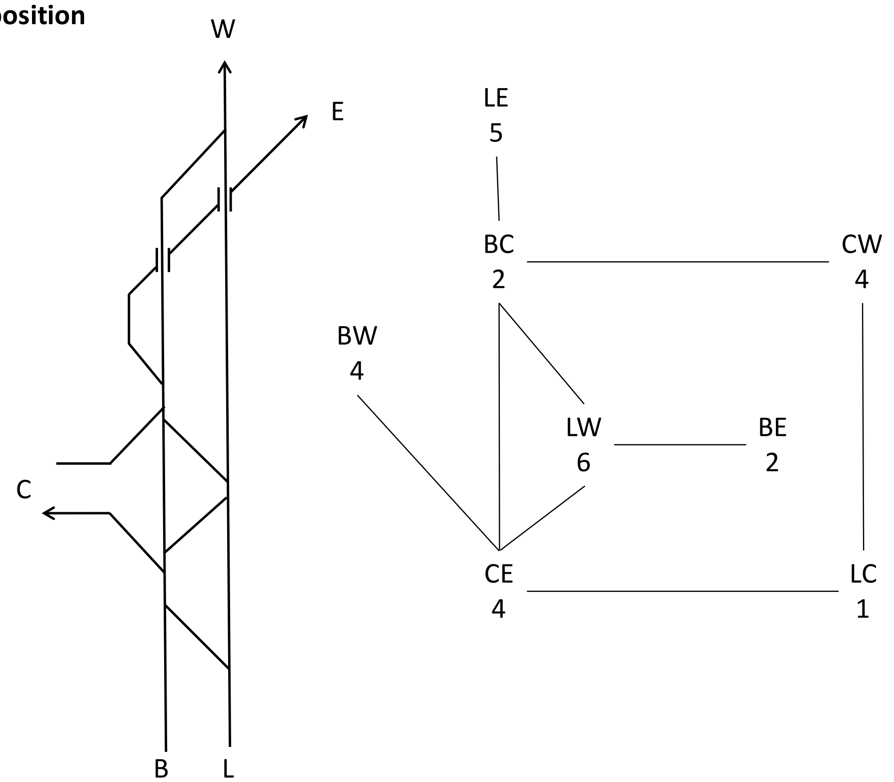


Each possible movement can be specified using two letters:

- LW for trains coming out of London with no stop at Birmingham Interchange (BI) that continue on to the Northwest
- BC for trains coming out of London with a stop at BI that go on to Birmingham Curzon St.
- CE for trains coming out of Birmingham Curzon St and continuing on to the Northeast
- Etc.

The schema below presents the existing proposition for a track layout, as provided by HS2 Ltd [22] (again, only in the South -> North direction), along with a graph indicating those movements which may take place independently of each other:

HS2 Proposition



To the left we see the schematic track layout, and to the right a graph.

Each node of the graph is a possible movement, with below it the number of times this movement is carried out each hour according to the assumed service pattern. For example, 2 trains per hour come from the London area, stop at BI and then continue on to the Northeast (movement BE). We see that there are a total of 5+2+4+4+6+2+4+1=28 movements per hour.

Each edge of the graph connects two movements that may be carried out in such a way as to be independent of each other.[19] That is, these movements can be carried out simultaneously during the same time "slot", because they involve different sets of infrastructure (tracks and switches).

For example, a train coming out of BI and then travelling to the Northeast (BE) may occupy the same slot as a train coming out of the London area that does not stop in BI and continues on to the Northwest (LW).

Of course, the concept of a "slot" is a simplification. We must keep in mind that different movements will likely occupy the Water Orton Delta junction for different spans of time.

Please note that we are only considering what happens at BI and northwards; the problem of fitting 18 paths per hour on the segment south of BI is not considered here.

In the paragraphs below, we calculate how many movements per hour may overlap each other, and thus how many "slots" are needed per hour. Begin by imagining that no

---

[19] Please note that this graph makes assumptions about the tracks used by the various movements, and only represents one solution of many. For example, it is assumed that, for a BE movement, a train stays on the « left » track, and does not hook over to the right track and back.

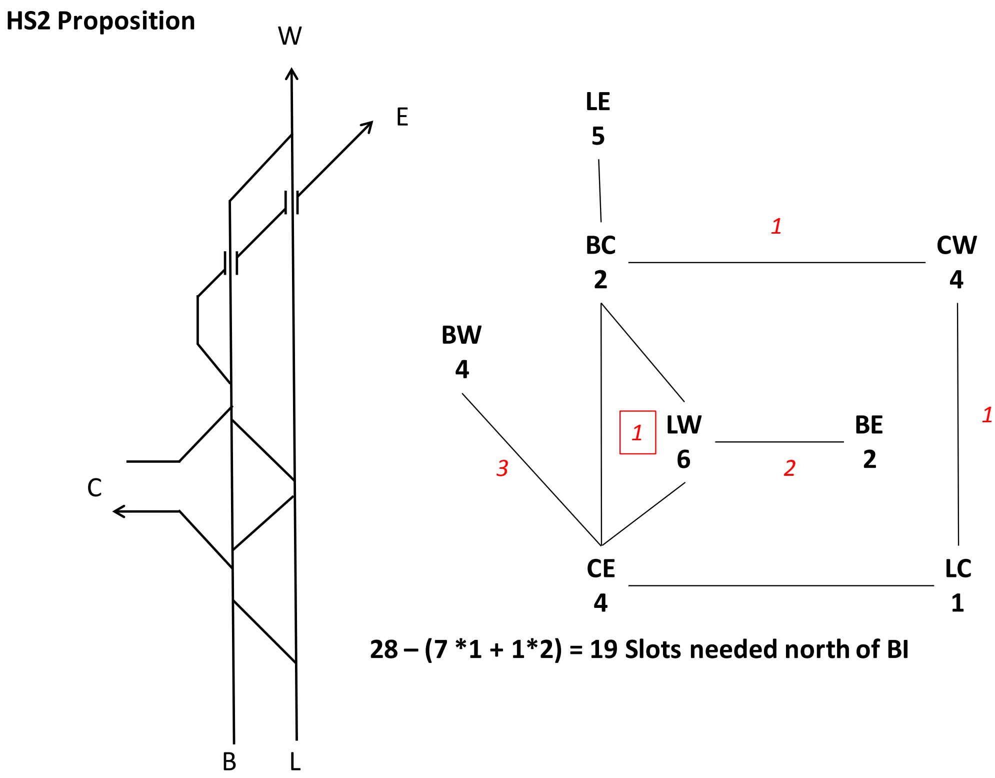
movements are independent; that is, only one train movement could be carried out in the Water Orton Delta Junction zone at a time. In this case, 28 “slots” would be needed per hour.

However, whenever a single slot can be shared by 2 movements, one slot less per hour is needed. The numbers in red italic in the schema below indicate the number of slots that may be shared by 2 or even 3 trains. ***This slot-sharing strategy is only one possible solution*****; other arrangements are possible**.

The number “1” in a box indicates that the movements BC, LW and DE can actually take place in a single slot. This means that 2 slots are actually saved (because 3 movements fit into one slot). In the other cases, 2 movements share 1 slot, thus only 1 slot is saved.

Clearly, each movement cannot share more slots than there are of that movement. For example, 2 services per hour stop in Birmingham Interchange, and then travel on to Birmingham Curzon St (movement BC). We consider here that 1 of these services shares a slot with the LW and DE movements, and another slot with the DW movement.

Again, we repeat that this slot-sharing strategy is only one possible solution; other arrangements are possible. For example, both BC services could share a slot with a DW service.

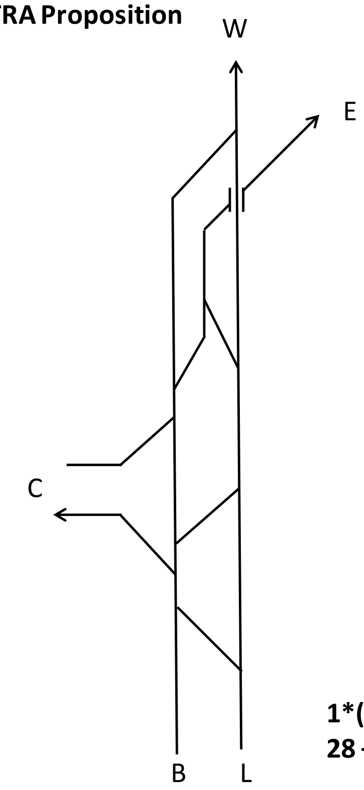


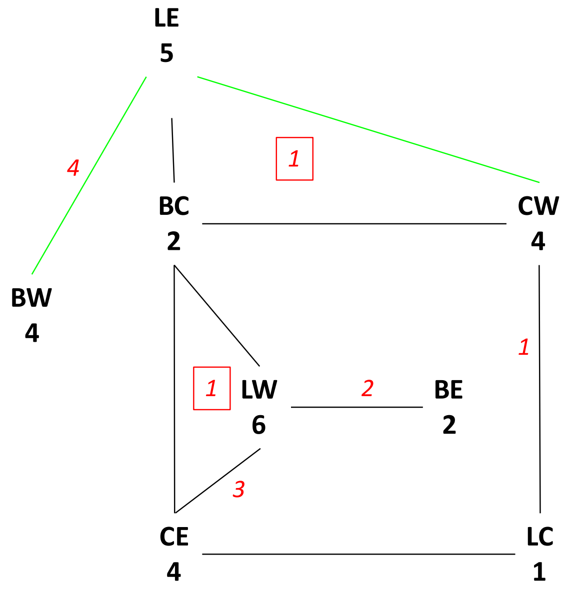
These shared slots lead to a savings of 9 slots, which means that 28 – 9 = 19 slots per hour would be needed.

“Slots” do not necessarily correspond to train paths; nonetheless, it can be said that reducing the number of slots needed per hour would facilitate operation of the Delta Junction.

The figure below presents an example of another possible track layout, allowing more independent movements (the added possible independent movements are in green).

SYSTRA Proposition



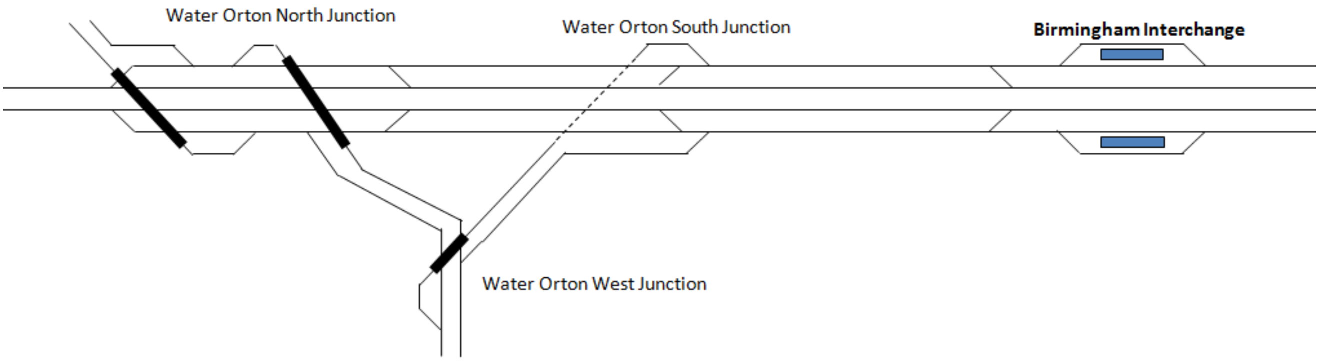


1*(4+2+1+3) + 2*(1+1) = 14 slots saved
28 – 14 = 14 slots needed north of BI

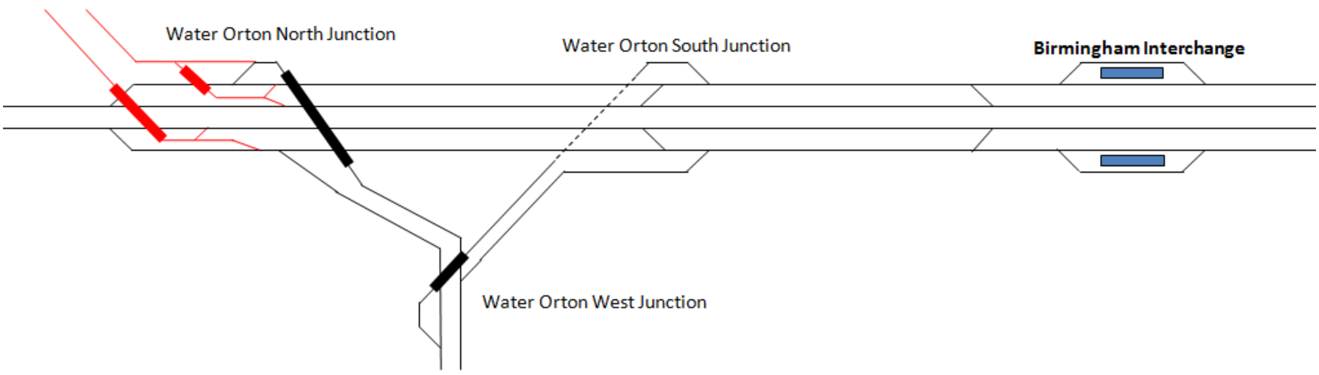
Once again, the slot-sharing strategy (indicated via the numbers in red italic) is only one possible solution. In this case in theory only 14 slots would be needed north of BI.

The schema below presents a possible track layout for both directions.

HS2 proposition



SYSTRA SCHEMA



North of Birmingham Interchange, we note that following installations are required:

- HS2 schema:
  - 20 switches
  - 3 over/underpasses
- SYSTRA schema:
  - 20 switches
  - 4 over/underpasses

In both schemas 4 of the switches are not strictly necessary with the envisaged slot-sharing scenarios. However, they may be desirable in order to increase ease of operations.

8 Reliability

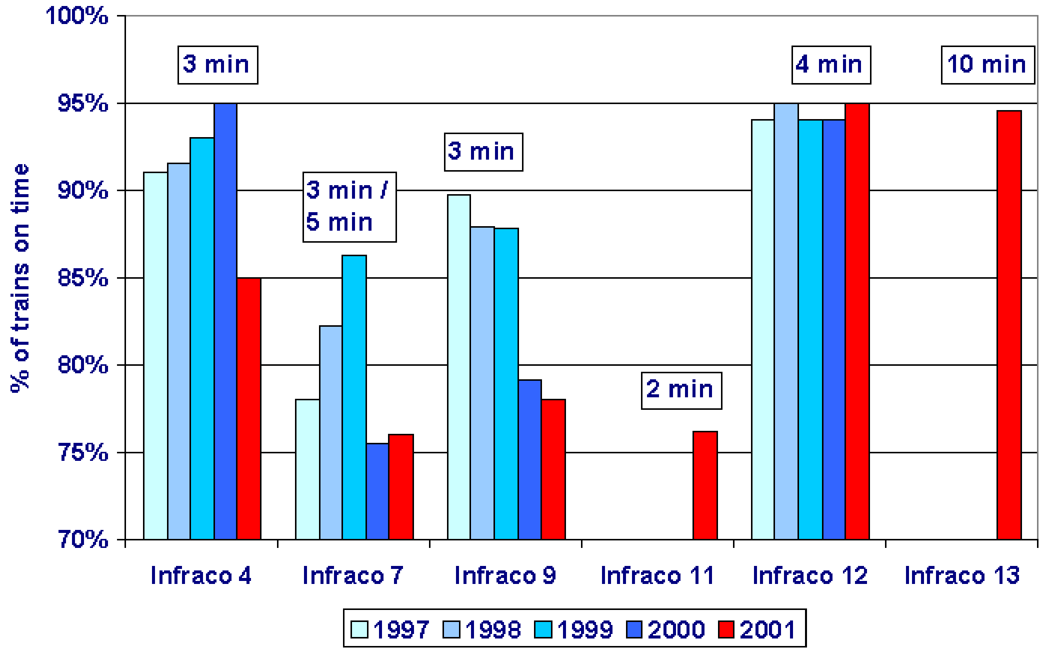
8.1 Introduction and definition

Reliability, is obviously associated with train delays and cancellations, but methods used to compute delays are markedly different from one network to another, and between train operators.

It is well known, for example, that the on-time performance in Japan is exceptional, and that the average train delay is counted in seconds. For example, the average delay on the Tokaïdo system is said to have been as low as 20 seconds in 2006.

However, it is less known how the Japanese train operators count the train delays. The delay of a train is said to be the average between the origin station departure delay and the terminating station arrival delay. If we consider that most trains depart on time, this method mathematically halves the real delay.

In general, delays smaller than one minute are not considered, and in many systems, the threshold is significantly higher[20].



Various companies, various thresholds, here from 2 to 10 minutes

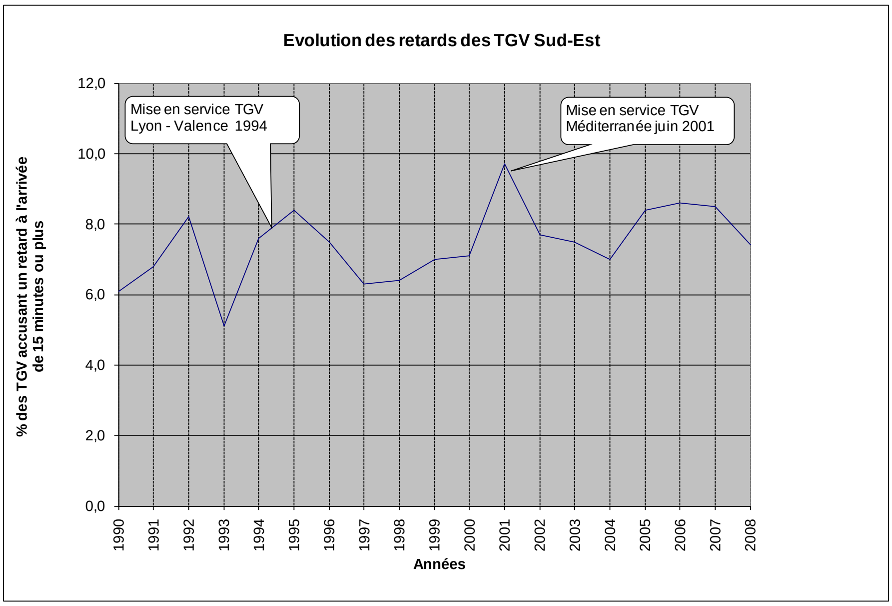
8.2 HSR performance in Europe

Generally speaking, the performance of the European High Speed Lines is such that a significant percentage of trains incur delays of 10 to 15 minutes. As we will see, the main

[20] Currently 5 minutes in North Europe, 10 minutes for long distance trains in the UK, 15 minutes in France and Italy.

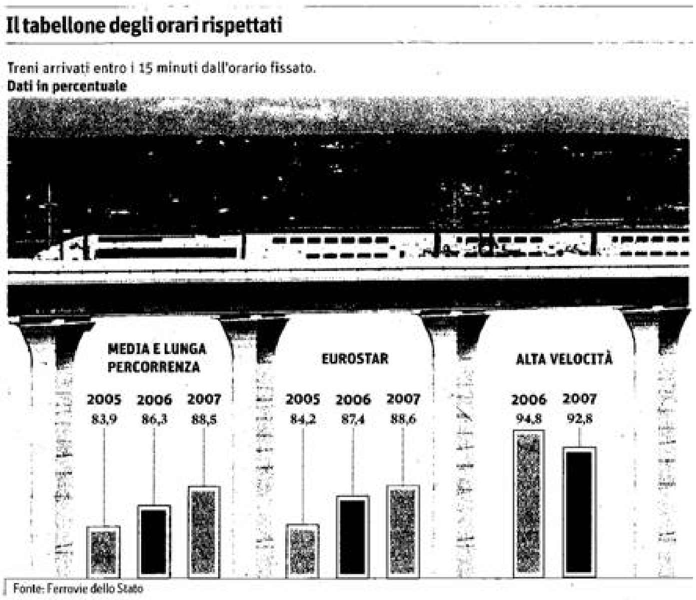
reason is that the trains encounter difficulties on the conventional network, after they leave the HSL, or, with greater consequences, before they enter the HSL.

On the French South-East HSL, which is the busiest in Europe, the graph below indicates that the proportion of trains delayed by more than 15 minutes slowly increased from 6% to 8% in 20 years, with peaks shortly after HSL extensions, first to Valence, then to Marseilles and Montpellier.



Percentage of trains delayed by 15 minutes or more on the French South-East HSL

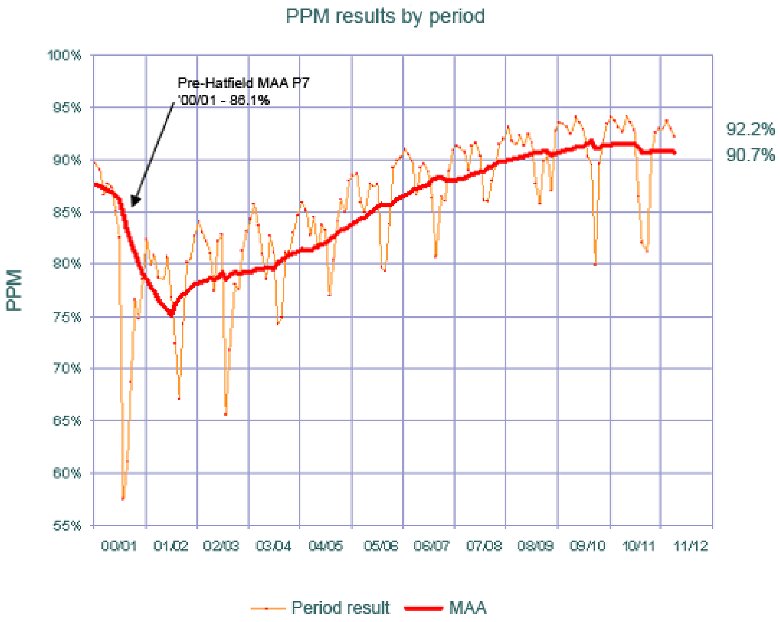
The situation is about the same on the Italian High Speed network:



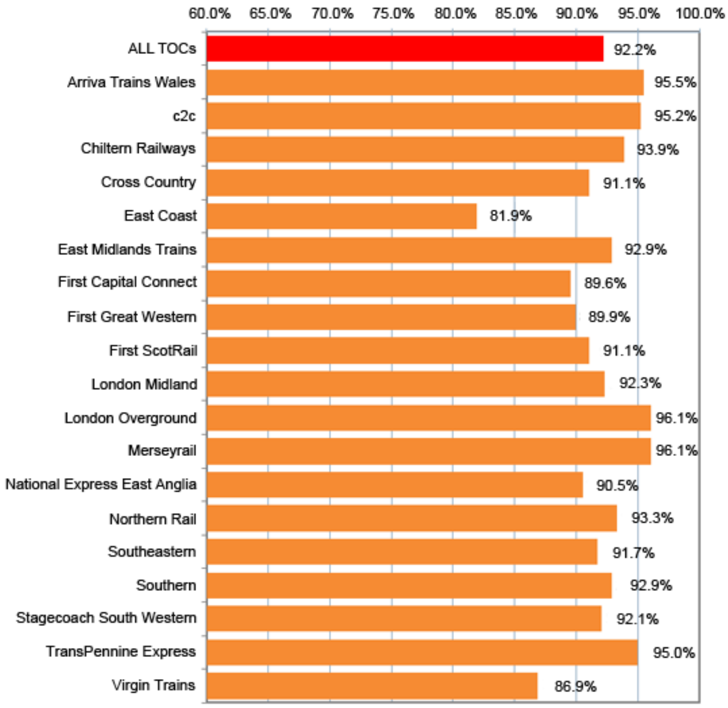
Percentage of HST on time or delayed by less than 15 minutes on the Italian network

After the Hatfield accident in the UK, the on-time performance steadily recovered but seems to have remained constant at slightly over 90% during the last few years.

However, when looking in detail line by line, one can see that the worst results appear on both the ECML and the WCML, with figures as low as 87% on the WCML (Virgin trains) and 82% on the ECML.



Percentage of trains on time or delayed by less than 10 minutes on the UK network



On time performance (10 minutes) on the various lines of the UK network

A close examination of the table below indicates that the above percentages are similar in the Netherlands as well, though most of the trains are regional with a relatively limited running time.

Table 1. Arrival delays of the trains at station Eindhoven (September 1997)

Line	From	To	Average [s]	St. dev. [s]	Share of late trains	Share of delays > 1 min	Share of delays < 3 min	Average of late trains [s]
IC 800	Haarlem	Maastr.	83	100	0.76	0.57	0.83	122
IC 800	Maastr.	Haarlem	39	130	0.46	0.33	0.86	148
IC 900	Haarlem	Eindh.	138	144	0.84	0.67	0.66	171
IC 1500	Den Haag	Heerlen	69	166	0.61	0.35	0.85	149
IC 1500	Heerlen	Den Haag	49	85	0.71	0.45	0.93	88
INT1800	Keulen	Eindh.	63	97	0.66	0.48	0.86	112
IR 1900	Rotterd.	Venlo	24	118	0.49	0.28	0.88	117
IR 1900	Venlo	Rotterd.	- 46	82	0.25	0.17	0.92	77
IR 2700	Venlo	Eindh.	7	49	0.50	0.23	0.96	48
IR 3500	Utrecht	Eindh.	85	124	0.80	0.60	0.69	132
AR5200	Deurne	Tilb.Wt.	20	85	0.55	0.27	0.94	77
AR6400	Weert	Eindh.	4	63	0.40	0.23	1.00	81
AR9600	Utrecht	Eindh.	- 1	62	0.41	0.19	0.96	62

8.3 Explanations

Unlike the Japanese Shinkansen system, most of the European High Speed network is "open", with trains running on the conventional network before and/or after their run on the high-speed lines.

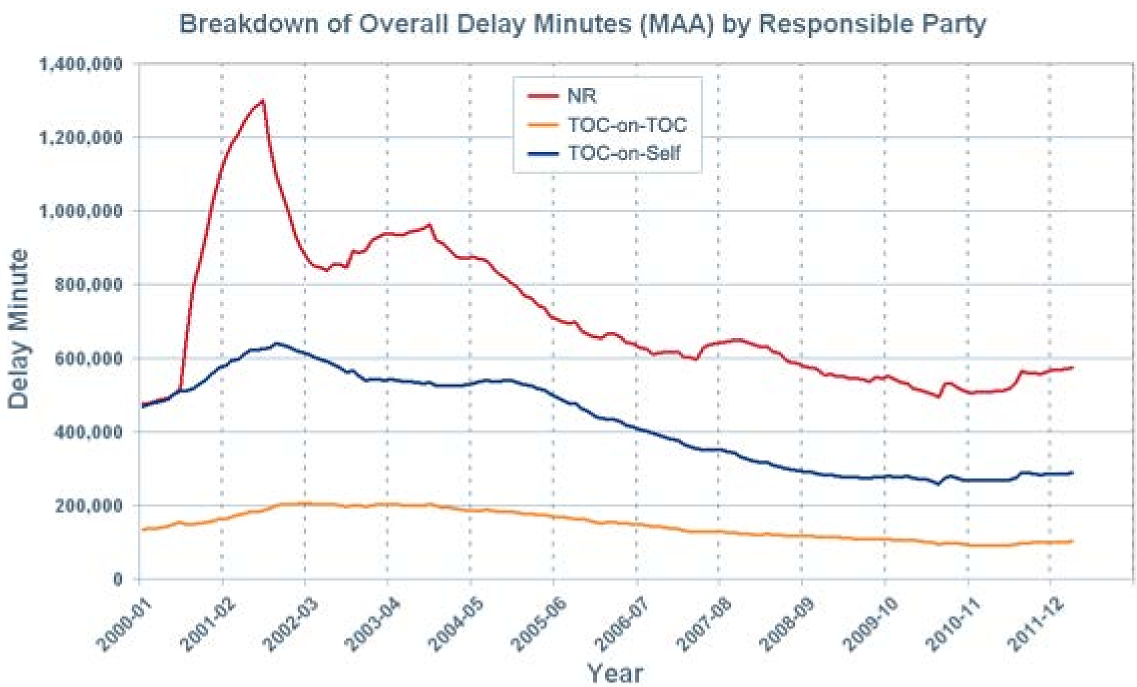
The exception is the Spanish High Speed network which, due to the track gauge difference, is "closed", the HST not being mixed with conventional trains on the rest of the network, which they cannot access. Along with a relatively low level of traffic (6 million passengers per year on the Madrid – Sevilla line, open in 1990), this chiefly explains the very good on-time performance, (and the fact that RENFE are prepared to reimburse the full price of the ticket in case of a 5 minute delay on Madrid – Sevilla, and 30 minutes on the other AVE services).

8.4 HS2 Expectations

HS2 operations will be partly on an open system, many of the trains beginning their trip at London Euston, running on the HS2 line, but continuing on the conventional network to serve destinations such as Liverpool, Preston, Glasgow, Edinburgh or Newcastle.

It is therefore interesting to investigate more accurately the reasons and the origins of the present European delay situation, to estimate if these reasons will still apply to HS2.

A first breakdown of responsibility can be made between the infrastructure manager (Network Rail in UK) and the train operators.



The total delay amounts to about 1 million minutes, of which 600,000 are Network Rail's responsibility (60%). The rest is shared between TOCs, a TOC being responsible for ¾ of its own delays (30% of the total), and ¼ being attributed to other TOC (10% of total).

In a perfect HS2 world, where the infrastructure would be faultless and no delay at all would come from HS2 infrastructure failures, only Network Rail routes would be concerned by the first item. We can assume that the trips of High Speed Trains outside HS2 (on Network Rail) would be approximately ¼ of the total, and therefore the infrastructure cause would be divided by 4.

We will also consider, optimistically, that the HS trains themselves will not have failures causing delays, and that this item is reduced to 0.

The TOC-on-TOC transmission of delays will of course remain identical, but only on ¼ of the total length of trips, and therefore also divided by 4.

We can therefore expect a far better percentage on HS2, equal to 17.5% of the general UK performance (1/4 of 60% for Network Rail, thus 15%, 0 for High Speed TOC, ¼ of 10% for TOC-on-TOC on the conventional network, thus 2.5%),

If we assume a 10% on time performance (10 minutes) on long distance in the UK (this is also somehow optimistic, as we have seen with ECML and Virgin Trains figures), this means that approximately 2% of the High Speed trains using HS2 would be delayed by 10 minutes or more: this means approximately 14 trains per day would be delayed by 10 minutes or more.

In a study on the "Delay Distribution in Railway Stations" conducted in the University of Delft and presented in a Transport Research Conference in Korea in July 2001, the authors concluded that the delay distribution followed a "Normal" law, and gave examples and evidence on this assertion, and that the density estimate would therefore follow an exponential law.

Other authors consider that, since trains are normally not in advance (or the advance is in all cases limited, when the delay is not), the distribution law should be Log-normal rather than Normal, of a Poisson's law, but that does not significantly affect the density estimate.

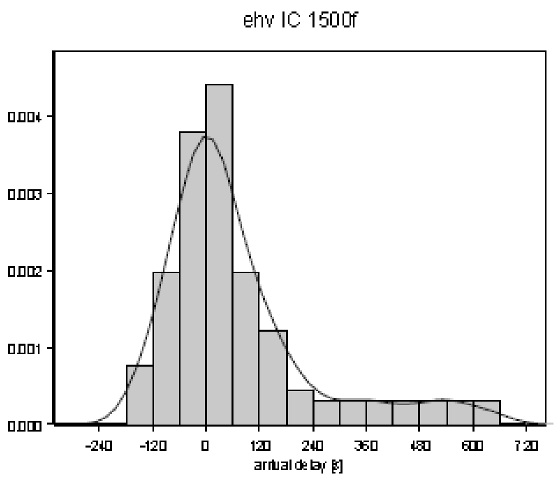


Figure 5. Histogram and kernel estimate of the arrival delay of IC 1500 Heerlen-Den Haag at station Eindhoven (September 1997)

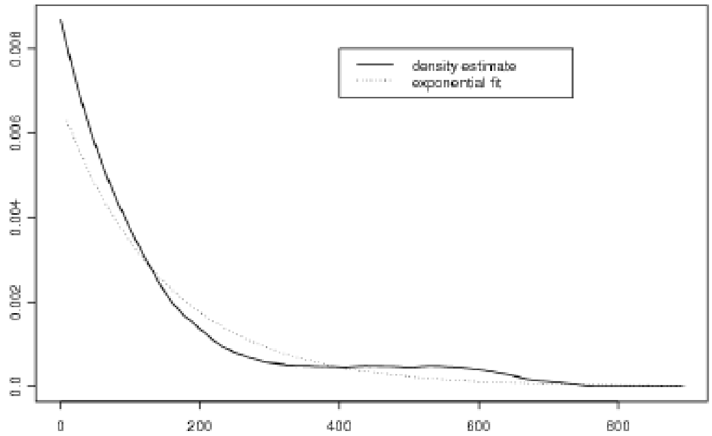


Figure 7. Density estimate and exponential fit of the late arrival delay of IC 1500 Den Haag-Heerlen at station Eindhoven (September 1997)

To conclude on the distribution of delays: various studies suggest that there are a great number of small delays (less than 1 or 2 minutes) that are neither known nor counted.

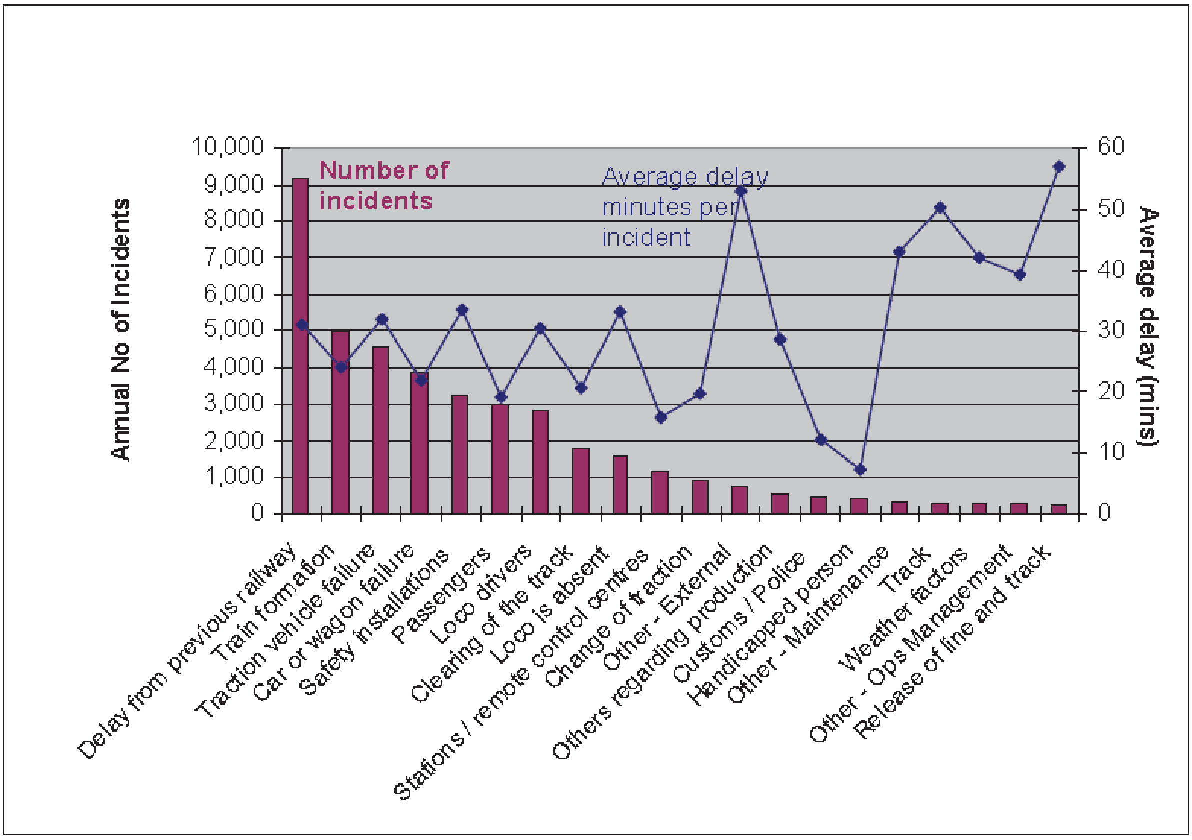
In the chapter about placing train paths, we have recommended that in the southbound direction, some significant intervals be kept blank in order to be able to accommodate late trains from remote origins, which could be on average 3 per day (10 minute delay).

Obviously, we do not at the stage have the required material to build a more accurate estimate of the smaller delays, in particular the delays smaller than one single minute, which could be critical for converging junction operations.

The detailed arrangement of paths, the interval between them according to the respective origin of the trains, and the training and instructions given to the drivers will be very important to ease the situation, that will have to be carefully studied.

A breakdown of delays by cause in the UK is provided below.

It is noticeable that, out of 40,000 delays, passengers themselves account for 3,000 (7.5%), with an average cumulative delay of 20 minutes (may be spread on several trains), and handicapped persons for more than 500, with a 7 minute delay.



In conclusion, we should point out that a 98% on-time performance is extremely high, practically unknown on the European High Speed network, and only comparable to Japanese and Spanish results, both in different and more favourable conditions.

This goal may be achievable, but it will require additional studies, principally on the potential external causes of delays (those occurring on Network Rail) and on the solutions to mitigate the consequences. Much attention will have to be given to path arrangement and driver behaviour. Of course, departing on time from stations will be of critical importance, and passengers' help will be required, in their own interest, so they are sufficiently disciplined to make the system operate more smoothly.

9 Conclusions and Recommendations

Any new railway has to assess the day-to-day operating reality of the line as well as the theoretical capability of the infrastructure. In our analysis we have attempted to offer the perspective of the train operator as well as the railway engineer.

We started this analysis with a short historical perspective, which reminded us of the facts that the demand for high-speed rail infrastructure and rolling stock will undoubtedly result in technological developments from which HS2 can benefit. The development of ETCS has not yet proven its value in terms of line capacity enhancements, but then that has not been its design development priority. There is no reason not to be optimistic.

9.1 Feasible headway

We looked in detail at the assumptions HS2 have made in relation to headway. It would be useful to standardise the assumptions and terminology applied, particularly in relation to duration to be allocated to the update of the movement authority.

We have taken forward two scenarios in relation to movement authority update time, to establish the impact that has on the calculation of capacity.

Timetables with 18 trains per hour and per direction, with trains running at a maximum speed of 360 km/h, appear to be feasible, even if we take input parameters that are less optimistic than those of HS2 Ltd (effectively increasing minimum headway in most cases by 10 seconds).

The most critical situation is that of slowdowns on line. Capacity losses due to slowdowns must be minimised by dividing the braking sequence into a series of discrete steps, although this approach leads to some increase in overall journey time (generally between 1 and 3 minutes, depending on the initial and target speed). In the case of permanent slowdowns, both capacity loss and journey time increase can be significantly reduced by the installation of shorter track sections (for a greater financial cost, of course).

However, even with somewhat less optimistic parameters, and rather significant temporary slowdowns (where track section length cannot be adapted), solutions can be found to maintain 18 trains per hour.

ATO (Automatic Train Operation) rather than manual driving could lead to an additional decrease in headway: not only would the delay related to response time be lower, but warning against the braking intervention curve in the case of ATO would not be needed, as no margin is needed between the desired and the in-practice curve. Nonetheless, the current guidance on ETCS for Great Britain [4] indicates that the driver controls the train, and that the ETCS onboard equipment automatically applies the brakes (as needed) only if the driver fails to do so (paragraph 4.6.2.2). Indeed, in the case of manual driving, initially Service braking is tripped by Service Braking Intervention (SBI, which is not safety critical), even before emergency braking is tripped by Emergency Braking Intervention. The SBI could be inhibited in the case of ATO driving and thus an even further benefit could be provided as compared to manual driving.

9.2 Recommendations

Among the various solutions to increase "real life" operational capacity while protecting punctuality, we suggest the following solutions:

- Assist drivers in achieving punctuality, then request them to follow their schedules and target speeds with a very high degree of precision, not forgetting the duration of stops in stations.
- Provide drivers with a very precise working timetable.
- Request station and control centres staff to dispatch the trains on time (target: actual departure within 5 seconds of the timetable time). This includes performing in due time all pre-departure steps.
- Constantly monitor the actual service and quickly take corrective measures.
- Place an adequate number of reserve trainsets at strategic locations during operating hours. In the case of a rolling stock breakdown, the presence of a reserve train nearby can keep delays down to an acceptable period (less than half an hour), where otherwise a cancellation or a very long delay would have been unavoidable. Clearly, the placement of reserve trainsets must take into account the different trains running during peak hours: high speed captive trainsets will not be able to replace compatible trainsets running on the classic network.
- Design infrastructure with an eye towards operational flexibility: supply sufficient crossovers, platform edges, etc., to cope with a wide range of service patterns.
- In the timetabling process, position properly the recovery margins:
  - In the northbound direction, maintain a regular spacing between trains. This will make it possible to quickly recover small delays and return to a normal service.
  - In the southbound direction, keep train paths closer together, in order to allow for occasional large gaps. As discussed above, in this direction there is more potential for major delays for trains coming from the classic network. Although these delays will necessarily be propagated to closely following trains, the timetabled gaps make it possible to swiftly return to normal service.
- Whenever possible, attempt to timetable consecutive trains that take a junction in the same direction, so as to avoid delays related to point movement.

9.3 Further work to be carried out

In relation to the UIC guidance, it may be possible to accept higher operational to theoretical capacity ratios, but before so doing, **a thorough assessment of the robustness of service scenarios should be conducted**. This would enable full account to be made of the UIC guidance for off-peak as well as peak services and enable the delay risks of expansion of 18tph throughout the day to be explored in further detail. This assessment should:

- Define timetables running during peak periods, including arrangement of various services within the hour in both directions.
- List the specific potential threats on the punctuality of each type, and expressing in minutes the delay caused by the most probable minor events.

- Simulate the operation of the overall HS2 Y network and the robustness of the envisioned train diagrams for each typical operational disturbance, modifying the time timetables as necessary in function of the results.
- Take into account track layout, ***most importantly the capacity of the West Midlands Delta Junction*** (discussed in chapter 7).

The Y network will be faced with a number of challenges that have at this date never been dealt with in an existing railway (18 tph at 360 km/h, but also the problems associated with the West Midlands Delta Junction), and an assessment as described above is absolutely necessary to draw out hidden issues and establish a high speed rail system that is clearly feasible.

Furthermore, this preliminary work may also contribute to testing and approving contingency plans, ready to be used "on the spot" by operational personnel.

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Appendix 1: Presumed service specification

The following figure, drawn from the document "Economic Case for High Speed Two" [14] depicts the proposed train services assumed in Phase 1 of HS2, when the new infrastructure will only extend from London to the West Midlands. It illustrates the services available using HS2 at any given hour.

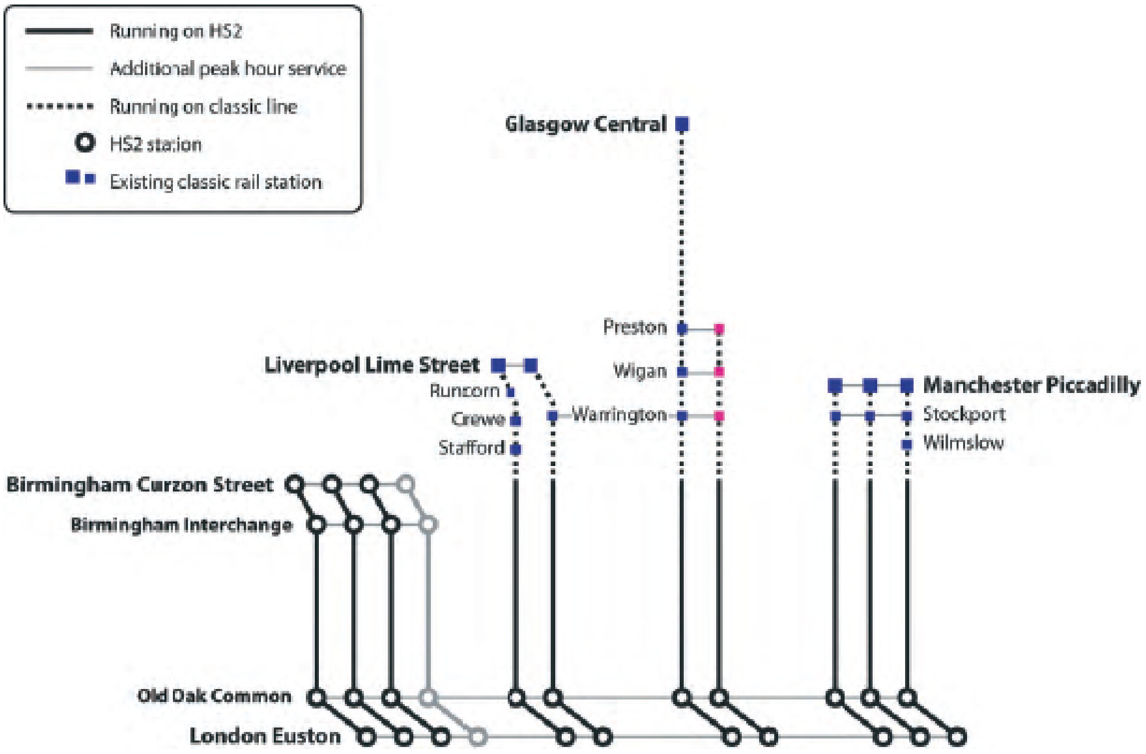


Figure A1 – Service specification for HS2 (London – West Midlands)

Assumed service specification in Phase 1 (London – West Midlands)

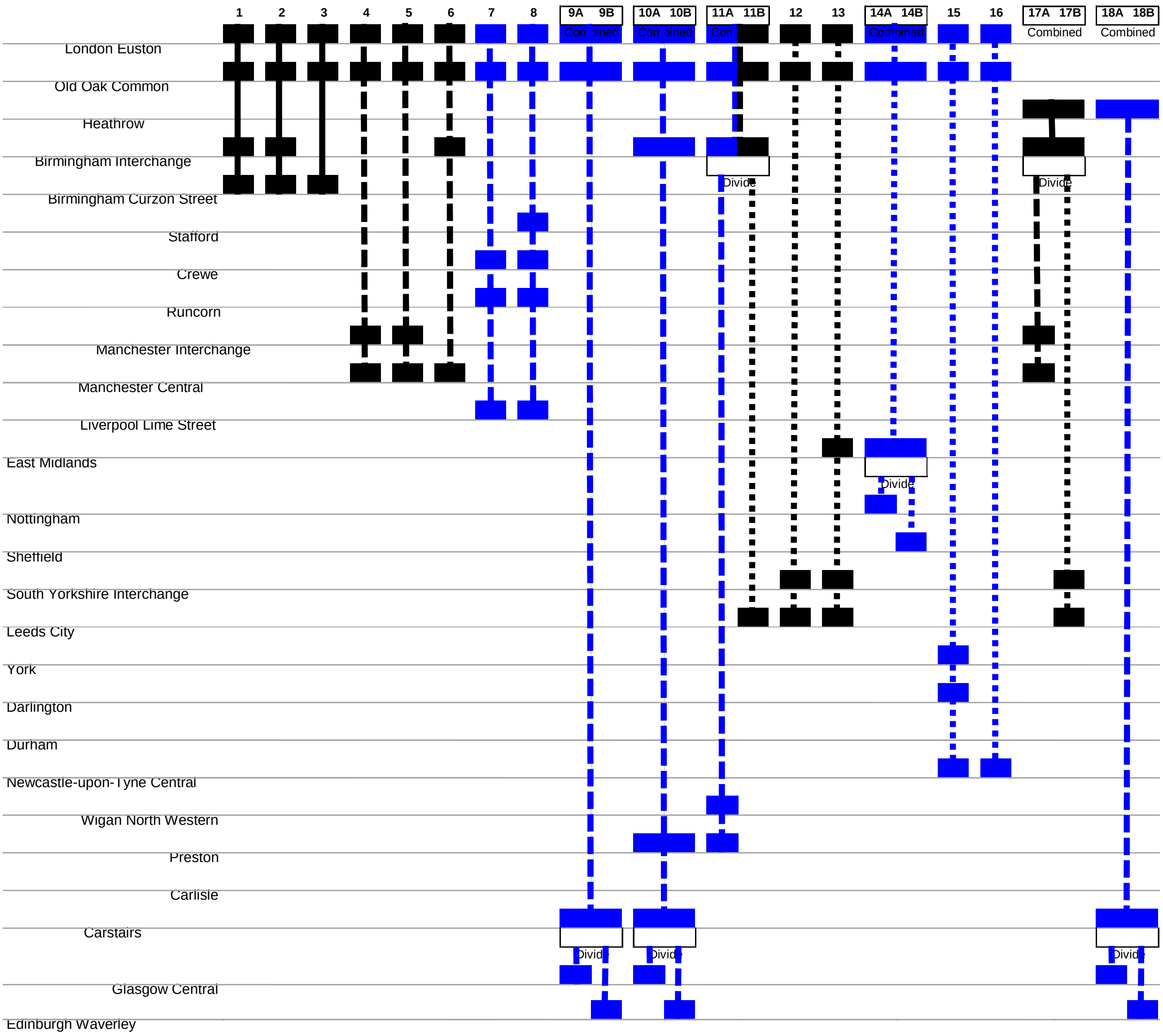
The following figures represent a specimen service specification developed for modelling purposes for phase 2 operation: London-terminus services (Euston or LHR) and Birmingham Curzon St. Terminus services [19]. Hourly services are represented. This service pattern will be provided throughout most of the day.

VARIATION Y52

Description **Base Case Y - Classic to Scotland via West Coast, Classic to Newcastle.**

Commentary resents an hourly service pattern.
= captive HS train (GB or GC gauge)
= classic-compatible HS train (UK gauge)
= London - West Midlands only
= Western branch
= Eastern branch

[redacted]

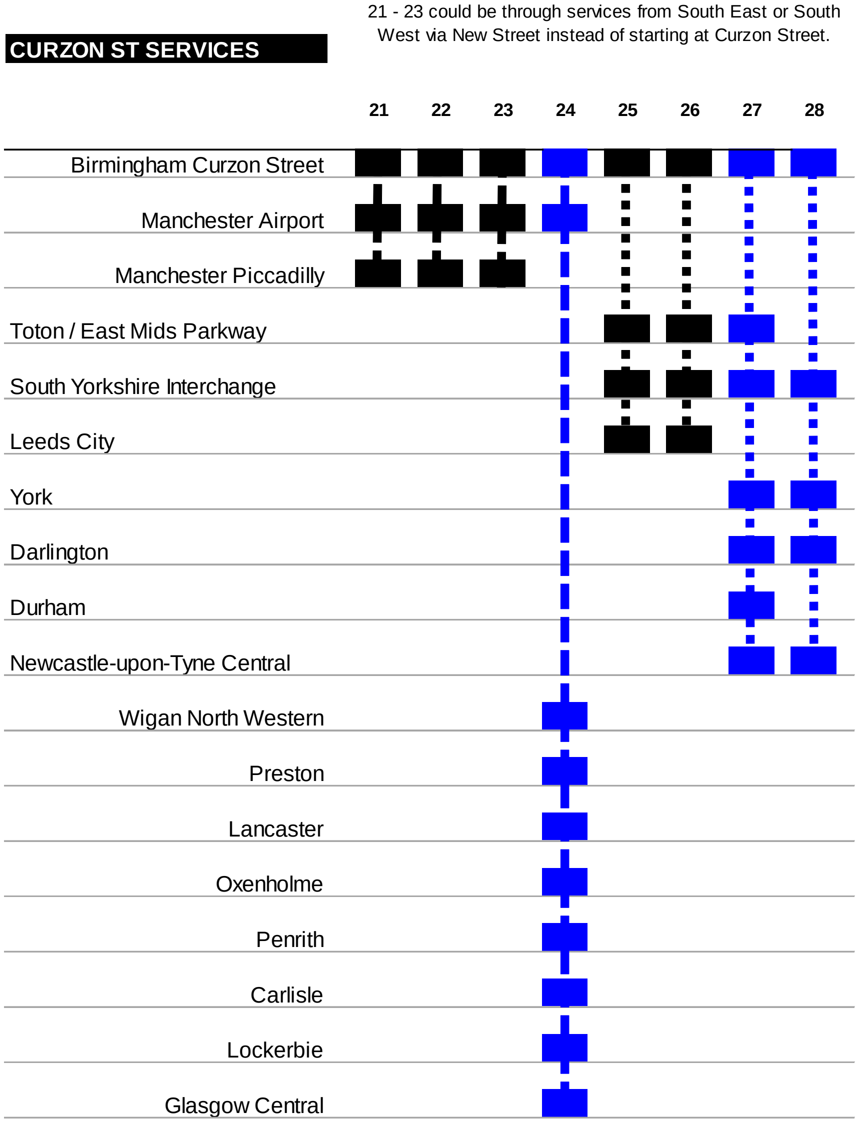


Assumed service specification in Phase 2 (London services)

VARIATION Y52

Commentary Represents an hourly service pattern.

- ■ = captive HS train (GB or GC gauge)
- ■ = classic-compatible HS train (UK gauge)
- = London - West Midlands only
- = Western branch
- = Eastern branch



Assumed service specification in Phase 2 (Birmingham Curzon St. services)