

High Speed Two Ltd

Signalling Headways and Maximum Operational
Capacity on High Speed Two London to West
Midlands Route

Revised and Updated 8th August 2011

Converging Diagrams added / typographical errors removed
14th October 2011

Version 3.1. Final

Andrew McNaughton

1. Scope

This paper sets out the base assumption of technical capability of the trains, infrastructure and control system specified for HS2 on the route between London and the West Midlands in order to assess the maximum capacity at 360kph (225mph) based on current technical capability. In addition potential improvements in the capability of both trains and control systems that are considered reasonably likely within the timeframe of 2032-3 (i.e. the date published by Government as the opening date of the route sections beyond West Midlands) are identified to present conclusions on ultimate achievable capacity of the trunk section, at 360kph and 400kph.

2. Headway Definition

The signalling headway between the trains is defined as the time between two trains passing the same location on a railway line at a defined speed profile. Whilst there is a theoretical calculation based on the inbuilt technical capability of the system, the actual headway is dependant on various location and system specific factors including, but not limited to, differing maximum speed and braking capabilities of trains, gradients (affecting stopping distances), granularity of train detection, junctions and operational stopping patterns.

The published technical and operational specifications underpinning the Government's consulted proposals include operation by trains with a single performance capability in terms of speed and braking characteristics and the absence of intermediate stations. Therefore some of the factors that affect practical capacity can be discounted. In addition, the infrastructure design for stations and junctions has been developed with sufficient platform capacity, approach tracks and grade separation to avoid conflicting movements.

The minimum signalling headway of the route will be defined by the worst case location or condition necessary to maintain safe separation based on maximum permitted speed between trains operating at the defined operational speeds. It is taken as the time between the front nose of successive trains passing any point along the line at the defined operational speed.

The practical planned maximum operational capacity is less than the sum of trains at minimum headways to allow some margin for day to day variability in operation including promptness of train dispatch, driving style etc. This is separate from timetabled allowance for delay which is captured in planned journey time, either at specific locations, principally before final destination or using the wider practice, adopted in most high speed rail operation, of timetabling trains at a percentage of maximum permitted speed.

3. Technical Factors

With a fixed block train detection system (assumed as track circuits or axle counters) the control system will detect the moment the rear wheels of a train of maximum length passes into the following track section. Until that moment the train can be at any point within the length of the first train section and has to be assumed at the most adverse position (i.e. at the start of the section).

The Train Detection (TD) system confirms the train has cleared the first section and reports this to control system. The latter updates the Movement Authority (MA) for the following train and transmits this to it by GSM-R radio under ETCS level 2. Until this moment the following train has to proceed with the capability of stopping before the start of the now cleared first track section. There are a number of processing and transmission actions by the train control system for which time has to be allowed.

The minimum stopping distance of the following train, in addition to its technical braking capability from its actual speed including any influence of gradient, will include the reaction time of the driver or Automatic Train Operation (ATO) system to receiving a command to stop the system; the reaction time of the system should the driver (or ATO system) not respond in that time; and the time for the brakes to build up to full effect.

Additionally there is a degree of uncertainty of the exact position of the train along the line. Whilst this is reset at the point of passing each European Train Control System (ETCS) balise group, during its passage between balise groups it is dependant upon on-board odometry which has a technical accuracy tolerance. The worst case for this positional tolerance is assumed as being that which could build up over the full distance between balise groups to the moment before reaching the next balise group (whereupon the positional uncertainty is eliminated). Whilst only under-estimation of distance travelled is adverse, in practice the full 4% range between maximum and minimum limits is often assumed. Even with this conservative assumption, at high speed odometry tolerance represents less than one second – and could be assumed to be zero by appropriate placement of balises at key headway locations.

With ETCS it is possible to locate the 'End of Authority' (EOA) in a different location to the 'Supervised Location' (SvL) – in signalling terms this is equivalent to a signal overlap. The EOA is defined as the location where the train is supposed to stop with the driver/ATO following the ETCS speed supervision curves – and this is generally where the block markers will be positioned (to facilitate degraded mode operations). The SvL is defined as the point in which the train is guaranteed not to pass. The distance between the EOA and SvL can be variable and used to provide additional tolerances.

For the purposes of this report an assumed EOA to SvL distance of 300m is considered (and is additional to other tolerance such as Odometer tolerance). The train would therefore take another 3 seconds to traverse this additional distance at 360kph.

4. Key Technical Parameters

4.1. Reference Train

Maximum permitted speed = 360kph (100m/s)

Maximum length = 400m

Allowance for driver reaction / response time = 6 seconds

Response time of Automatic Train Operation (ATO) = 3 seconds

Brake actuation time = 3 sec

Braking retardation rate assumed for headway calculation = 7%g
(0.687m/s²)

Maximum braking retardation rate = 9%g (0.88m/s²)

4.2. ETCS Level 2 Control System

Train detection (TD) system reporting time = 2 seconds

Interlocking processing and transmission time = 5 seconds

Movement authority (MA) transmission time = 2 seconds

Train On-Board ETCS reaction time = 1 seconds

Odometry error +/- 2 %

End of Authority (EoA) to Supervised Location (SvL) = 300m

4.3. Limiting Infrastructure Characteristics

Maximum permitted diverging speed at turnouts = 225kph (62.5m/s)

Standard length of track sections for train detection = 1600m

Length of track detection section at turnout = 400m

Turnout operational time = 9 seconds

Turnout locking and processing time = 3 seconds

Gradient profile taken from Route 3 details as published for consultation.

Summary of Operational Parameters

Headway Element	Technical Element	Value	Headway Contribution(s)	Comment
Braking Distance (BD)		7280m	73	Braking rate 7%g (0.687ms ⁻²) Value for braking to rest from 360kph (100ms ⁻¹) (Bespoke calculation used where required)
Acceleration Distance (AD)			Bespoke	Distance required for the train to re-gain linespeed Values taken from HS2 reference train performance data.
Train Protection (TP)	Overlap	300m	3 (@360kph)	Difference between End of Authority and Supervised Location (EoA and SvL)
	Odometry Tolerance	+/- 2% (80m)	1	Worst case positioning
Total			4	
Train System (TS)	ETCS response time	1s	1	Receipt of a MA message to interface with the train systems / Driver Machine interface
	Brake Actuation	3s	3	Time from brake command to start of retardation
Total			4	
Driver Response (DR)		6s	6	Time from DMI display to actuation of controls. (Note for acceleration this also includes train system response of 2s).
Driver Assist Response (DAS)		3s	3	Time from system input to interface with train systems
Train Location Section (TLS)		1600m 400m	16s 4s (@360 kph)	Length of the infrastructure based sections used to identify train positions – Open route and Junctions
Train Detection (TD)		2s	2	Detect and report/process at interlocking
Junction Operation (JO)	Interlocking Processing	3s	3	Issue instruction to move, report/process detection at interlocking
	Junction Movement	9s	9	Trackside mechanical movement
Total			12	
Issue Movement Authority (IMA)	Interlocking / RBC Processing	5s	5	Interlocking processes route / transfer to RBC. RBC evaluates and constructs MA
	RBC Transmit	2s	2	MA processed, transmitted and received by train
Total			7	

4.4. Ratio for Calculating Maximum Capacity

The maximum capacity in trains per hour (tph) is taken as no more than 75% of the number of train paths per hour at the worst case signalling headway in line with recommendations from the UIC (International Union of Railways).

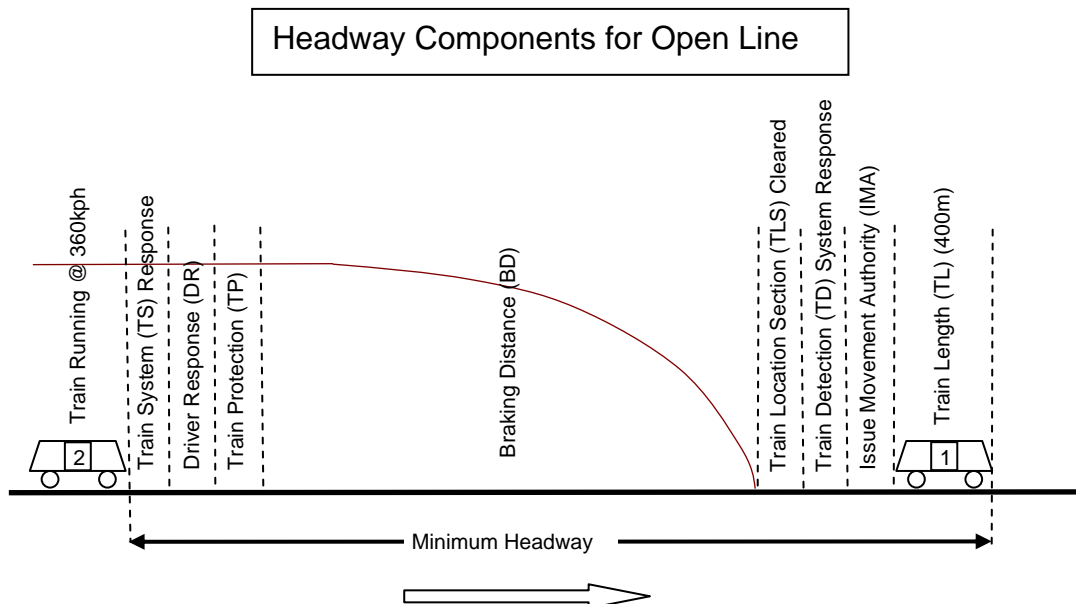
5. Calculation of Signalling Headway

5.1. Open Line

This is the general service condition calculated for the maximum permitted speed. The gradient is treated as level given the absence generally of long continuous sections of rising or falling gradients on the route section over which 360kph (or 400kph) would be permitted.

These factors are shown in the diagram below:

:



Using the technical assumptions:

The time for the first train of maximum length to traverse a standard track section and then to clear it is 20 seconds $(1600\text{m}+400\text{m}) / 100\text{m/s}$

The braking distance of a train is defined as $s=v^2 / 2a$. Assuming a service braking rate of 7%g (0.687m/s^2) this gives a service braking distance of 7280m. A train travelling at 100m/s will take 73 seconds to traverse this distance.

Therefore signalling headway is $(20 + 4 + 2 + 7 + 6 + 4 + 73) = 116$ seconds

The maximum number of signalling paths per hour is then $3600 / 116 = 31$.

The maximum operational capacity is $31 \times 0.75 = 23$ paths per hour.

5.2. Approaching a Diverging Turnout

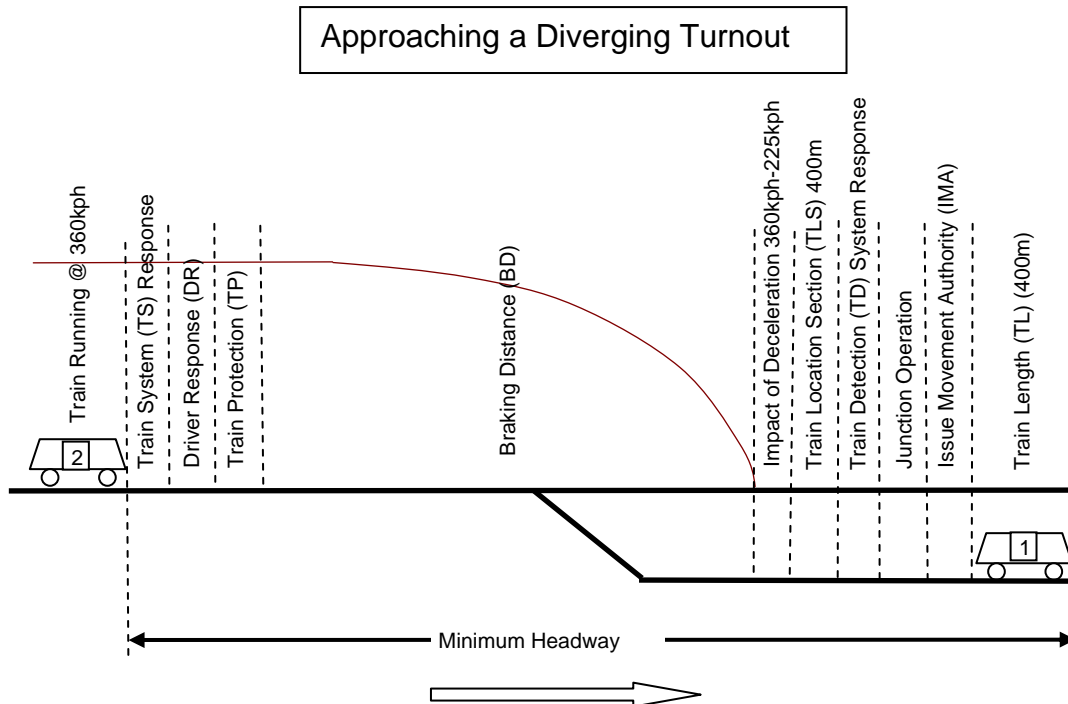
The specific condition is that of approaching the diverging turnout at approx KM153.5 in the northbound direction for trains slowing to stop at Birmingham Interchange Station. The route to the south of the diverging point is undulating but within the overall braking distance is rising slightly. Given the gradient profile, for the purposes of this condition, the line is considered level and any potential positive impact of slightly rising gradient ignored.

The worst case is that of a first train slowing to diverge at the turnout but the following train continuing at full speed on the through route. Although there is a reduction in maximum permitted speed on the through route at Km158, the second train would receive MA for full speed during its approach to the turnout location.

The situation is different from simple open line in that the operation of and train detection around the turnout has to be considered.

The first train would slow using service braking to pass across the turnout at reduced speed (assumed 225kph). A short train detection section is provided, assumed conservatively here to be 400m long. When the train is positively detected to be clear of the turnout, it can operate to restore from diverging to normal (though) running. The time allowed includes for the movement of the switch rails and locking and detection. After that the control system can update the MA for the following train to enter that track section containing the turnout.

These factors are shown in the diagram below:



The time for the first train to slow is $(100 - 62.5) / 0.687 = 55$ seconds.

The distance travelled in this time is 4461m which the following train travelling at 360kph would cover in 45 seconds, thereby catching up the first train by 10 seconds. Then the first train covers the 300m between the EoA and SvL and passes over the turnout track section (400m plus the train length of 400m giving 1100m in all) in 18 seconds, during which time the following train has caught up a further 7 seconds having covered the same distance in 11 seconds. Thus the headway has closed by $(10 + 7 =)$ 17 seconds.

After being commanded, the points may then start to change after which locking and detection is confirmed and transmitted to the interlocking, which takes 12 seconds in all. The interlocking processing and MA updating for the following train then are as previously.

The signalling headway of the second train is thus:

$$17 + 2 + 12 + 7 + 6 + 4 + 73 = 121 \text{ seconds}$$

In the worst case, alternating trains could be signalled for diverging and through line running. This would give a combined signalling headway of two trains every $(121 + 116) = 237$ seconds. If two successive trains were slowing the absence turnout operation time would produce a shorter signalling headway.

Therefore in the worst case the maximum capacity of the line at this point would be $(3600 \times 2 / 237) \times 0.75 = 22$ paths per hour.

In practice it would be more likely to timetable sequences of trains to lessen the impact of such unnecessary continual turnout operation but that is not relied upon for this calculation.

5.3. Approaching a Converging Turnout

At both Birmingham Interchange and further north, trains would be converging on the core section through 225kph turnouts. Trains on the through route would be travelling at up the maximum permitted speed which is constrained by a section at 350/320kph. However, for the purposes of this paper and as a general worst case the maximum speed is taken at 360kph.

The calculation is from the moment a non-stop through line train has been detected as passing over the converging turnout at up to 360kph.

The time delay before the MA is updated, and allowing for reaction times as before is $(2 + 12 + 7) = 21$ seconds.

The second train approaching at a nominal 225kph would require a braking distance of 2844m plus 300m between EoA and SvL which it would cover in 50 seconds at 225kph. At the same speed it would traverse the turnout track section plus its length (800m total), taking a further 13 seconds.

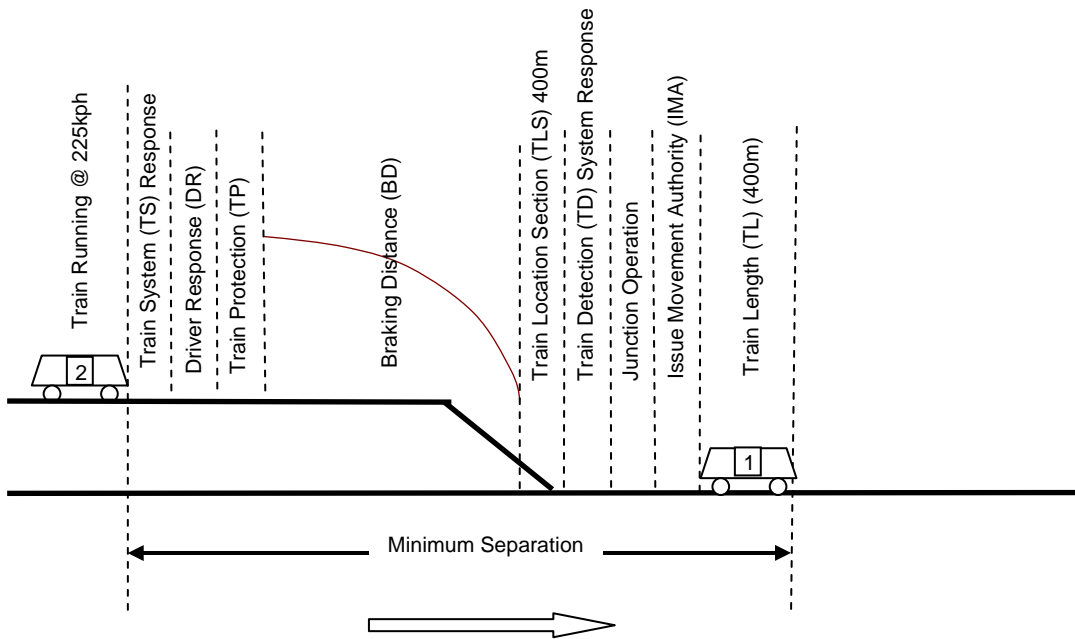
Once through the turnout the second train would receive an updated MA for full speed and start to accelerate. It would continue to lose time to the first train until it achieved the same speed. From 225kph this would take some 264 seconds and 22km, a distance covered by the first train in 220 seconds. Therefore the gap between the trains would widen by up to a further 46 seconds.

Thus the minimum signalling headway between a through non-stop train and a following train converging at 225kph would be $(21 + 50 + 13 + 2 + 46) = 132$ seconds.

If successive trains were scheduled as through and converging services then the combined headway would be $(116 + 132) = 248$ seconds. Whilst in practice trains would be timetabled to avoid this worst case situation, in this instance the maximum operational capacity of the line would be reduced to $(3600 \times 2 / 248) \times 0.75 = 21$ paths per hour.

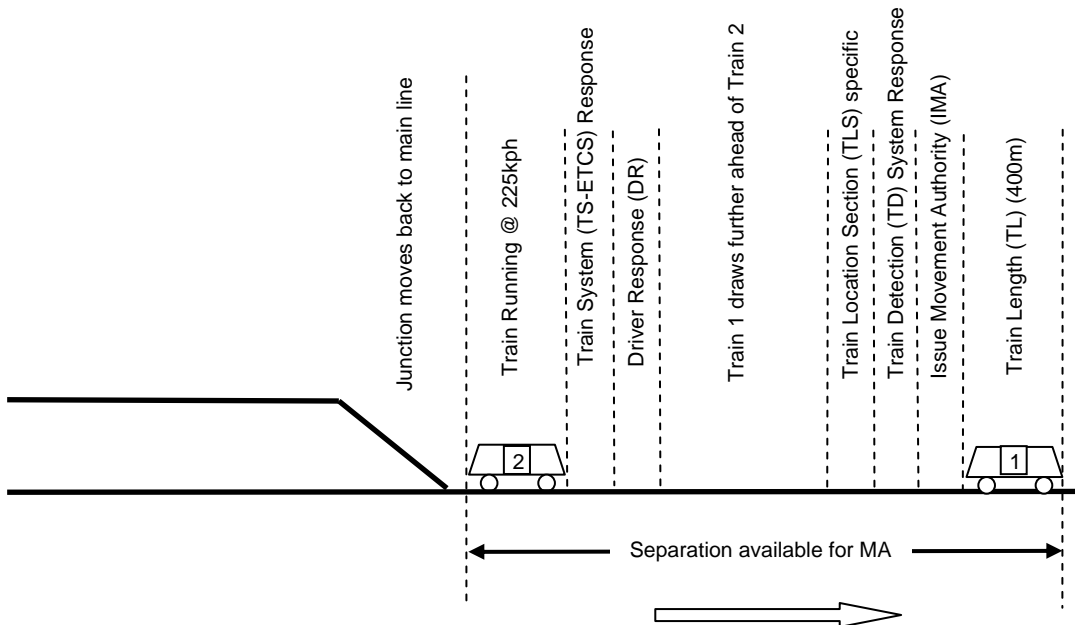
These factors are shown in the diagrams below.

Headway Components for Converging Turnout (1 of 3)



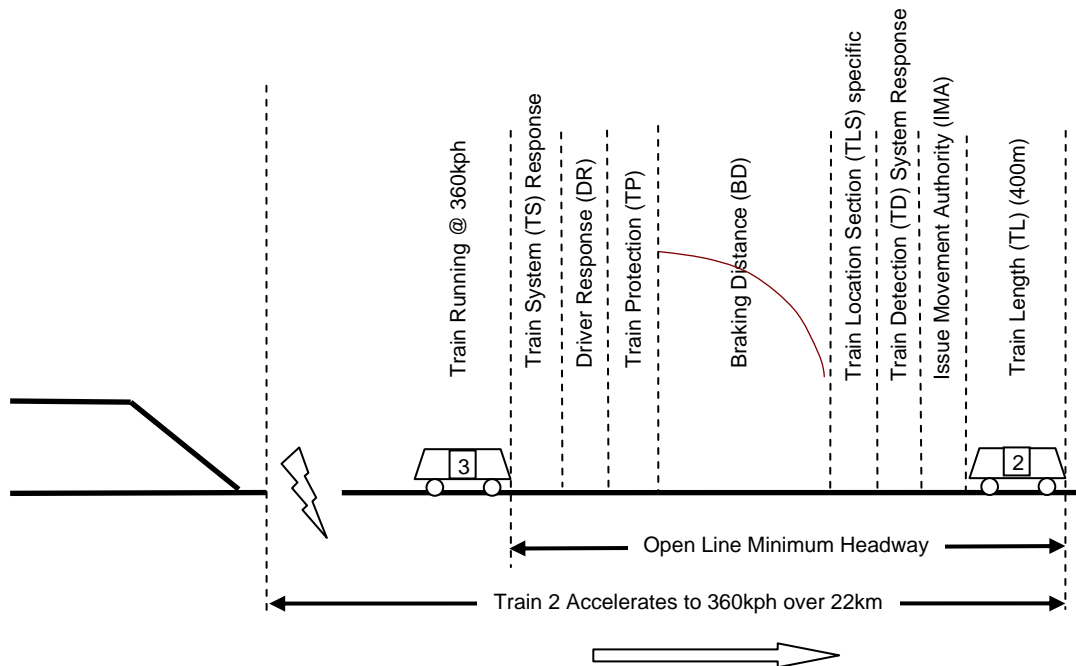
Stage 1 : Minimum separation train 1 to train 2, as train 1 clears the turnout and train 2 receives MAs to approach the junction unimpeded @225kph

Headway Components for Converging Turnout (2 of 3)



Stage 2 : Train 2 clears the junction and applies MA (first of a sequence) allowing unimpeded acceleration to 360kph

Headway Components for Converging Turnout (3 of 3)



Stage 3 : Train 2 attains 360kph, which defines the closest position of Train 3

Potentially as an alternative, the second train could be starting from a station stop at Birmingham Interchange accelerating to converge at 165kph or 225kph. The former would be the case if the acceleration track south of Birmingham interchange was limited to no more than about 2.5km before a converging turnout.

If this second train was accelerating towards a 165kph turnout onto the main line from a stop at Birmingham Interchange, at the moment the train would be receiving an update of MA its speed would be no more than 120kph and therefore its braking distance would be 792m. The time to cover this distance, the 300m EoA to SvL and the train detection plus train length of 800m would be 45 seconds. Accelerating having passed over the turnout from 165 kph to full speed would take some 25.5km and 324 seconds. The gap from the first train would have widened a further 69 seconds during this period.

Therefore the signalling headway between a through non-stop train and a following train converging at 165kph, accelerating from a stand at Birmingham Interchange would be $(21 + 45 + 69) = 135$ seconds.

As before, if successive trains were timetabled in this way the combined headway would be 251 seconds which would give a maximum operational headway of $(3600 / 251 \times 2 \times 0.75) = 21$ paths per hour.

5.4. Effect of Downhill Gradient Section

In this case the minimum signalling headway is considered for open line running as in 5.1 but in the northbound direction over the area of maximum downhill gradient in the vicinity of Km52. The average gradient over the extent of service braking would be slightly under 0.9% therefore the braking distance is extended by approximately 15%. However, the maximum speed of trains at the top of the gradient is anticipated to be no more than 330kph due to the proximity of the Amersham tunnel which is limited to 320kph.

In this case the braking distance would be $(91.7^2 \times 1.15 / 2 \times 0.687) = 7038\text{m}$ which is less than the Open Line distance at full speed. Therefore it is not a limiting case.

If increased performance permitted up to say 350kph at the top of the gradient at some time in the future this distance then the downhill braking distance could be up to 7910m at 7%g. The additional distance is less than half the average block length used for earlier calculations for plain line. Therefore it will be possible to compensate for this additional braking distance by providing 800m train detection sections on this specific stretch of line instead of the 1600m proposed for sections of track approximating to level gradient.

6. Potential Improvements by 2032/3

The principal improvement anticipated is the potential adoption of ATO under driver supervision. Such systems are fully developed for other rail applications, principally for metros, with extensive operational experience over the last 50 years. They are not safety critical systems and the sole development activity would be to integrate such systems with the ETCS Level 2 control system.

Such development is seen as low risk, and it may be assumed that operation with ATO is achieved with the Day One (2026) service to build up specific experience on HS2 from the earliest possible date. The effect would be the reduction in the element of system reaction time represented by the allowance of driver response to MA commands. A reduction from the assumed 6 seconds to no more than 2 or 3 seconds (to allow for system response time) would be a realistic benefit.

Therefore by 2032/3 (and in all likelihood some time before 2026) it is considered that the signalling headway would be reduced for each train by a minimum of a further 3 seconds. Given that the worst case capacity highlighted above is 21 trains per hour (rounded down) associated with slowing to or accelerating from turnouts, the reduction in headway through adoption of ATO could permit a maximum capacity of up to 22 trains per hour.

The figure of 7%g has been used throughout for braking rates although the Reference Train is shown as achieving 9%g reliably. It could be expected that this rate would show further improvement in a 400kmh design but factors

including passenger comfort could be expected to limit higher braking rates to non-routine operation such as emergency braking. Certainty of high braking rates can be achieved in low adhesion conditions through use of eddy current braking in addition to the normal regenerative system.

Other likely train technology improvements are anticipated to centre on the brake actuation which may be expected to improve. Three seconds is relatively slow for an electrical system therefore a future value of no more than 2 seconds could reasonably be expected. The service braking rate on 9%g might also improve further but the limiting factor would start to become passenger comfort at much over 1.1%g.

Considering the effect of adopting 9%g braking (0.88m/s^2) along with 400kph (111.1m/s) maximum permitted speed, the Open Line braking distance would become $(111.1^2 / 2 \times 0.88) = 7013\text{m}$. The time to cover this distance at 400kph would be 63 seconds. The initial 2000m of train detection section plus train length would be covered slightly faster in 18 seconds. Assuming ATO was being operated:

Signalling headway would be $(18+4 +2 + 7 +3+ 4 + 63) = 101$ seconds.

From this it may be seen that the improved braking performance more than outweighs the impact of increasing maximum permitted speed to 400kph.

Capacity at the converging junction would be marginally improved by the higher braking performance. Greater benefit could be assumed from improved acceleration which could be from higher power or lower air and rolling resistance. A combination of these factors would be expected in order to produce a 400kph capability train design. In the absence of specific figures it would be prudent at this stage to assume no more than the 21 or 22 paths per hour already achieved with the existing reference design and the adoption of ATO.

.Further areas of improvement not relied on for this analysis but reasonably likely in the medium term include reduced swing and detection time of turnouts and, more particularly, development of ETCS with moving block. Whilst the former would improve signalling headway at diverging and converging junctions, but only marginally, the latter would not, being only of significance on the open line. Therefore the benefit of development of moving block detection should be seen principally as reducing the extent of fixed infrastructure, hence cost of maintenance, at some point in the future.

7. Conclusions

On opening of the first section of the network, from London to the West Midlands, operating up to 14 train paths per hour in each direction is comfortably achievable, allowing for the limited number of trains operating wholly or mainly on dedicated high speed infrastructure and for the build up of experience in the first years of operation.

Upon opening of the sections of line to the Manchester and Leeds areas in 2032/3, operation with up to 18 train paths per hour in each direction would be reliably achievable without technical development provided the overall infrastructure system – speed and positioning of turnouts – is as currently proposed. However benefit should be taken from the early adoption of automatic train operation under driver supervision.

From a train control system perspective, more than 18 paths per hour, certainly up to 21 paths per hour could be timetabled. However, the network in 2032/3 would still have a significant proportion of trains using existing classic railway for material sections of their journey. Whilst it would be possible to account for the reliability risk by introducing additional time in those trains before joining the high speed network, thus insulating it from day-to-day perturbation to a greater extent, this would have a detrimental effect on overall journey times from the destinations concerned. Therefore it is still considered prudent to develop the Y network on the basis of 18 trains per hour normally.

The technical development of ETCS Level 3 (“Moving Block”) train control system would have potential benefit for reduction in lineside infrastructure and hence maintenance workload and cost. However it would be of little practical benefit to signalling headway at the limiting points on the network at junctions. Therefore it is not considered.

Operation at 400kph would be possible at some point in the future without compromising the capacity of the route given assumptions on train braking based on already existing capability. The limiting capacity would continue to be signalling headway at converging junctions.