THE FUTURE OF TRANSPORT

PROJECT REPORT CPR2282

Options for Capacity Measures/Metrics

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Contents

Executive Summary

Railway capacity is a prominent issue for government, railway industry and passengers, yet the industry has no standardised way of measuring it. The objective of this study was to find a set of measures that could provide both a means of tracking changes in the provision and use of the existing rail infrastructure capacity and a basis for incentivising Network Rail to increase capacity, whilst maintaining the right balance between capacity usage and performance. A measure can help by providing better understanding of this balance and demonstrating any improvement delivered.

The study was carried out in four stages:

- Literature Review and Stakeholder Discussions
- Workshop with ORR, DfT and Network Rail
- Analysis of a "Worked Example"
- Conclusion and Recommendations

The literature review revealed that extensive work in this area has been carried out by operators and academics, but the fundamental problem remains the same: That the theoretical capacity of a combination of track with a single type rolling stock can be calculated exactly, but the practical capacity of a route or network cannot be measured in isolation from the use to which it is put. A railway which carries homogenous services will always achieve higher throughput and better utilisation of capacity than one which (like much of the GB network) carries mixed traffic providing a variety of services with different origins, destinations, stopping patterns and performance characteristics.

The stakeholder discussions involved passenger operators, a representative of the freight industry, Network Rail, DfT and Transport Scotland as well as two regulators (OFWAT and OFGEM). Common views were that opportunities to run extra trains are sometimes missed because of perceived risk to performance and that the industry does need a capacity measure to set alongside PPM. There was divergence as to whether the current Timetable Planning Rules (TPR) and the related planning processes are fit for purpose and whether Network Rail takes a balanced view when considering applications to run extra trains. The governmental stakeholders believed that any capacity measure would need to be a regulated output to be effective. Most others believed that an indicator would be better. The view of the freight industry representative consulted was that the focus should be on path quality (average speed achieved) and on flexibility (the ability to change the plan at short notice).

A set of desirable characteristics, together with many suggestions for a good capacity measure were collected and the barriers to maximising the potential capacity of the network explored. The "loss of capacity" between theory and practice was mapped in a cascade (Figure 1), showing the stages in creating a timetable and the factors which

influence the amount of capacity that can be utilised at each stage. It is notable that Network Rail is not in sole control of any stage; all require co-operation with service specifiers and operators.

Prior to this study ORR had developed and consulted on outline concepts for capacity measures at four levels (Notional, Plannable, Capacity in Use and Throughput)[1]:

Throughput represents the services that actually run on any given day, taking into account the timetable produced by Network Rail, but also any additional short term requests accommodated (via the short term plan), any cancelled services due to incidents on the network and reflects the actual length of the trains. A large number of measures (or proxy measures) already exist in this space, (e.g. Passenger journeys, Passenger km, Number of freight train movements, Freight moved (tonnes), Distance covered (passenger and freight), Crowding (PiXC)) and early in the project, it was agreed that Throughput was out of scope.

Nothing from the first stage of work invalidated the remaining three concepts, and they were therefore turned into potential measures following the development of more detailed definitions. Each one was associated with a number of options which were taken through to the analysis stage. Analysis was based on a "worked example" – a software simulation of services on South West Main Line between Waterloo and Woking. The methodology was tested, values for the various measures were extracted and their variability over the route, with types of service, with time of day and with rolling stock type examined. Their practicability was then evaluated against the criteria established during the stakeholder discussions. Two of the proposals passed this evaluation and one did not.

"Notional Capacity" represents the maximum number of trains that could potentially run on a route, at a minimum safe distance and as a result of the physical nature of the infrastructure, using best performing rolling stock. The capacity measure proposed is aligned closely with the well-established concept of signalling headway and measures the maximum "green to green time" of any block in the given section. Network Rail has both the data and tools to calculate this value and already does so as part of its process for the improvement of TPR. It is used as an input to the assessment of "planning headway" but currently it is not separately declared. However, to use 'Nominal Capacity' as a useful indicator, changes would be needed to make it suitably reliable and comparable between routes. One recommendation from this study therefore is that the process be made more transparent, objectively defined and measured and not subject to subjective adjustment or rounding.

[1] Original definitions proposed by ORR and revised definitions developed as part of the project are included in Section 3 of the report

“Plannable Capacity” represents the maximum number of trains that could run over a route during a specific time period, based on the TPRs. The worked example (and in particular the methods needed to create a realistic value) brought out the problems with this concept. TPRs have to be applied selectively during the creation of the timetable, depending on the rolling stock type, stopping pattern and service sequence. Creating a standardised value for a route therefore demands the creation of a standardised service pattern, which is in effect the first stage of creating a timetable. The problem with this is that it requires detailed knowledge of the route and for judgement to be used in the selection and sequencing of the planned services. This will not meet the criteria for simplicity, low cost or objectivity and will inevitably be open to challenge.

“Capacity in Use” aims to measure the capacity actually delivered by the final timetable, taking account of the rolling stock used, service stopping patterns, frequencies and departure times. The capacity measure proposed uses data already available within the industry (some in the public domain) to show trains operated per hour per track. This can be measured at any timing point on the network. However it varies hour by hour and along the route, so a wide range of information can be extracted for a complex route such SWML (examined in the Worked Example). A possible enhancement is to add train length data (calculated from number and type of units or vehicles excluding the locomotive making up the train), so that train-metres per hour passing a point is measured. This would be a useful analogue for passenger capacity and would (for example) show the positive impact of train lengthening.

Recommendations for capacity measures are therefore:

- “Notional Capacity” – a standardised calculation based on non-stop signalling headway calculated using an appropriate simulation tool using an industry-agreed process and set of parameters including the appropriate rolling stock from a simplified list, to be published annually by Network Rail for selected subsections of Network Rail’s eight routes and updated regularly as part of the TPR review process; route sections can be defined in terms of two end stations or junctions and those operating close to capacity selected for inclusion, by agreement with the relevant TOCs and DfT; and
- “Capacity in Use” – values of train flow (trains per hour per track) measured at key points on each route, enhanced with train consist data to provide also “train metres per hour per track”, published annually for key nodes on the network.

The measures proposed above could be incorporated into a range of complementary measures for a route (probably split by train operator), bringing together “Capacity in Use” figures for the AM peak and PM peak with the appropriate performance and journey time values for the same route section, with the possible addition of throughput (see Figure 5).

The value in this approach would be in showing how capacity in use and throughput are changing (and are planned to change) over time.

1 Introduction

Railway capacity is an increasingly prominent issue for government, Network Rail, passenger and freight operators and users, yet the industry has no standardised way of measuring it. A key objective of this study was to find a measure or a small number of measures that, taken together, could provide an objective and valid means of tracking changes (improvements) in the provision and use by Network Rail of rail infrastructure capacity during CP6. Of equal importance is for the measure to provide a basis for incentivising the industry, and Network Rail in particular, to increase capacity utilisation, whilst maintaining the right balance between capacity use and performance. A measure can help by providing better understanding of this balance and demonstration of its improvement.

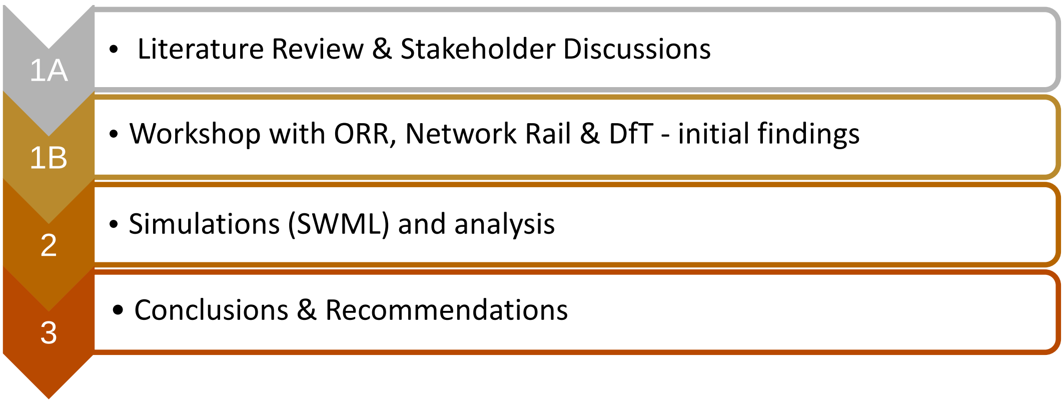
The capacity of a railway route is a complex emergent property of the system, i.e. it cannot be directly specified but can be defined in a number of different ways and is influenced by a wide range of factors and parameters. In this project "capacity" is used to mean the ability of a section of railway to carry trains. Often, discussions of 'capacity' refer to measures such as, 'seats' or the number of passengers carried, passenger train km, number of freight tonnes moved etc. In this project these are referred to as "throughput".

The capacity which a railway can achieve depends on the way it is used. A railway carrying homogenous services will deliver higher throughput/ capacity utilisation than one carrying a variety of trains with a range of different services and stopping patterns. The comparison of capacity that could be achieved within the constraints of the network configuration with what is actually being delivered is therefore complex and cannot be completely divorced from the user service specifications.

ORR has commissioned TRL to undertake a study to develop one or more capacity measures that can provide an objective and valid means of tracking changes (improvements) in the utilisation of the capacity of the Network Rail infrastructure during CP6:

- To enable a clearer view of whether Network Rail is delivering as much capacity out of the network as possible;
- To incentivise Network Rail to ensure existing capacity is being put to best use;

This study was carried out in four steps:



This report summaries the methodology, findings and recommendations for this study.

2 Literature Review and Discussions with Stakeholders

2.1 Literature Review

A literature search into the definitions and assessment of the capacity of railway networks and any metrics that have been proposed to support better management of the railway network capacity was undertaken through the following information channels.

- Academic papers available through the Library of Glasgow Caledonian University:
- SPARK, the Railway Industry Information resource managed by RSSB:
- Other industry sources and the Internet:

The Operation Planning Module from the degree course of the Institution of Railway Operators (IRO) was a useful source of relevant information.

The detailed report from the literature search is provided in Appendix A and a summary of the results is given below.

2.1.1 Capacity definition

Many of the papers identified looked at specific types of network operation, using analytical or simulation techniques to provide a basis for the assessment of capacity within a specified train service pattern. The consensus which emerges from published literature is that there can be no single, absolute measure of rail system capacity. The UIC asserts that “Capacity as such does not exist; railway infrastructure capacity depends on the way it is utilised”. The second part of this statement is clearly true. The first part might be better expressed as “There is no such thing as an absolute measure of capacity”; however useful measures capturing certain aspects of capacity provision and use could be developed.

2.1.2 Capacity Evaluation

The use of Capacity Utilisation Index (CUI) and UIC 406 methods for calculating the differences between the actual and compressed timetables for a specific network/route seem to be the most commonly used evaluation techniques. These approaches however contain some inherent weaknesses, including sensitivity to the length of the section being analysed and the complexity of performing these analyses through nodes. Other techniques primarily compared differences between theoretical, practical (planned) and utilised capacity, through a number of approaches, to determine where capacity is available, how this capacity was lost and what effect using this spare capacity would have on the performance of the network.

The National Rail Freight Infrastructure Capacity and Investment Study used volume-to capacity levels to identify the routes on the American Railroad system that are at, near or over capacity across the network. This is a potentially useful first step in communicating the status of the network and contributing to a better understanding of where capacity is needed and could be available.

2.1.3 Capacity Metrics

From this review it is clear that, although the most intuitive way of determining capacity utilisation is to establish the maximum number of trains operated over the network in a given time period, defining and measuring capacity using a single metric is challenging. A single measure cannot give any indication of the efficiency of utilisation or show the difference between potential capacity and that actually achieved. The review found a large number of both capacity and capacity utilisation metrics (Reference from Appendix A) across the literature that have been previously used for measuring the complex trade-off between the various influencing and conflicting factors associated with capacity. A combination of a number of capacity metrics could provide a range of useful indicators for the effective monitoring of capacity.

2.1.4 Summary of results

The literature paints an overall picture in which railways generally lack a detailed and accurate understanding of available capacity, usage and predicted demand. Unsurprisingly, there is no common view on the key drivers of capacity constraint, because the changes that would deliver higher capacity utilisation and throughput are dominated by the particular characteristics of each railway and the way its lines and routes are used. An improved understanding of current capability gaps is required to better match supply with demand so that the railway can deliver a consistent service valued by its customers. Analyses of the utilisation of the capacity being delivered by the system can help identify crucial bottlenecks.

A common view in the published literature is that there is no single way of determining the absolute capacity of a railway network as the way in which it is used influences the plannable capacity and the subsequent throughput of trains. Key influences are:

- Train and service mix;
- Infrastructure and signalling;
- Performance and reliability parameters;
- Utilisation of track infrastructure and trains.

There is generally an inverse relationship between capacity use and performance, holding cost constant. In the absence of any mitigating measures, as capacity utilisation increases, the knock-on impact of any delay increases so that performance tends to go down, to a break point where it becomes unacceptable as the maximum capacity of a line is approached. However the relationship between the two is complex and predicting the effect of enhancement requires a sophisticated approach and a very detailed model of the railway system and particular network configuration.

2.2 Stakeholder Discussions

Stakeholders from across the rail industry were consulted to gather an up to date pan-industry view on the use of capacity on the network and the potential for improvement. The discussions used a structured set of questions (Appendix B) but with flexibility to address issues particularly relevant to the consultee[2]. We also had discussions with representatives of two non-rail organisations: OFWAT and OFGEM. There were initial plans to talk to someone in the NHS but this proved difficult due to the non-availability of an appropriate consultee.

The organisations consulted are listed in Table 1.

No.	Organisation
1	Arriva Trains
2	Association of Train Operating Companies (ATOC)
3	Department for Transport (DfT)
4	Institution of Railway Operators (IRO)
5	Network Rail (NR)
6	Rail Delivery Group (RDG)
7	Rail Freight Group (RFG)
8	The Gas and Electricity Services Regulator (OFGEM)
9	The Water Services Regulation Authority, OFWAT
10	South West Trains (SWT)
11	Transport for London (TfL)
12	Transport Scotland (TS)
13	University of Birmingham
14	University of Leeds
15	Virgin Trains

Table 1 Stakeholder Organisations

2.2.1 Summary of views based on stakeholder interviews

As can be expected there was convergence in some of the views, but some difference of opinion too. The key points from the discussions were:

1. Areas of Convergence
    - Political pressure focuses unduly on performance and the general view is that passenger satisfaction starts to be severely affected only when the PPM reduces below 90%;

[2] Detailed notes of the meetings have been provided to the ORR as a separate document.

- Opportunities to deliver increased capacity are not always exploited, mainly to protect against any increased risk to performance. Specific examples where requests for additional paths from TOCs were either turned down or met only after a formal appeal process were mentioned; (It was notable that this view was strongest on multiple-operator routes, but where there was a single operator the process was felt to work better);
- There was a common view that the industry does need capacity metric(s) to enable a proactive effort to improve delivered capacity and also that any introduced must be:
    - Practical/easy to understand, not vulnerable to gaming but realistic and valid
    - Useful/valuable such that it incentivises right behaviours
    - Capable of being set in a “basket” with performance
    - Not complex or costly to implement.

2. Areas of Divergence
    - While the current framework of incentives is seen by some in the industry as effective and balanced, the majority view is that changes needed to improve the level of capacity made available from the physical network are given insufficient weight and this has limited the capacity delivered compared to what could be achieved;
    - The status of a prospective capacity measure(s) was agreed to be important but views diverged as to what this should be. Some (TfL, TS) felt that it would result in a difference in behaviour only if it is a regulated output, others (most operators, NR) thought that this would result in gaming and that an indicator would be better. At the same time it was felt that a period of piloting any proposed metric(s) was necessary and therefore it might be better to adopt a staged approach by first introducing any new capacity metrics as indicators with a view to encouraging co-operative behaviour and once established, transfer into regulation;
    - While NR, ATOC and some operators believe that the quality of the TPR is good, is achieved by consensus and is updated regularly, there are some alternative views as well. TfL, TS and some operators have said that the TPR are over-restrictive and a significant constraint on capacity;
    - The views of the freight industry representative were different in some areas from those of Network Rail and the TOCs:
        - Obtaining paths at short notice and being able to run longer trains is particularly important for freight; however, the timetabling process is currently slow at responding to short-term needs;
        - "Quality of paths" is very important such that the ‘end to end’ average speed is not severely affected through unnecessary stops; a key requirement is to target capacity lost through engineering access.

3. Capacity Metrics

   The interviewees suggested that any proposed metrics should:

- Take account of the different characteristics and journey requirements at different times of day, service etc (e.g. peak/off-peak & at night/weekend; metro/intercity etc);
- Incentivise timetabling which makes efficient use of capacity – an example suggested was ‘harmonising run times by sharing out stops’;
- Incentivise minor capacity enhancements during other planned renewal works (e.g. lifting of PSRs);
- Be geographically differentiated and take account of differences in patterns of use;
- Recognise inherent conflicts (e.g. reducing crowding can results in greater carbon emissions/passenger km);
- Show the performance vs capacity balance.

4. Barriers

   Key barriers to maximising the provision and use of the available capacity of the network were put forward by the interviewees as:

   - The focus on performance with very high PPM targets;
   - NR and operators are incentivised to maintain large performance buffers and there is limited incentive for NR or TOCs to improve TPR to specifically address ‘useable capacity’ (for example TPR improvements to date have been focused on improving PPM);
   - Some factors that impact on capacity tend to be hidden within the complexity of the timetabling, franchise agreement etc;
   - Ability and motivation of Network Rail to improve the provision of more usable capacity:
     - Needs a higher level incentive than current to provide extra train paths;
     - Volume incentive is weak and ineffective; and
     - Risk aversion has increased due to loss of competence in operations planning.

2.2.2 Summary

Ideas put forward by the stakeholders as to the behaviours (of NR, Operators and franchising authorities) that could be influenced and improved by a clear and transparent set of capacity measures included:

- The items that Network Rail and operators need to work together to make best use of current capacity include:
  - Matching capacity in use to demand;
  - Better balance of capacity allocation between different kinds of service;
  - Making better decisions when specifying services;
  - Show the impact on services of the choices made by policy-makers ;
  - Encouraging best use of train paths by TOCs and FOCs;
  - Acknowledgement of potential downsides of “clock face timetables”;
  - Co-operative response to additional train service proposals;

- Response based on analysis rather than judgement/defensive reaction
    - Working outside existing commercial and process constraints to optimise capacity.
    - Incentivising investment of capex on small capacity improvements (for example elimination of PSRs))

- Aspects of system operation that need to be improved (with most requiring the active co-operation of operators) include:
    - Improving VSTP (Very Short Term Plan) so that fewer contingency paths are required;
    - Improving quality of paths (average speed), in particular for freight;
    - Intelligent timetabling to maximise use of capacity e.g. by harmonised average speeds;
    - Speeding the timetable planning process so that it matches demand better;
    - Improving TPR.

Some items suggested by the freight stakeholder representative are not within the scope of the current project:

- "Reducing impact of engineering works" (this is being addressed by ORR separately);
- Give higher (than now), priority to freight trains to improve their average speeds from the current low of 25 mph; in addition to inefficient use of freight paths this also makes it difficult for rail freight to compete against road freight.

3 Development of options

An iterative process was used to identify potential options for taking forward to the analysis stage. Building on the findings from the literature review and stakeholder discussion, initial ideas were presented at an interim workshop with attendees from the ORR, DfT and Network Rail.

Following the workshop it was reiterated that the primary focus of the work was the incentivisation of Network Rail to make best use of current capacity of the infrastructure and deliver as much capacity out of the network as possible to meet demand, subject to the achievement of an acceptable level of performance.

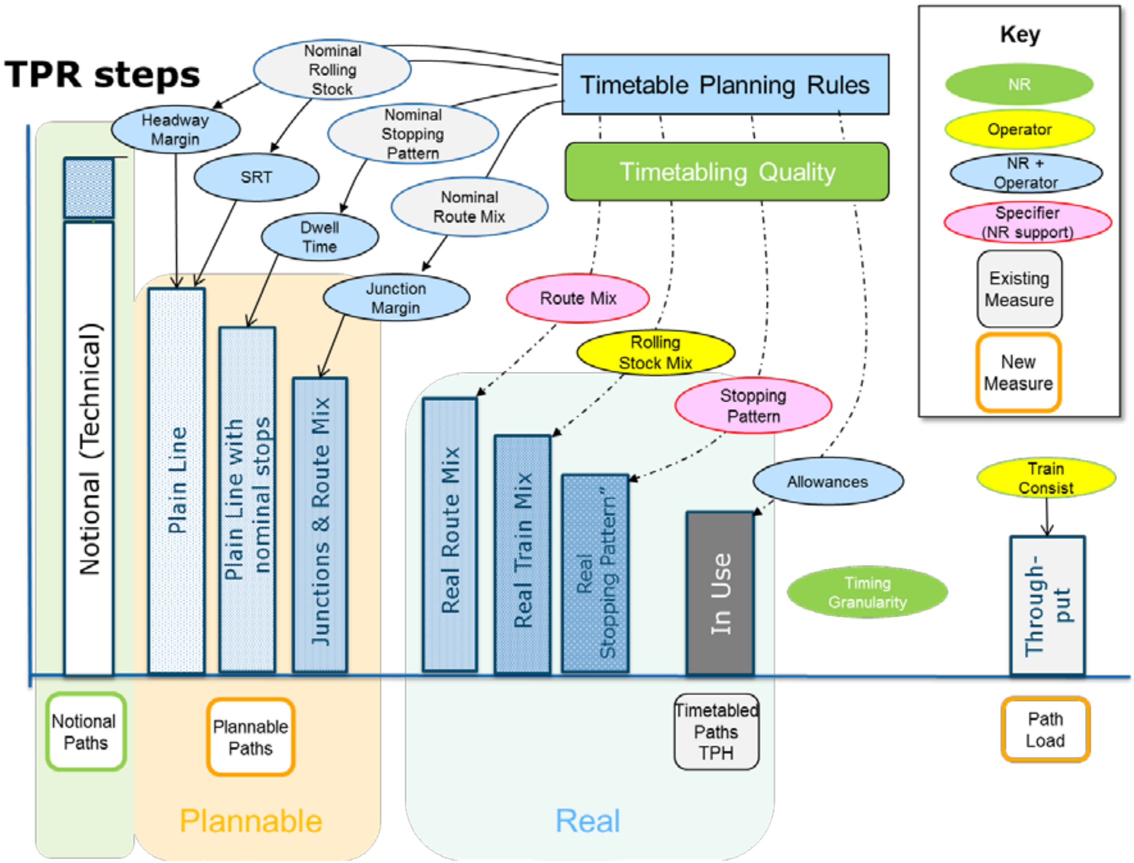


Figure 1 Capacity Cascade

As a first step, Figure 1 was developed to show how capacity-in -use (the number of trains in the timetable) cascades down from notional level. It summarises the factors which lead to the reduction in train flow at each level and provides an indication of responsibility. Current and potential additional measures are also included. Starting from the left the columns are:

- Notional Capacity (assumed to be based on worst-case green to green time). The increment shown in blue is the potential for improvement implied by the difference between worst case and mean;

- The next three columns show how notional capacity is "lost" through the application of planning rules, as "Plannable Capacity" is derived;
- "Plain Line" includes any margin included in planning headway, plus sectional running times;
- "Plain Line with nominal stops" includes dwell times;
- "Junctions and Route Mix" shows the effect of mixing services with different route patterns, including junction margins at conflict points;
- The next three columns show where the real "losses" in capacity occur, as the timetable is developed based on the services actually specified;
- "Capacity in Use" and "Throughput" have the meanings assigned previously in the report.

The following points are emphasised:

- The diagram is not intended to be to scale, but just to indicate in principle how the process affects capacity utilisation;
- Network Rail has an involvement at every level. The involvement varies from leading and achieving consensus on changes to TPRs, to supporting the Specifier in developing the service requirements and stopping pattern;
- The process of developing the timetable from Signalled Headway to a completed Timetable is described in the TPR, including operator involvement at every stage;
- The box "detailed route analysis" identifies the area where separation of the various factors involved is route specific and a detailed analysis is required to identify them and separate their impact;
- The "Throughput" step focuses on performance on the day and the carrying capacity created when a train is introduced into a path, on the day. (A "planned" level could be associated with this also).

A detailed description of the steps, responsibilities, proposed additional measures and way in which the measures may provide clarity and incentive at each level are described in more detail in the following subsections.

3.1 Notional Capacity

The concept of "Notional Capacity" was described in the ORR ITT as follows:

"Physical characteristics of the infrastructure, such as the signalling system, stations and junctions and/or the existence of single/double track, affect the number of trains that can run. We define the number of trains that could potentially run on a route, at a minimum safe distance and as a result of the physical nature of the infrastructure, as the notional capacity of a route. This assumes the best-performing rolling stock available is deployed, one standard train length and no stops."

3.1.1 *Existing Measures*

The following measures currently used in the industry are similar in intent to the concept of "Notional Capacity":

- Signalling Headway is an almost universal measure of the basic potential of a route to carry trains. It measures the minimum time separation of trains running at constant line speed without needing to brake at a signal. It is often called "green to green time". This refers to the time from when a train passes a signal (at which point it changes from green to red) until the signal is back at green, as the train passes on down the line The maximum capacity of the route or section will be limited by the block with the longest green to green time of those which make it up;
- Network Rail calculates a value called "Technical Headway". It is defined in National Timetable Planning Rules (TPR) section 5.4, (for Track Circuit Block (TCB)). Network Rail bases it on the signalling headway (the preferred tool for calculation being a VISION® model). The notes accompanying the definition are summarised as follows:
  - Complete signalled infrastructure with Permanent Speed Restrictions (PSRs), gradients etc;
  - Range of trains usually using route:
    - 95% of maximum power;
    - braking curves in accordance with professional driving policies;
    - weight as supplied by operators;
  - All combinations of stopping and non-stopping trains in the proposed timetable for the route where TPR are under review (see below);
    - Including variable allowance for signal sighting (8-45s);
  - Longest and shortest technical headway values taken forward to calculate Planning Headway.

The above only applies for track circuit block colour light signalling. Different rules apply for Absolute Block areas and single lines. The TPR make it clear that the above is how the Technical Headways are re-calculated when there is a need to make changes, but when this is not the case existing values are rolled over.

3.1.2 *TRL Initial Proposal*

TRL proposed that Notional Capacity is calculated as for signalling headway (maximum green to green time on a section), transposed into a "trains per hour" value) modelled using a dynamic simulator (VISION or equivalent) using:

- Fixed signal sighting allowance (8s – consistent with minimum read time in GE/RT8037[3] - allowance fixed at minimum value because this is the last point at which the driver can react to an aspect stepping up);
- Best performing rolling stock allocated to route and capable of achieving line speed;

[3] Note that this standard has been superseded (June 2016) by RIS-0737-CCS which provides for minimum response time to be assessed specifically for each signal. The 8s figure may need adjusting, but the use of a standard value for the assessment of notional capacity remains logical

- Fully loaded condition - i.e. performance is calculated with the train carrying its maximum normal load (not crush load).

The modelled stopping pattern is an important issue. Simulating a non-stop run is more objective and does not require a stopping pattern or dwell times to be agreed. On the other hand this will give a notional capacity which exceeds by a large margin what can actually be achieved for a line or track on which all (or virtually all) trains stop and may raise unrealistic expectations. The following options were therefore taken forward to the "Worked Example":

- No stops – simpler to calculate and less sensitive to variations out of NR's control (but very theoretical);
- Minimum stopping pattern (rather than no stops) - i.e. only include stops made by all (or virtually all) trains on target track. This is closer to reality and may be more credible but it requires judgement as to which stops should be included.

A simulation of this kind is normally used to determine the "worst case" green to green time in a section, which determines the minimum headway (maximum continuous train flow) which the section can carry. However in the process, the "green to green" times at each signalled block are calculated. Analysing the results in detail will allow calculation of the following, each of which may have value in the context of Notional Capacity:

- Limiting Headway (worst case "green to green") - forms the basis of practical capacity;
- Mean Block Headway (average of all "green to green" times in section) - provides an illustration of the potential of the route if constraints could be removed;
- Standard Deviation (of "green to green" times in section) - gives an indication of the consistency of the infrastructure along the route.

Notional capacity should provide the theoretical maximum capacity of a route based on the actual infrastructure. Its purpose is to provide a reliable (but necessarily abstract) baseline measurement of the capacity available. The proposed measure shows the upper theoretical boundary of capacity for a single homogenous train flow on the route, with no contingency or allowance.

Notional Capacity modelled in this way would not be achievable in practice and its value is in providing an objective baseline for other measures (e.g. for comparison with capacity in use when timetables are being optimised), for tracking movement over time (e.g. for determining whether objectives have been achieved when an enhancement is made to the network) and for making comparisons between routes.

3.2 Plannable Capacity

The concept of "plannable capacity" was described in the ORR ITT as follows:

"Network Rail is responsible for developing a set of Timetable Planning Rules (TPRs) – e.g. minimum time between services (planning headways), junction margins, and station dwell times at the terminal station. The number of trains that could run over a route, during a specific time period, based on the TPRs is the plannable capacity of that route. This assumes best-performing rolling stock available is deployed and a standard train length, and no stops"

3.2.1 *Current Measures*

There is no recognised standard for a “Plannable Capacity” measure of the kind envisaged. The nearest in GB practice is "Planning Headway". The following definition of Planning Headway is based on National TPR section 5.4. It is calculated by uplifting Technical Headway (and therefore derating capacity) according to the following guidelines:

- "Metro" (homogenous) services: up to 25%*
- "Intermediate" services , <= 100 miles/<=75mph/mixed traffic: 26% to 57%*
- "Long Distance", >100 miles/>75mph: 75% to 100%*

*= rounded up to the next 30s

The actual "Uplift" value to be used should take account of rolling stock mix, stopping patterns, flat junctions etc. (The selection of a value clearly requires judgement and knowledge of the route and the way it is used).

This measure is only part of TPR. Other elements applied depending on infrastructure and train sequence are:

- Sectional Running Time (time taken for a train to move from one timing point or station stop to the next). Values specific to each section and type of train and for pass and stop combinations as appropriate are calculated using a simulator and stored in a legacy database called BPLAN., The appropriate values are selected and applied by the planner, with rounding based on cumulative time along route;
- Dwell time (wheels stop to wheels start at a station) The planning value should be calculated to cover 75% of all trains with a minimum of 30s, based on measurement of actual values;
- Platform Reoccupation Time (wheels start to next train wheels stop at a station);
- Junction Margins (fixed time for separation of conflicting moves, specific to a junction).

Note that Junction Margins and Platform Reoccupation Times can be allocated a separate margin of up to 25%, rounded up.

It should be noted that similarly to Technical Headway, the above is how the values are re-calculated when there is a need to make changes, but when this is not the case existing values are rolled over.

3.2.2 *TRL Initial Proposal*

TRL proposed “Plannable” Trains per hour (Plannable Capacity Units) simulated as follows:

Based on Technical Headway;

- Best performing rolling stock available for the route – fully loaded – i.e. the class normally used on the route, but if there is a choice, the one with the most appropriate combination of maximum speed, acceleration and braking capability for the type of service;
- Longest train used on the service assumed as standard;
- “Nominal” service pattern for each track;
- Including sectional running times (with margins), headway and junction margins (where appropriate);

- With standardized or TPR dwell times (see options);
- Not including Recovery Time or Engineering Allowances.

Freight capability could be assessed by either:

- Measuring plannable tph as a separate value (using freight train characteristics) (maximum speed, acceleration & braking rate, length); or:
- Calculating the reduction in plannable passenger tph caused by the introduction of each freight path.

Characteristics of freight trains vary widely – e.g. Class 4 (multi-modal, max75 mph) versus Class 6 (bulk materials, max 60 mph).

The proposed measure shows the maximum potential capacity available to planners at the time the service specification is created, assuming optimised rolling stock and service pattern. Comparison between Notional and Plannable is intended to show the impact of TPR.

- In theory it would be undesirable to base this measure on Planning Headway as specified in TPR because this already contains judgements based on rolling stock mix and stopping pattern (however in the example selected this does not seem to be the case – see below);
- Service and stopping pattern – initially it was proposed to use a homogenous service based in a standardised stopping pattern for each track. Criteria for inclusion of a station were considered as follows:
    - Key point on the network (e.g. interchange location);
    - % of trains that actually stop;
    - Station usage (% of passengers using the route, based on passenger numbers published by DfT and ORR)

However when carrying out preparatory work for the Worked Example (Section 4) it became clear that this was not a realistic approach. Although SWML is a 4-track railway, the use of a standardised stopping pattern (for a track such as the fast lines into Waterloo) forced a choice between a non-stop and stopping service and in practice the timetable contains a mixture of the two. Furthermore, it was not possible to include realistic mix of TPR such as would be used in a timetable. Therefore it was decided that a synthetic service pattern (rather than a standardised stopping pattern) would be used. The same approach was applied to the SWML slow lines in terms of the service pattern (train sequence) although in this case an “all trains stop” scenario was explored. A 2-track railway would require the same approach.

- For dwell times, a number of options could be used:
    - set to zero (good for consistency but not for realism);
    - set to the value in TPR;
    - set to a standard value calculated from passenger flow, station and train characteristics (as used by London Underground).

In the example simulations, dwells were set to the value in the TPR.

- For Junction Time (including Margin) –a number of options could be considered:
    - Leave out (optimistic, excludes an important element of TPR)

- Base on simplified/standardised service pattern (more realistic but complex)
- Include as a calculated adjustment to main line following headway (could be subjective)

In the example simulations, the second option was taken forward.

3.3 Capacity in Use

"Capacity in Use" was defined as follows in the ORR ITT:

"A high proportion of passenger services are currently specified by government through the franchising process. The ORR allocates capacity through track access agreements for franchised, open access and freight operators through its decisions on access agreements. Network Rail is responsible for timetabling these services, as well as those which are not specified by government.

The final timetable produced has to take account of the rolling stock available, service stopping patterns, frequencies, departure times and/or the departure time range. Some of these parameters, such as calling patterns and frequency, are affected by market demand. We call this capacity in use"

3.3.1 Existing Measures

Measurement of 'capacity in use' represents one of NR's principal outputs – i.e. the number of trains able to run on the track. The railway industry has developed many measures in this area. The ones most commonly used on the GB main line railway are:

- Timetabled Capacity (trains per hour) - calculated from the completed working timetable
- Capacity Utilisation Index (similar to UIC 406)
- Train.km/track.km (as presented in NR System Operations dashboard)

3.3.2 TRL Initial Proposal

TRL proposed to take the following measures forward for evaluation in the "Worked Example" (Section 4)

<u>Timetabled Capacity (trains per hour per track)</u>

This sounds like a simple measure but in fact it is quite complex to calculate and evaluate. It varies both with time and along a route; therefore the value can change at each node (which can be as simple as a fast-slow line crossover) and it can be measured at any point. Measuring a value for each track section between timing points would be consistent with industry practice, but would result in a large quantity of data. Measuring for each link (node to node) may be better. In either case a rationale for summarising upwards will be needed.

The question of time of day is also significant. The focus tends to be on peak capacity, but the trains per hour value for AM and PM peaks can be significantly different. Night service is a consideration on some routes and is important for freight.

Train.km/track.km

This has been proposed by Network Rail as a measure of capacity utilisation for its System Operations Dashboard. In the Network Rail consultation document[4] a global value for the network for a year's operation is proposed. It would be possible to produce values per route.

Average speed

Network Rail has proposed "Total distance run (in timetable) divided by total time taken" as a measure of train performance for its System Operations Dashboard. In the consultation document a global value for the network for a year's operation is proposed. However a "per route" or "per operator" measurement could give better long term value in assessing where capacity/performance trade-offs have been made. Extra contingency in the timetable would appear as a reduction in average speed whereas any loss of capacity might not be detectable directly.

[4] "Improved reporting of our network system operator activities – an NSO Dashboard (Annex A)". Network Rail website

4 Worked Example and Analysis

The Capacity Measures study being carried out by TRL for ORR includes the production of a "worked example". This consists of a simplified model of a real world route section using our software based multi-train simulator. The objective is to test the candidate measures which have emerged from the first part of the study, to try out options and to see how the outputs vary with changes in service, planning rules etc so that the measures can be refined and problem areas identified.

The simulation was carried out using a software toolset with an extensive pedigree of use on similar work for Network Rail, DfT, RSSB, STIF, Banedanmark, Infrabel, Société du Grand Paris, Toronto Transit Commission and many others. It contains a dynamic train movement model with multi-train capability and accurately represents the effect of gradients, speed restrictions and signalling control.

4.1 Modelling Specification

The detailed modelling specification is contained in the following document:

ORR Capacity Measures: Worked Example – Specification for Modelling v0.12 and is included in Appendix C. This is an updated version of the one initially submitted to ORR; the original proposed sequence of trains for the simulation runs for Plannable Capacity was adjusted following initial runs.

A brief summary of the basis of the model is as follows:

- Geographic Scope - included the South West Main Line (SWML) from Waterloo to the next stations south and west of Woking. The "Windsor" lines via Barnes were excluded. The fast and slow lines were included together with representative parts of the East Putney, Epsom, Teddington, Kingston and Oxshott (Guildford New) branches.
- Infrastructure data (distances, line speeds, block boundaries, permanent speed restrictions, gradients) was sourced from Network Rail "5-mile diagrams"
- Signalling - four aspect, track circuit block with block sections located as accurately as reasonably practical given the data source
- Driver behaviour – based on experience of "defensive driving" using parameters agreed with Network Rail for earlier work
- Rolling stock parameters were available from our software library as provided or approved by Network Rail for previous work. Classes 159, 450 and 455 were included plus a representation of Class 66-hauled Class 4 freight.

4.2 Modelling Notional Capacity

In order to explore "Notional Capacity" the model was set up to calculate train to train following headway (and thus notional trains per hour) using a representative selection of services covering all tracks and branches and with both stopping and non-stopping options. The results show how this parameter varies along the route and allows comparison both with existing measures and with "Plannable Capacity" and "Capacity in Use" for the same route sections and tracks.

In each run the nominal following headway ("green to green time") was measured. Figure 2 shows the output of a typical non-stop run in chart form. The chart plots following headway as the trains move along the route. The y-axis shows nominal headway in seconds; the x-axis is distance onto which the locations of stations and key junctions have been plotted.

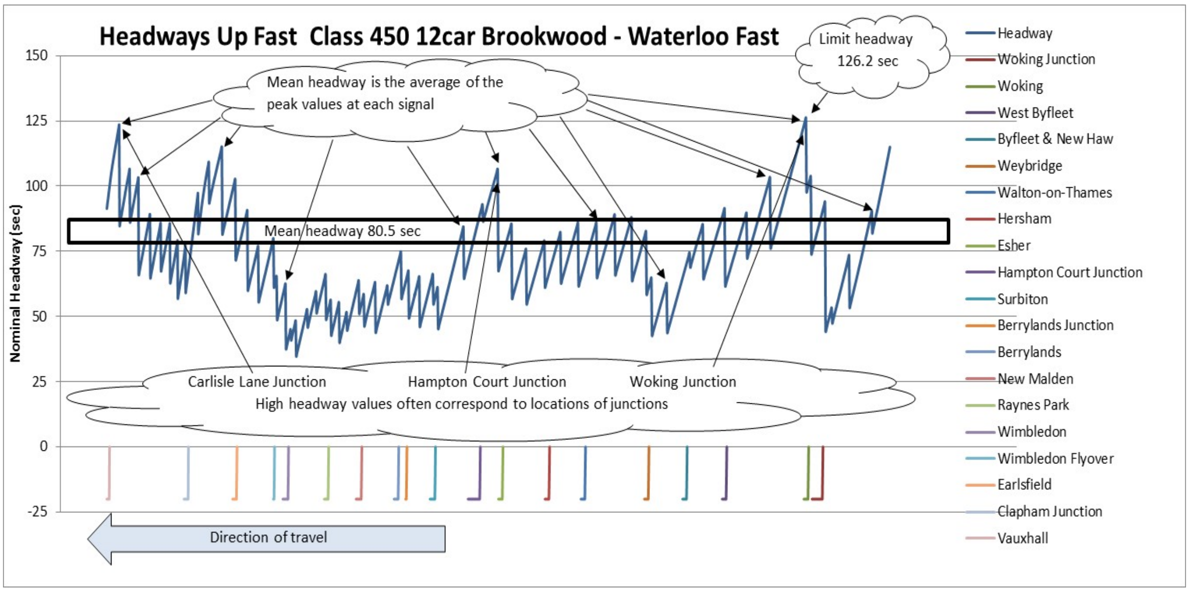


Figure 2 Illustrative Output of Model Run

The "zig zag" line shows how the headway (minimum time interval between trains) varies at each block boundary along the route and the larger the value of headway, the lower the capacity. The limiting headway (worst case green to green time) is the highest value on the track section being modelled. Notional Capacity (in trains per hour) is given by dividing this into the number of seconds in an hour. In this case the limiting headway is 126.2 seconds, measured at Woking Junction' giving a Notional Capacity of 28.4 trains per hour. Significant constraints (high values of block headway) can be seen also at Carlisle Lane Junction (approach to Waterloo), Clapham Junction and Hampton Court Junction.

The services run and detailed results in numerical form, calculated as trains per hour, are provided in Appendix D. Table 2, Table 3, Table 5 and Table 6 provide the limiting and mean block headway values (converted to notional trains per hour) and standard deviation for each track and direction, covering non-stop and stopping runs respectively.

4.2.1 Non-stopping runs

The non-stopping runs can be considered as a test of the ability to measure notional capacity, using an entirely objective set of assumptions. These assumptions are abstract, in the sense that they do not represent a real situation (both fast and slow lines actually carry a mixture of services)

The results (in TPH) for the Non-stopping runs (Up and Down Lines) are given in Table 2 and Table 3.

Route Section	Class x cars	Limit	Mean	Std Dev
Brookwood to Waterloo Up Fast	450 x 12	29.1	44.7	8.6
Brookwood to Waterloo Up Slow	450 x 12	22.2	40.1	7.0
Epsom to Raynes Park	455 x 8	31.0	37.8	5.5
Teddington to New Malden	455 x 8	22.6	29.1	4.2
Hampton Court to Surbiton	455x 8	15.2	29.7	10.5

Table 2 Notional Capacity Non-stop Up Lines (TPH)

Route Section	Class x cars	Limit	Mean	Std Dev
Waterloo to Brookwood Down Fast	450 x 12	30.1	40.1	5.9
Waterloo to Brookwood Down Slow	450 x 12	21.2	37.2	6.7
Raynes Park to Epsom	455 x 8	17.9	28.2	7.5
New Malden to Teddington	455 x 8	19.8	27.4	5.7
Surbiton to Hampton Court	455x 8	17.0	19.9	2.4

Table 3 Notional Capacity - Non-stop Down lines (TPH)

4.2.1.1 Commentary – Non-stop Values

The "limit" values for non-stop notional capacity lie in the expected range (see Table 4 for comparison with Network Rail's published values for technical headway). This measure is consistent with standard signalling practice and is likely to be understood and seen as valid by the industry.

The "mean" values suggest that the potential of this route, even with current signalling, is considerably higher than what is now achieved. However any idea that this means that extra capacity could easily be delivered would be an incorrect interpretation. This route has been studied and optimised extensively and the remaining constraints are substantive ones. They are associated with junctions (Woking, Hampton Court, and Carlisle Lane) or with sections of route with permanent speed restrictions (Clapham Junction) which cannot easily be changed. (There are additional constraints associated with terminals which have not been assessed in this work). It is worth noting that the "spare" capacity apparently available at block sections between limiting constraint points does have value, in that it makes the system more resilient. A route where all blocks have the same limiting headway would (when running at that limit) propagate delays from one end to the other without possibility of recovery. The fact that this difference between mean and limit is relatively large may help to explain why SWML can run in the peak at nearly 90% of its limit capacity (standard texts suggest a maximum of 80% to support acceptable levels of reliability).

The “standard deviation” values suggest that the Up Fast is less consistent than the Down Fast. The Up Fast also has a higher mean. It is notable that the Up Fast actually carries a higher peak load than the Down Fast.

The “mean” and “standard deviation” values need more study (taking examples on other routes) to determine whether they are useful in practice.

Network Rail’s declared headway values for SWML (Table 4) between Waterloo and Hampton Court Junction are 2 min (fast) and 2.5 min (slow). The Wessex TPR do not say whether they are Technical Headways or Planning Headways – presumably the latter since they are included in TPR. Note that in TPR “fast” means the headway between non-stop trains and “slow” the headway between stopping trains – not the track that they are running on.

Line	**Section**	**Up**		**Down**	
		Fast	**Slow**	**Fast**	**Slow**
Main	Brookwood - Woking	3	3.5	3	3.5
Main	Woking - Hampton Court Junction	2	3.5	2	3.5
Main	Hampton Court Junc - Waterloo	2	2.5	2	2.5
Epsom Br	Epsom - Raynes Park	2	2.5	2	2.5
Teddington	Teddington - New Malden	2	2.5	2	2.5
Hampton Ct	Hampton Ct - Hampton Ct Junction	3	3.5	3	3.5
Guildford New	Hinchley Wood - Hampton Ct Junction	2	3.5	2	3.5
Portsmouth	Worplesdon - Woking Junction	2	3.5	2	3.5

Table 4 Network Rail Planning Headways (min)

The “Notional Capacity” values from our simulation for a non-stop train on the fast line of 29.1 TPH (Up) and 30.1 TPH (Down) are very close to Network Rail’s “fast” planning values (equivalent to 30 tph each direction).

The “Notional Capacity” values for a non-stop train on the slow lines of 22.2 TPH (Up) and 21.2 TPH (Down) are significantly less than Network Rail’s “slow” planning value (equivalent to 24 TPH). This is a surprising discrepancy at first sight. However they are calculated over different sections of route – the “Notional Capacity” value covers the whole of Waterloo to Woking whereas the Network Rail 24 TPH figure applies only as far as Hampton Court Junction. From there to Woking the figure is 17 TPH (3.5 min headway). However the Network Rail values apply strictly to the gap between stopping trains – according to the words in the TPR the “fast” 2 min headway (30 TPH) should apply to non-stop trains on the slow line. This is clearly unrealistic. However in practice only empty stock and freight runs without stopping on the slow line. These discrepancies point up the fact that technical headway (with non-stop trains) is not a very useful measure for tracks on which all service trains stop.

4.2.2 Stopping Runs

The stopping runs test whether this option provides useful information on the extent to which stopping 'uses' notional capacity. The only objective test is to stop all trains at all stations. This, again, is abstract in that most routes and tracks do not operate in this way (although some do).

The results (TPH) for the stopping runs (Up and Down Lines) are given in Table 5 and Table 6.

Route Section	Class x cars	Stops	Limit	Mean	Std Dev
Brookwood to Waterloo Up Fast	450 x 12	Woking	15.0	40.9	11.9
Brookwood to Waterloo Up Slow	450 x 12	All	11.9	20.3	8.6
Epsom to Raynes Park	455 x 8	All	18.4	20.0	1.0
Teddington to New Malden	455 x 8	All	16.3	19.9	2.4
Hampton Court to Surbiton	455x 8	All	12.7	15.3	2.7

Table 5 Notional Capacity - Stopping Up Lines (TPH)

Route Section	Class x cars	Stops	Limit	Mean	Std Dev
Waterloo to Brookwood Down Fast	450 x 12	Woking	14.2	36.2	9.9
Waterloo to Brookwood Down Slow	450 x 12	All	11.4	19.2	4.4
Raynes Park to Epsom	455 x 8	All	19.3	28.3	8.5
New Malden to Teddington	455 x 8	All	11.9	15.2	3.1
Surbiton to Hampton Court	455x 8	All	15.8	17.8	1.5

Table 6 Notional Capacity – Stopping Down Lines (TPH)

4.2.2.1 Commentary – Stopping Values

The Notional Capacity "stopping values" show what capacity could be achieved if all trains on the lines stopped in the same pattern.

On the fast line the simulation shows that if all trains stopped at Woking in the fast line platforms, capacity would be reduced to 15 TPH. This shows the extent to which a Woking stop "uses" notional capacity. In practice the timetable contains planned sequences which limit use of the fast line platforms, particularly in the peak.

On the slow line the values are surprisingly low. The limiting constraints are (on the down line) the "green to green" times at Wimbledon and Surbiton stations. When a train enters the station the preceding train is still occupying the third block beyond the starting signal so the incoming train faces a double yellow at the platform starting signal. This is not a constraint in practice because by the time the dwell time has expired the starting signal will have cleared. On the up line the constraint is at Woking Junction/station. If these exceptions are excluded the capacity would be about 18 TPH (up) and 15 TPH (down).

The "mean" values reflect the lower block headways which can be achieved by a train running at lower speed.

The "standard deviation" values reflect the varying speed profile of the train as it accelerates and decelerates to station stops. This masks the variation in block length. They are not, therefore, useful in the context of a notional "stopping" value.

4.2.2.2 Impact of Rolling Stock Type

The runs using different rolling stock provide a test of the extent to which lower performing rolling stock 'uses' notional capacity and therefore whether rolling stock selection is significant. The trains used are of maximum length achievable with the rolling stock classes selected. This would be typical of a peak service. Shorter trains (3, 4, 6 or 8 cars) are used in the off-peak and would not be significant in terms of a notional capacity calculation.

Table 7 and Table 8 show the effect on the limit values of Notional Capacity (TPH) of changing rolling stock type on the fast and slow lines.

Route Section	Class x cars	Stops	Limit
Brookwood to Waterloo Up Fast	450 x 12	Woking	15.0
Brookwood to Waterloo Up Fast	159 x 9	Woking	15.2
Waterloo to Brookwood Down Fast	450 x 12	Woking	14.2
Waterloo to Brookwood Down Fast	159 x 9	Woking	16.3

Table 7 Impact of Rolling Stock Type – Fast lines (TPH)

Route Section	Class x cars	Stops	Limit
Hampton Ct to Waterloo Up Slow	450 x 12	All	16.7
Hampton Ct to Waterloo Up Slow	455x8	All	18.7
Waterloo to Hampton Ct Down Slow	450 x 12	All	11.4
Waterloo to Hampton Ct Down Slow	455x8	All	12.4

Table 8 Impact of Rolling Stock Type – Slow lines (TPH)

In Table 7, the effect of a change from Class 159 to Class 450 is seen on a service stopping at Woking on the fast lines. It is notable that the difference favours the Class 159. The model shows that the dominant factor is train length. The longer 12-car Class 450 takes longer to clear the platform block as it accelerates, despite its better performance.

In Table 8, the effect of a change from Class 455 to Class 450 is seen on services stopping at all stations between Hampton Court and Waterloo, on the slow lines. In the same way as above, the model shows that the dominant factor is train length. The longer 12-car Class 450 takes longer to clear the platform block as it accelerates, despite its better performance. If the trains were of equal length the Class 450 would achieve marginally higher capacity figures than the Class 455. The conclusion is that using a defined train length is more important than the train performance. In the context of Notional Capacity it makes sense to use the longest train consists likely to be used in practice, since these will deliver the highest throughput.

4.2.3 Conclusions – Notional Capacity

The results show overall that measuring Notional Capacity in this way works, that a set of objective measures can be created, that alternatives (stopping/non-stopping) can inform the understanding of what is 'consuming' notional capacity and that there are choices in how notional capacity is reported.

The measure can be useful and provides a benchmark against which other measures can be scaled, but is not appropriate for day to day monitoring and measurement. Nevertheless, ensuring that it is measured consistently and regularly across the network can provide a standard candle for comparison of route capacity and tracking of change over time.

There are a number of choices about how a metric is created from the results of the analysis and these may have value in different ways:

- Limit – shows the maximum capacity across the route as a whole. Subsections may have higher/better values, so reporting sub-sections that make operational sense might be helpful and could avoid over-concentration on a single pinch-point.
- Mean – an aggregate measure that could capture minor improvements over time, but that don't necessarily translate into new services.
- Standard Deviation – provides an indication of the extent to which there is a significant variation in the limit across the route. It is not clear how this will have value in practice.

4.3 Plannable Capacity

4.3.1 Service Pattern

For the analysis of "Plannable Capacity", a synthetic service pattern was produced, combining the individual services modelled for "Notional Capacity" with numbers of each service which reflected approximately the mix of peak services currently timetabled, in a sequence which appeared to offer the best use of available route capacity (i.e. would give a Plannable Capacity closest to the Notional value).

The sequence chosen was modified during the preparatory stages of the work as that initially selected was clearly capable of improvement. The version of the "Worked Example Specification" referenced above contains the updated sequence.

4.3.2 Timetable Planning Rules

The timetable planning rules used have been extracted from Network Rail document "Timetable Planning Rules – Wessex – 2017 Timetable – Version 3.0" dated 1st April 2016 and applied in accordance with "Timetable Planning Rules – National – 2016 Timetable" Version 3.0 dated 27th March 2015. Version 4.0 dated 15th July 2016 for the 2017 Timetable was also consulted but contained no changes relevant to this work.

Spreadsheet <160614 Extract from Wessex TRP v0.2> (Appendix E) contains the extracted material.

The following policies were adopted in including allowances etc, where judgement is required:

- Planning Headway – included in all cases, at the values stated in TPR for the appropriate track;
- Dwell Times – included at TPR values;
- Junction Margin – applied only where there is a conflicting move (none in this set of results);
- Sectional Running Times – applied as differentials where needed for successive trains, depending on sequence. (SRT values from Network Rail were not available so PRIME modelled values were used).

4.3.3 Results

Table 9, Table 10, Table 11 and Table 12 present the results of the analysis, the total Plannable Capacity TPH for each of the proposed sequences.

Seq #	Origin & Destination	Stops	R/S	Notes	Headway	Margins applied to notional headway
1	Brookwood- Waterloo	None	450x12	Fast Line headway with margin	2	None
2	Brookwood- Waterloo	Woking (Plat 2)	450x12	Impact of Woking stop	4	Difference in SRT between stop and non-stop at Woking
3	Brookwood – Waterloo	Woking (Plat 1)	450x12	Slow to fast at Woking (east crossovers)	2	None (Difference in SRT between #2 and #3 as #3 accelerates from Woking East can be ignored because #2 is accelerating from Woking stop)
4	Worplesdon – Waterloo	Woking (Plat 2)	450x12	From Portsmouth Line at Woking Junction	2	None (#4 will follow #2 through Woking Plat 2 then follow technical headway behind #3 from Woking East)
5	Woking - Waterloo	None on fast	450x12	Slow to fast at Berrylands	2	Difference in SRT between through and switched service at Berrylands is small so can be ignored
6	Brookwood – Waterloo	Woking (Plat 2)	159 x 9	Impact of rolling stock difference	2	None (#6 will follow #4 through Woking Plat 2; difference in SRT between types of rolling stock small compared with headway needed for #5)
7	Brookwood- Waterloo	None	450x12	Fast Line headway with margin	2.5	Section run time difference between #7 and #6.
8	Brookwood – Waterloo	Woking (Plat 1)	450x12	Slow to fast at Woking (east crossovers)	4	Difference in SRT between #8 and #7 as #8 accelerates from Woking East
9	Worplesdon – Waterloo	Woking (Plat 2)	450x12	From Portsmouth Line at Woking Junction	2	None (#9 will follow #7 through Woking Plat 2 then follow technical headway behind #8 from Woking East)
10	Woking - Waterloo	None on fast	450x12	Slow to fast at Berrylands	2	Difference in SRT between through and switched service at Berrylands is small so can be ignored
		Total cyle time	**24.5**	**Trains per hour**	**24.5**	

Table 9 Plannable Capacity – Up Fast

Seq#	Origin & Destination	Stops	R/S	Notes	Headway	Margins applied to notional headway
1	Waterloo Brookwood	None	450x12	Fast Line headway with margin	3	Difference in SRT between stop and non-stop at Woking - apply only deceleration difference because once past Woking trains can separate without affecting Waterloo-Woking capacity
2	Waterloo Brookwood	Woking (Plat 4)	450x12	Impact of Woking stop	2	None
3	Waterloo Worplesdon	Woking (Plat 5)	450x12	To Portsmouth Line at Woking Junction	2	None (#3 follows #2 with same speed profile as far as Wokng East)
4	Waterloo Woking	None on fast	450x12	Fast to slow at Berrylands	2	Difference in SRT between through and switched service at Berrylands is small so can be ignored
5	Waterloo Brookwood	Woking (Plat 5)	450x12	Fast to slow at Woking (east crossovers)	2	None (#5 follows #3 into Plat 5)
6	Waterloo Brookwood	None	450x12	Fast Line headway with margin	2	None
7	Waterloo Brookwood –	Woking (Plat 4)	159 x 9	Impact of rolling stock difference	2	None
8	Waterloo Worplesdon	Woking (Plat 5)	450x12	To Portsmouth Line at Woking Junction	2	None
9	Waterloo Woking	None on fast	450x12	Fast to slow at Berrylands	2	Difference in SRT between through and switched service at Berrylands is small so can be ignored
10	Waterloo Brookwood	Woking (Plat 5)	450x12	Fast to slow at Woking (east crossovers)	2	None
		Total cyle time	**21**	**Trains per hour**	**28.6**	

Table 10 Plannable Capacity – Down Fast

Seq #	Origin & Destination	Stops	R/S	Notes	Headway	Margins applied to notional headway
1	Brookwood-Waterloo	All to Surbiton	450x12	Slow line headway with margin & dwells	3	30 sec at Surbiton
2	Hinchley Wd – W'loo	All	450x12		3	30 sec at Surbiton
3	Hampton Ct – Waterloo	All	455x8	Hampton Ct line headway with margin & dwells	4.5	30 sec at Surbiton + section run time
4	Teddington – Waterloo	All	455x8	Teddington line headway with margin & dwells	2.5	None
5	Epsom – Waterloo	All	455x8	Epsom line headway with margin & dwells	2.5	None
6	Teddington – Waterloo	All	455x8	Teddington line headway with margin & dwells	2.5	None
7	Epsom – Waterloo	All	455x8	Epsom line headway with margin & dwells	2.5	None
8	Brookwood-Waterloo	All to Surbiton	450x12	Slow line headway with margin & dwells	3	30 sec at Surbiton
9	Teddington – Waterloo	All	455x8	Teddington line headway with margin & dwells	4	Section run time
10	Epsom – Waterloo	**All**	**455x8**	**Epsom line headway with margin & dwells**	**2.5**	None
		Total cyle time	**30**	**Trains per hour**	**20.0**	

Table 11 Plannable Capacity – Up Slow

Seq #	Origin & Destination	Stops	R/S	Notes	Headway	Margins applied to notional headway
1	Waterloo -Brookwood	All from Surbiton	450x12	Slow line headway with margin & dwells	3	30 sec at Surbiton
2	W'loo -Hinchley Wd	All	450x12	Rolling stock differentials	2.5	30 sec at Surbiton
3	Waterloo - Hampton Ct	All	455x8	Hampton Ct line headway with margin & dwells	4.5	30 sec at Surbiton + section run time difference
4	Waterloo -Teddington	All	455x8	Teddington line headway with margin & dwells	2.5	None
5	Waterloo -Epsom	All	455x8	Epsom line headway with margin & dwells	2.5	None
6	Waterloo -Teddington	All	455x8	Teddington line headway with margin & dwells	2.5	None
7	Waterloo -Epsom	All	455x8	Epsom line headway with margin & dwells	2.5	None
8	Waterloo -Brookwood	All from Surbiton	450x12	Slow line headway with margin & dwells	3	30 sec at Surbiton
9	Waterloo -Teddington	All	455x8	Teddington line headway with margin & dwells	4	Section run time difference
10	Waterloo -Epsom	All	455x8	Epsom line headway with margin & dwells	2.5	None
		Total cyle time	**29.5**	**Trains per hour**	**20.3**	

Table 12 Plannable Capacity – Down Slow

4.3.4 Commentary

The Plannable Capacity results for the fast lines fall in the expected range. (Comparison with "Capacity in Use" values showed that they are slightly lower than the peak values actually achieved. The possible reasons for this are discussed in section 5).

The results for the slow lines are considerably higher than the notional values. This is because the standardised headways in the TPR do not need to take account of the issue described in Section 4.2.2.1, where trains enter stations and stop with the platform starting signal showing a restrictive aspect. This is an example of where it is not necessary to apply the TPR rigidly (if rigid rules were applied the current service could not run because the Technical Headway would be greater than that actually timetabled).

The production of these figures required:

- Extraction of the relevant data from the Timetable Planning Rules;
- Some degree of knowledge of the route to allow the TPR to be interpreted;
- Consultation with the Operator on application of one parameter;
- Extraction of train services from the timetable;
- Creation of a "synthetic service pattern" and its adjustment to create a "best" result.

The process was not simple. But more importantly, it is also very much open to challenge both because judgement is involved and because the TPR are not intended to be used in this way, as spreadsheet values. They are intended as parameters to be used in the creation of a timetable through a train graph. When used in the way intended they can be applied at the right geographic location, at the right time (as the train passes the appropriate point). Applying them as generalised values to a train service does not work very well. The right way to create a "Plannable Capacity" would be to go through the initial stages of creating a timetable.

4.4 Capacity in Use

For the Worked Example a series of planned values of trains per hour were extracted from current train running data on the public website <realtimetrains.co.uk>. Planned and actual train times are provided on the website for each station and timing point, the trains being referenced by their 4-digit headcode with origin and destination shown. This data is derived from TRUST/TD.net via a Network Rail data portal. Extraction was done manually into an Excel spreadsheet. It was simple but repetitive. However, it would be straightforward to automate the process, with suitable applications created for industry (or even public) use.

4.4.1 Results

The information created is in two forms.

Figure 3 intends to capture the SWML fast and slow line flows at the top of the AM peak, for comparison with the Notional and Plannable values. To show how train flows vary with space, the flows are charted at various points between Woking and Waterloo, timed to capture the peak flow as it rolls into London.

Figure 4 shows the variation in flow with time at a single point. Vauxhall (a convenient timing point just outside the Waterloo station throat) was chosen for this, but similar charts could easily be produced for any timing point or station on the route.

4.4.2 Commentary

The information presented shows clearly the variation of Capacity in Use with:

- Geography – every node changes the flow on each track
- Time – the Up Fast AM peak flow is sustained for only one hour of the day
- Direction – the Up fast AM peak flow is not mirrored in the PM peak. The PM peak is much flatter in shape, being prolonged into the evening, whereas the AM peak has a short rise time.

Other point to be noted, for example:

- The up fast line has a peak in the afternoon, leading and actually higher than the peak on the down fast. This is because empty trains are moved from the Clapham sidings into Waterloo at this time, in order to become outgoing peak services and this adds to the rising inward flow of passenger-carrying trains.

This kind of information can easily be extracted from industry data already in the public domain.

4.4.3 Conclusions – Capacity in Use

The results show that Capacity in Use (train flow) can easily be measured from existing industry data. The measure is objective (the trains either ran or did not) and requires little work to produce. It can measure the train flow for each track on a route.

The data can support a very large number of measuring points (every station and timing point on the network) and can be averaged over any chosen period. “Planned” (timetabled) and “Actual” values can be extracted and compared with each other. The data would also allow the following subsets of information to be extracted:

- Passenger-carrying trains only (excluding empty trains)
- Freight
- Trains by operator
- Trains calling at a station (rather than just passing)

All of these could have value to operators and others (for example Local Authorities) and some may be of interest to passengers. However the focus of this project is on infrastructure capacity made available by Network Rail, in which case total trains per hour would be the best measure, with a possible split between passenger and freight. Where there are distinctly different long distance and local or regional stopping services a differentiation by operator might be of value.

For comparison with Notional Capacity, the peak hourly flow (rolling 60 minute average) should be used.

Location of the measuring points used is important. The following criteria are suggested for selection:

- “Plain line” timing point (makes analysis much easier);
- At known maximum flow points (for example the approach to terminals);
- At a maximum point on each branch or connecting route (usually adjacent to the junction with the main route).

Some specific suggestions for SWML are made in Chapter 5, which also includes a comparison between Notional, Plannable and Capacity in Use for the worked example.

A useful addition to this information would be the consist allocated to each service. This would enable train capacity in use (rather than the number of trains in use) to be measured. Planned consist data is available in TRUST, so should be easily added.

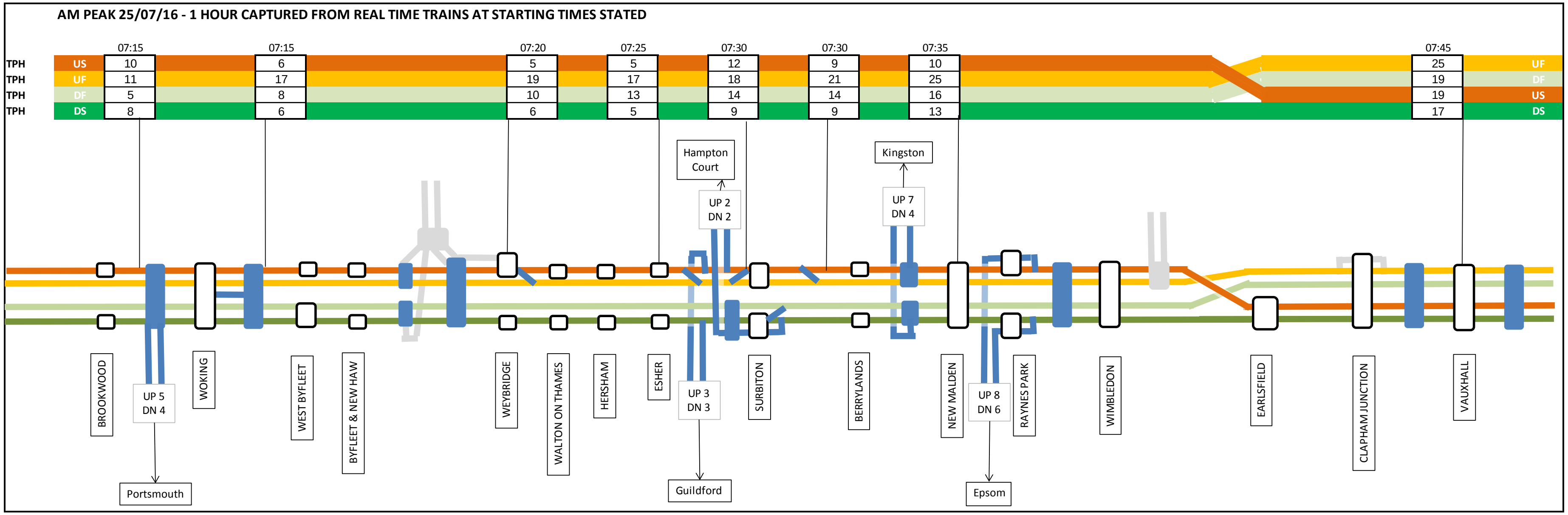


Figure 3 SWML Fast and slow line flows (am peak, 1 hour)

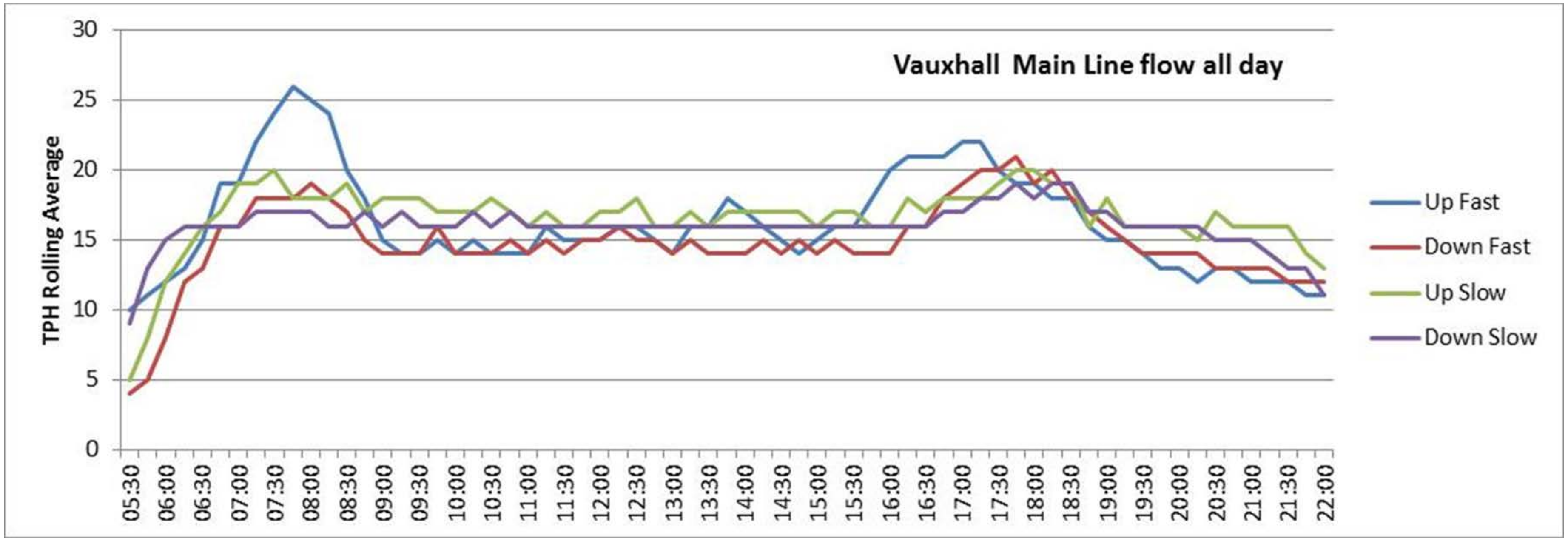


Figure 4 Single point (Vauxhall) Variation in flow

4.5 Freight

An important aspect that needs to be considered when developing potential capacity metrics is the different needs and requirements of passenger and freight services. This is because, as previously stated, capacity depends on the way it is utilised. The needs of freight and passenger services can be different (as emphasized by the stakeholder discussions).

In general, over the majority of the network (with the exception of dedicated freight lines and some trunk routes at night) passenger trains predominate in numbers. Also freight is perceived as being less time-critical than passenger, mainly because passenger time has a specific economic value and freight trains tend to have lower maximum speeds. Freight paths tend, therefore, to be fitted in between passenger services and often include time "looped" or held at junctions waiting for the path to open on the next section of route.

Primary freight industry concerns set out by the freight industry representative were:

- Path "quality" – i.e. average speed from end to end; avoiding unnecessary stops;
- Ability to increase train length;
- Short notice path availability.

The "Worked Example" included freight trains in its model set. SWML does not carry significant freight traffic east of Basingstoke, so an artificial scenario was created of a Class 4 freight running from Brookwood and exiting the main line via Wimbledon Park (East Putney route).

Notional Capacity Freight			
Route Section	**Class x cars**	**Direction**	**Limit**
Brookwood to Wimbledon Park FT	Class 4 freight	Up	21.1
Wimbledon Park FT to Brookwood	Class 4 freight	Down	14.3

Table 13 Notional Capacity - Freight

Table 13 shows the notional capacity for a continuous sequence of freight trains, such as could occur at night on some routes. The value is similar to stopping service.

The "plannable capacity" evaluation also considered freight and the results are given in Table 14 and Table 15.

Origin & Destination	Stops	R/S	Notes	Headway	Margins applied to notional headway
Brookwood – Waterloo	All	450 x 12	Main Line, Up slow	2.5	None
Brookwood – Wimbledon Park	None	Class 4 freight	Main Line, Up slow	2.5	None
Brookwood – Waterloo	All	450 x 12	Main Line, Up slow	27	Section run time difference
	Trains per hour (with single freight)			14.2	

Table 14 Plannable Capacity Up Lines- Freight

Origin & Destination	Stops	R/S	Notes	Headway	Margins applied to notional headway
Brookwood – Waterloo	All	450 x 12	Main Line, down slow	2.5	None
Brookwood – Wimbledon Park	None	Class 4 freight	Main Line, down slow	24	Section run time difference
Brookwood – Waterloo	All	450 x 12	Main Line, down slow	2.5	None
	Trains per hour (with single freight)			15.4	

Table 15 Plannable Capacity Down Lines - Freight

Table 14 and Table 15 show the impact of a single freight train on a service consisting otherwise of a continuous sequence of stopping trains on the SWML slow line. Comparison with Table 11 and Table 12 shows that clearing the route so that a freight train can run at its maximum speed and achieve minimum run time through this route section "loses" about 5 or 6 theoretical stopping train paths, because the freight achieves faster run times than a stopping passenger service. A number of ways to reduce this impact exist. It would be possible to slow the freight so that its overall run time matches that of the passenger service, in which case the "loss" would be much less, but the freight path would achieve a lower average speed. It would also be possible to sequence a freight train within the slow line service (Table 11 and Table 12) so that it avoided most of the impact, because west of New Malden there are in practice considerable gaps between passenger services on the slow line. So the idea that there is a definable "loss" of passenger capacity for each freight train is not valid. It can equally be looked at as a "loss" of journey time by the freight operator. The problem is a mismatch between average speeds. The impact depends on the length of route under consideration – the longer the route the greater the difference in run time. It must be emphasised that these figures are entirely synthetic. They would be very different in a different context on another route.

It is perfectly feasible to create a separate Notional Capacity measure for freight (see Figure 13). However the question is whether such a measure would have any value on a mixed route where the predominant services are for passengers (unlike the situation in North America, for example, where the position is reversed). The impact which subdivision of available capacity between passenger and freight has on overall capacity in use depends firstly on the difference in average speed between the services, secondly on freight train length, thirdly on freight train performance and only fourthly on the characteristics of the infrastructure. It would also be possible to create a "Plannable Capacity" measure for a mixture of freight and passenger services but the critical issues would be the same and would overwhelm any differential effect of the TPR. It is therefore suggested that in respect of freight, efforts should be concentrated on the issues which the freight stakeholders raised. These were (see Chapter 2):

- Improvements to the timetabling process so that fewer contingency paths need be held
- Improving the "Quality of paths"

Measures could be derived which would enable improvements to either or both of these to be tracked. Tracking the actual number of freight train kilometres run compared with those planned in the timetable would reveal the level of contingency paths. Tracking the average speed of freight trains would reveal the quality of paths.

5 Conclusions and Recommendations

This project has explored the issue of capacity measures in a number of different ways. A literature search has brought to light many ideas, but also confirmed that the potential capacity of a railway cannot be defined in isolation, outside the operational context within which it is to be used. Discussions with the Client have confirmed and consolidated ideas. Discussion with industry stakeholders has established that the objectives of the project are generally understood, outlined existing practice and explored the practicability of initial ideas. These ideas have been taken through a process of exploration in the "Worked Example" as a result of which some appear practicable and realisable and some do not.

At an engineering level there is less room for divergence of ideas and the picture is simpler. A "Notional Capacity" measure can be aligned closely with the well-established concept of "signalling headway". Given a set of infrastructure data this value can be established using one of a number of software-based simulators which include an accurate dynamic model of train movement combined with the ability to accurately model signalling and track infrastructure. Network Rail has an ongoing programme aimed at acquisition, consolidation and maintenance of its infrastructure data and has the appropriate modelling tools. It already carries out such modelling both to support infrastructure improvement schemes and to support progressive review of its Timetable Planning Rules (TPR). It is suggested that this process should be made more transparent and subject to a more precise definition of the parameters to be established and how they should be selected in each case (the current rules in TPR are somewhat vague). Currently the modelling is carried out in the background with the declared parameter (Planning Headway) already subject to trade-off and rounding. The "Notional Capacity" of a route should be objectively defined and measured and not subject to subjective adjustment or rounding. The industry's current planning tools, processes and measures work to a "granularity" of 30s – so TPR work in general to the nearest 30s as does the working timetable. This adds to the constraints within the timetabling process and should not be reflected in the base measure. Reducing this (as is Network Rail's long term plan) will help release more capacity in densely used areas.

The "Plannable" capacity of a route is much more difficult. ORR's objective is to show how the application of TPR affects the available capacity to run trains. The problem (see Figure 1) is that TPR are applied in a selective way depending on the sequence and stopping pattern of the services it is desired to run. Determining the optimum service sequence and combination of stopping patterns to deliver the desired levels of service to customers whilst maintaining best use of route capacity is the science and art of timetabling, so finding a value for plannable capacity inevitably means carrying out part of the timetabling process. The problem with this is that it is hard to automate and will be subject to challenge based on the use of judgement. There are other possibilities. Capacity Utilisation (in accordance with UIC 406) is a parameter which can be calculated. However it does not meet ORR's objective of showing the impact of TPR; it is also variable with stopping pattern and it varies with the length of route under consideration.

"Capacity in Use" is easy to measure at the level of trains per hour per track. Both planned (timetabled) and actual on the day (throughput) values can be acquired and tracked using data in the public domain. This can provide information which is clear, detailed and not subject to judgement and potential dispute. The difficulty is the complexity of the picture. Route capacity in trains per hour tends to be considered as a single value, but brief consideration of "Capacity in Use" shows that it varies enormously with both location along the route and with time of day and between tracks and directions.

Location of the measuring points used is important. The following criteria are suggested in Chapter 4:

- "Plain line" timing point (makes analysis much easier);
- At known maximum flow points (for example the approach to terminals);
- At a maximum point on each branch or connecting route (usually adjacent to the junction with the main route).

In the "Worked Example" the following points could be considered:

- Vauxhall (main, slow and Windsor) – measuring total "Main Line" flows into Waterloo;
- West Byfleet (main and slow) - measuring longer distance and outer suburban flows;
- Brookwood (main and slow lines) – measuring flows from Southampton, Alton and Salisbury routes;
- Worplesdon – measuring Guildford and Portsmouth line flows.

The Role of 'Capacity in Use' is mainly to establish the planned traffic flow following the application of the service specification, the TPR and the timetabling process. For comparison with Notional Capacity, the peak hourly flow (rolling 60 minute average) should be used.

However the information could have a variety of uses beyond this. Tracking changes in capacity provision vis a vis crowding and growth in footfall could be valuable. Comparison between routes may also be useful and could trigger ideas for releasing additional capacity.

Measuring capacity in use at a relatively few key points on the network would seem to make sense.

The question then is how to present the information. One possibility is a route "dashboard" (see Figure 5). However it is understood that many other possibilities are already under consideration for the presentation of industry performance data and the information could be fitted in with whatever format is decided on at industry level. A quite simple system of selection would allow AM and PM peak flows to be automatically picked out and presented.

Other information such as average flow over the railway day (say 06:00 to 22:00) might also be of value. Data already available in the industry should allow planned and daily values to be extracted and the change in achievement over time to be tracked.

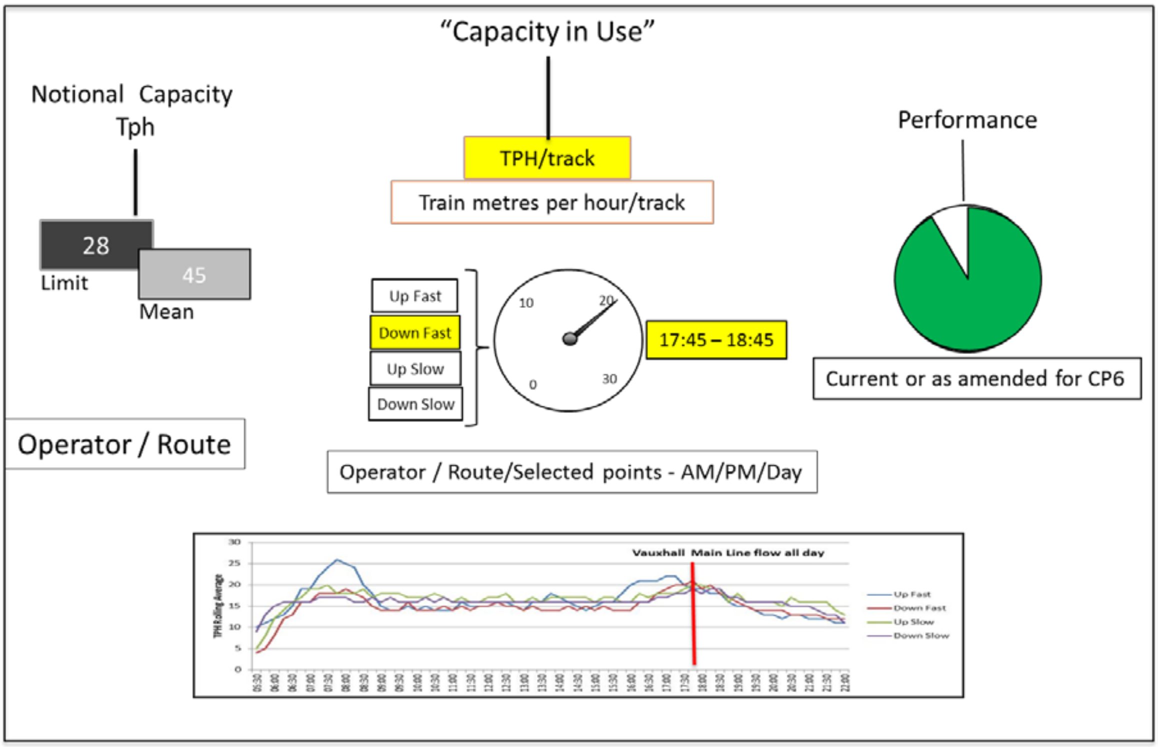


Figure 5 Example Dashboard

Other possibilities to enhance and focus this information include:

- Adding train consist data (available from TRUST and Operators) to produce a "train metres per hour" figure passing a point – this would be a useful analogue for passenger capacity and would show the positive impact of train lengthening;
- Separating "capacity in use" values by train operator and routes would be simple to do;
- Freight movements could be distinguished from passenger, and separate values published. Values for paths allocated and paths actually used would be very useful and by giving an idea of capacity left unused as a result of inflexibility in short term planning will provide justification both for path requirements and changes required;
- Excluding empty stock movements from the figures. This might be considered unfair to Network Rail since these movements are essential to operating the railway, but would give a more passenger focused picture; comparison between routes and between TOCs could also give a measure of efficiency with which rolling stock is used and the potential for increasing passenger/freight paths
- Producing "capacity in use" figures for a station, including only trains calling there.

5.1 Recommendations

The industry should consider the use of the following capacity measures:

- "Notional Capacity" – a standardised calculation based on non-stop signalling headway calculated using an appropriate simulation tool using an industry-agreed process and set of parameters including the appropriate rolling stock from a simplified list, to be published annually by Network Rail for each route and updated regularly as part of the TPR review process;
- "Capacity in Use" – values of train flow (peak trains per hour per track) measured at key points on each route, enhanced with train consist data to provide also "train metres per hour per track", published annually for key nodes on the network.

This study has not identified a "Plannable Capacity" measure which meets ORR's criteria without being complex and time consuming to create and importing a high level of subjectivity. At this stage, therefore, we can make no recommendation in this area. It would be possible to use the UIC406 measure of "Capacity Utilisation". This gives a view of the level of loading on the route and some indication of whether there is spare capacity available. However, it does not meet ORR's criteria for Plannable Capacity.

The measures proposed above could be incorporated into an "industry dashboard" for a route (probably split by train operator), bringing together "Capacity in Use" figures for the AM peak and PM peak and PPM values (split by route if available).

5.2 Next Steps

We suggest the following next steps:

- Validation of Proposals

  The proposals presented in this report have so far been tried only on one example route (with a single TOC, where Network Rail and the TOC have worked together to optimise the timetable). They need to be validated on another main line section with more than one TOC operating and significant freight traffic (West Coast Main Line would be a suitable target) and also on a regional route with lower traffic, before any further roll out is considered. A route which has just been resignalled would be very suitable as current up to date values of technical headway should be available.

- Consultation with Network Rail

  We understand that ORR intends to consult these proposals widely within the industry. Before this is done, it would be helpful to discuss them further with Network Rail to ensure that they are consistent with its understanding of how its processes work. It may also be possible to align the "Notional Capacity" concept better with these processes, so that duplicated work is avoided.

6 Acknowledgements

The project team would like to thank the rail industry stakeholders for their participation and input to the discussions through interviews and attendance at the workshops.

We would also like to thank William Barter, Dave Fisher and Tim Kendell for sharing knowledge and expert input to the project work.

Appendix A Literature Review

A.1 Introduction

The capability of the transport network to meet the growing demands being placed upon it is a growing concern world-wide. In addition to congestion on the road networks, crowding in public transport (road and rail) is becoming a serious issue. In the case of railways, the reality is that the demand which has shown strong growth over the last decades, particularly in the passenger sector, is not evenly distributed on either a spatial or a temporal basis. Recent years have seen significant growth in some sectors, routes, times of day etc. For example, where commuters are the primary consumers, services have become overcrowded during peak hours with numerous examples of excessive crowding on a number of routes. Crowding has effects on railway operations (e.g. operating speeds, dwell times, travel time reliability and modal choice) as well as passenger experience (e.g. well-being and value of time) and it is therefore crucial to understand where, when and why additional railway capacity is needed. Railway capacity and how to improve it are currently among the most significant concerns of many governments, infrastructure managers and operators worldwide (EC, 2011; RTS, 2012).

This report summarises the results of a literature search into the definitions and assessment of the capacity of railway networks and any metrics that have been proposed to support better management of the railway network capacity.

The literature search has been undertaken through the following information channels.

- Academic papers available through the Library of Glasgow Caledonian University.
- Spark, the Railway Industry Information resource managed by RSSB.
- Other industry sources and the Internet
- The Institution of Railway Operators (IRO) degree course - Operational Planning Module.

The Academic papers give a wider view on the assessment of capacity through research reports and presentation from various conferences. Spark holds a wide selection of research briefs and reports from studies undertaken by RSSB for DfT and other strategic research programmes. The IRO module text also gives a view on how capacity can be assessed and managed for the GB rail network.

In parallel, discussions were held with stakeholders and reports identified by Stakeholders as relevant to this study have been included in this review. Whilst not all items initially identified proved relevant, the search revealed a considerable amount of published material and the most significant ones are further described in this report.

A number of definitions of capacity and its assessment have been published, together with models and proposals for improving the utilisation of the available capacity. The papers and reports identified can be split into several categories ranging from methods to assess capacity, reviews of how capacity is utilised and general discussions on potential metrics. The published literature also has a number of papers discussing methods of evaluating railway capacity including pure analytical, optimisation and simulation methods.

In addition to railway capacity, a limited search of the internet was also carried out to understand how capacity issues are addressed in the water and gas industries and in the Highways sector in the UK.

A.2 Railway Capacity Definitions

There appears to be general consensus in the literature that railway capacity is an elusive concept and it cannot be uniquely defined or quantified (Kozan & Burdett, 2004; Kozan & Burdett, 2005; Krueger, 1999; UIC, 2004). Consequently, definition of railway capacity is often related to the context in which it is being considered. An example of various views is shown in Table 16.

Market (customer needs)	Infrastructure planning	Timetable planning	Operations
Expected number of train paths (peak) Expected mix of traffic and speed (peak) Infrastructure quality need Journey times as short as possible Translation of all short- and long-term market-induced demands to reach optimised load	Expected number of train paths (average) Expected mix of traffic and speed (average) Expected conditions of infrastructure Time supplements for expected disruptions Maintenance strategies	Requested number of train paths Requested mix of traffic and speed Existing conditions of infrastructure Time supplements for expected disruptions Time supplements for maintenance Connecting services in stations Requests out of regular interval timetables (system times, train stops, etc.)	Actual number of trains Actual mix of traffic speed Actual conditions of infrastructure Delays caused by operational disruptions Delays caused by track works Delays caused by missed connections Additional capacity by time supplements not needed

Table 16 Different views of railway capacity (UIC 2004)

Capacity is often expressed in terms of the number of passenger kilometres per year and freight tonne kilometres per year or passengers per hour and freight tonnes per hour. This relates to the carrying capacity of the railway and reflects both infrastructure capacity and train capacity. However, while this concept is often used to express the scale of a railway in comparison with other railways or with other modes of transport, it is rarely used in day-to-day railway operations. In practice, railway capacity is often associated more with the ability of infrastructure to accommodate train traffic.

A.2.1 Definitions

According to Kozan & Burdett (2004, 2005), “the simplest approximation and the most prevalent encountered is that the capacity of a single line is the total number of standard train paths that can be accommodated across a critical section in a given time period, where a standard train is defined as the most prevalent type to traverse the corridor".

The International Union of Railways (UIC) has attempted to provide a definition of railway capacity which is supposed to work for as broad a spectrum of scenarios as possible (UIC, 2004).

"The capacity of any railway infrastructure is:

- *the total number of possible paths in a defined time window, considering the actual path mix or known developments respectively and the Infrastructure Manager's own assumptions;*
- *in nodes, individual lines or part of the network;*
- *with market-oriented quality."*

The process used by UIC 406 for calculating capacity utilisation takes into account the planning headways, the traffic mix and any buffer time required for reliability. This is undertaken by using an existing timetable that reflects peak utilisation over a set period. The timetable is compressed so that each train is at the minimum buffered time apart.

Some of the set parameters will change according to the number of trains, homogeneity of the services, average train speed and service stability. These characteristic vary between types of railway and thus explain the apparent disparity of declared capacity between routes. UIC 406 uses the diagram in Figure 6 to illustrate this disparity.

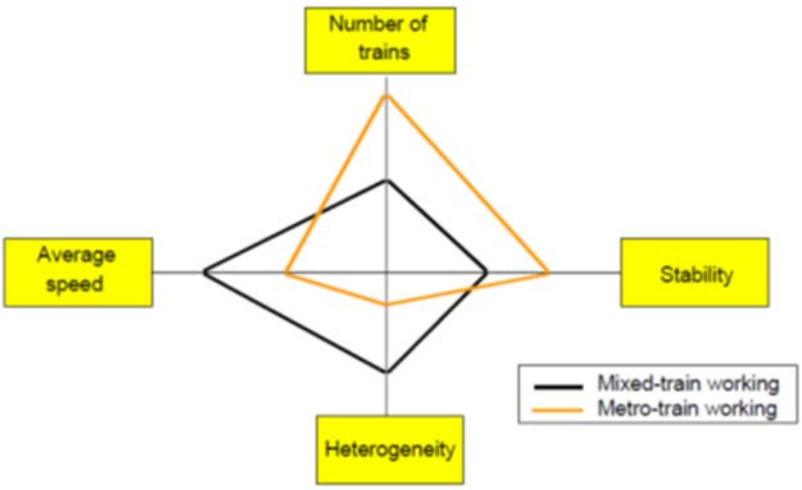


Figure 6 Characteristics affecting balance of declared capacity between routes (UIC 406, 2004)

Krueger (1999) of the Canadian National Railway adopted the following general definition:

"Capacity is a measure of the ability to move a specific amount of traffic over a defined rail line with a given set of resources under a specific service plan."

He also provided various specific definitions and measures of capacity as follows:

*"**Theoretical (Physical) Capacity**: This is the theoretical maximum upper boundary of capacity. It assumes all trains are the same, with the same train consist, equal priority, and are evenly spaced throughout the day with no disruptions. It ignores the effects of variations in traffic and operations that occur in reality."*

> *"**Practical Capacity**: The practical limit of "Representative" traffic volume that can be moved on a line while achieving a defined performance threshold. "Representative" traffic reflects actual train mix, priorities, consists, power to weight, and traffic bunching."*
>
> *"**Used Capacity**: The actual traffic volume occurring over the territory. Reflects actual variation in traffic and operations that occur on the line."*
>
> *"**Available Capacity**: The difference between Used and Practical Capacity. It is an indication of the additional traffic volume that could be handled while maintaining the predefined performance threshold."*

According to Krueger, practical capacity is the most significant measure of track capacity since it relates the ability of a specific combination of plant, traffic and operations to move the most volume within an expected service level.

Abril et al (2007), in their study on the Assessment of Railway Capacity, have added to the discussion on the definitions proposed by Kruger and described what they refer to as the four types of capacity used in the railway environment:

- *Theoretical capacity*: is characterised as an upper theoretical limit of line capacity and is calculated using an empirical formula. As such it is a mathematical representation of the maximum number of trains that could be used by a railway line in ideal conditions during a given time period (but not actually achievable);
- *Practical capacity*: Traffic flow that can be offered under normal operating conditions, driving on the railway line with an acceptable level of reliability. This is calculated using more realistic assumptions related to the expected operating quality and system reliability; It is quoted as being about 60 to 75% of the theoretical capacity; similar to Kruger, the practical capacity is seen as the most significant measure of track capacity.

The proposed relationship between theoretical and practical capacity is shown in Figure 7 which also demonstrates that as capacity utilisation increases, performance tends to go down.

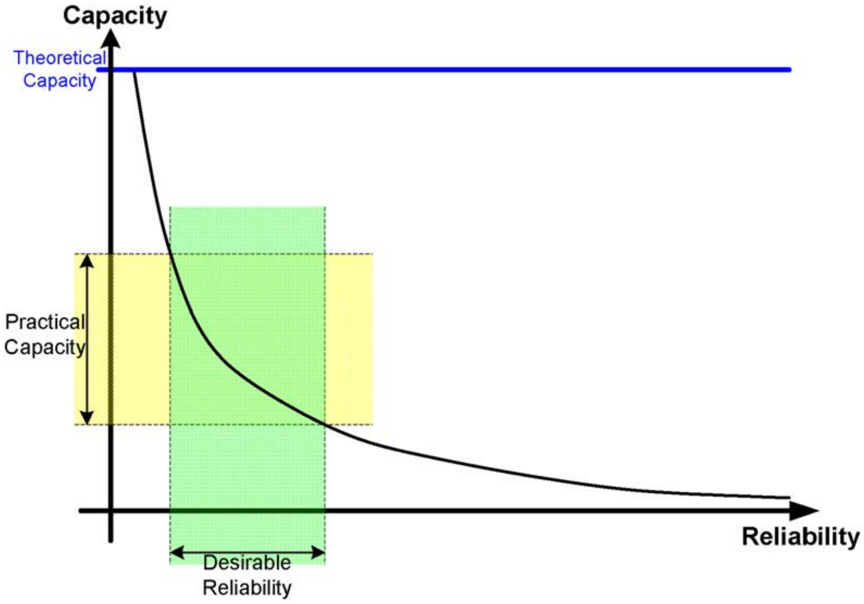


Figure 7 Theoretical and Practical capacity (Abril et al, 2007)

- *Used capacity*: The effective traffic flow that is canalized through the line (and is usually less than the practical capacity);
- *Available capacity*: Difference between the practical and the used capacity and is an indication that additional trains could be run on the route.

Dingler (2010) looked at the 'impact of operational strategies and new technologies on railway capacity', specifically due to the recognised need to meet the forecasted increase in demand for rail freight in North America. One aspect covered in the doctoral research was more efficient use of existing capacity through better understanding of operational practices, as 'operational changes are more flexible and rapidly implemented'. Following an in-depth review, the thesis notes that capacity is influenced by the complex relationships between infrastructure, operations, motive power, rolling stock, maintenance and human resources and falls back on the general definition that railroad capacity is '*the ability to move a specific amount of traffic with acceptable punctuality'* and these can be based on location (line, network, terminal), calculation (theoretical, practical) and utilisation (maximum, used, or available). Dingler then used the four categories of capacity as the common terms to represent calculated capacities.

A.2.2 Summary on Capacity Definition

The overall consensus is that there is no standard definition or measure of rail system capacity. This is also supported by the report produced by RSSB's Knowledge and Technology Transfer Services on "Limits to capacity" (S103)[5] that reviewed a range of papers. Many of the papers identified looked at specific types of networks, operations with analytical or simulation techniques to provide a basis for assessment of capacity within the specified train pattern. The study concluded that the UIC assertion that *"Capacity as such does not exist. Railway infrastructure capacity depends on the way it is utilised"* is a correct representation.

A.3 Capacity evaluation/utilisation

A thorough review of the UIC 406 capacity utilisation procedure was performed by Landex et al (2006) in an analysis of the use of UIC 406 on Danish Railway line sections. The results of this report found that, although it was easy to make annual capacity utilisation statements on maps, capacity utilisation was sensitive to the characteristics of the network being examined. UIC 406 should therefore only be compared relatively, along the same line sections each year, rather than absolutely. The report further notes that, even though the analysis may show that an extra train could be run on a section of track, this may not be possible if there is no suitable capacity on adjacent sections of the network.

One such example of capacity utilisation mapping was the 2008 West Midlands and Chilterns RUS (Figure 8), which had a section on Capacity Utilisation Indices (CUI) alongside the plans for the network covered by the RUS. The plans showing the CUI for various elements of the network shows the impact of the nodes and line sections that constrict capacity.

[5] This report is available only on RSSB's SPARK database, accessible only by its members.

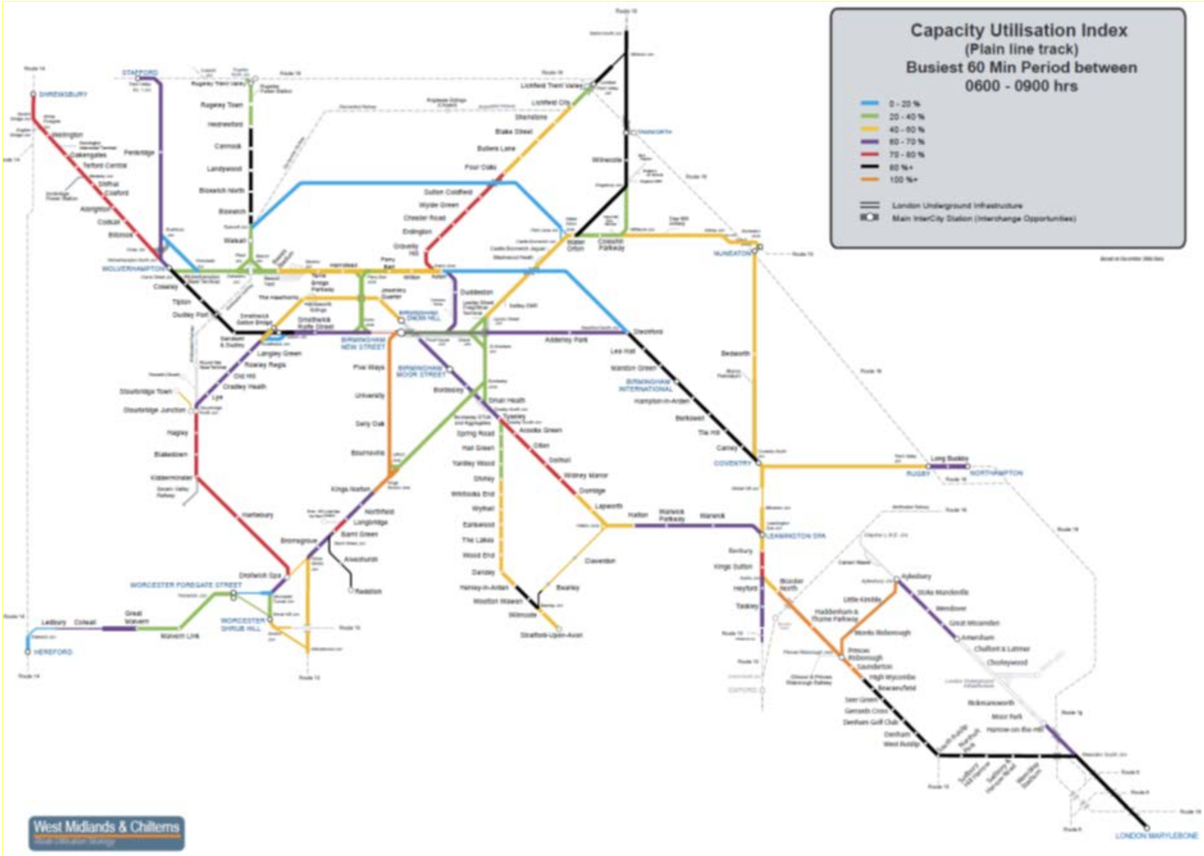


Figure 8 Capacity Utilisation Index map for the West Midlands and Chilterns Rail Utilisation Strategy, 2008 (Network Rail, 2008)

Figure 8 shows some highly utilised route segments between Coventry, Birmingham New Street and Wolverhampton that are commercially important and represent a capacity constrained route. Other parts of the diagram show isolated, high utilisation, hot-spots amongst more lightly utilised areas such as Bearley Junction near Wilmcote. In our view, based on our understanding of the routes, these may be due to specific layout or signalling constraints that do not impinge on the general route capacity or have significant commercial importance; many of the constraints could be relieved at a relatively small cost but without any significant overall benefit to the route or the TOC.

Any metric developed should not be unduly sensitive to these small isolated areas of high utilisation where their resolution would not make significant improvement to capacity for meeting demand. Solving an isolated area of high utilisation may not release significant capacity if there is another hot spot nearby that could become critical; a route based analysis would be required to ensure that the consequences of isolated improvements is understood and this should be encouraged by any metric.

The National Rail Freight Infrastructure Capacity and Investment Study (AAR, 2007), carried out by the Association for American Railroads, identified the enhancements needed to meet rail freight demand in 2035. As part of the study, analysis was carried out to determine the congestion levels, represented as the Level of Service (LOS) for all primary rail freight corridors in the US, using the train volume-to-capacity ratio. The analysis was all carried out using existing and publicly available data and followed a simple methodology.

Current corridor volumes, in trains per day, were estimated for each corridor using data sampled from an annual survey of railcar movements and scaled up to represent all annual railcar movements across the US. The maximum capacity, also in trains per day, of each of the corridor was estimated based on the combination of the number of tracks, type of signalling control system and the mix of train types (for each combination of number of tracks & TC system, the maximum number of trains that can be accommodated was determined by the mix of trains on that corridor).

The volume-to-capacity levels across US primary railroad freight corridors are shown in Figure 9.

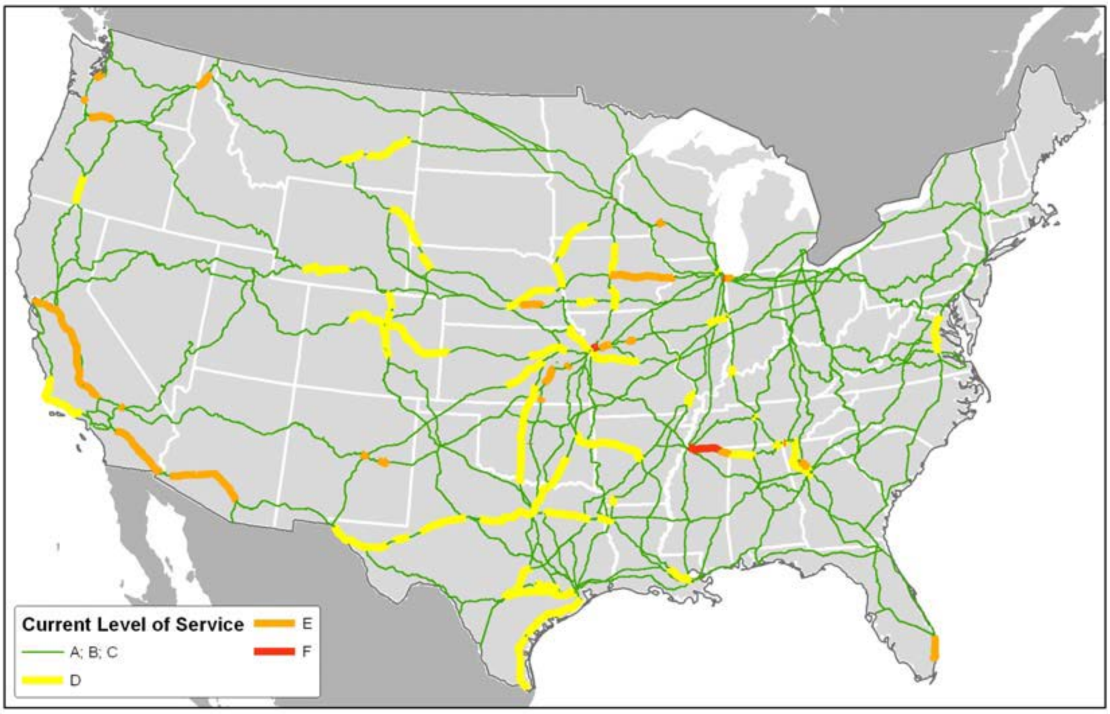


Figure 9 Current train volume-to-capacity ratios on the US primary railroad freight corridors. Level of Service (LOS) Grades A, B, C: <70%; LOS Grade D: 70-80%; LOS Grade E: 80-100%; LOS Grade F: >100% (AAR, 2007)

The analysis identified areas operating below, at and above capacity. Corridors operating at LOS C were expected to have stable train flows, while those operating at LOS D and above were sensitive to perturbations, with recovery times on an increasing trajectory for the D, E and F levels. The study also showed that at the time of the analysis, 88% of the network operating below capacity with only 1% operating above capacity.

Huber and Herbacek (2013) further analysed the use of the UIC 406 Code for calculating capacity utilisation through nodes. This research concluded that reduced line section lengths significantly improved capacity utilisation, when using the UIC 406 capacity utilisation procedure. Furthermore, the analysis of capacity utilisation through a node requires a “third dimension” associated with the occupation and release of block sections through the node. However, as the authors of this report noted, this approach is much more complicated than the technique for calculating capacity utilisation on simple line sections.

Other studies looked at how to analyse absolute capacity using several logical, probabilistic, junction occupancy or network bottleneck approaches, whilst taking into account the traffic mix, signalling systems, dwell times and the characteristics of the network being considered.

Several studies have used or developed simulation methods to demonstrate the relationships between theoretical capacity and practical throughput. Two examples that are specifically relevant are described below.

- Confessore et al (2009) adopted three categories of capacity, theoretical (maximum train paths in ideal circumstances), commercial capacity (realistic circumstances and reflecting market orientation) and usable capacity (difference between theoretical and commercial). The paper describes an approach for estimating the commercial capacity of railways, intended as the number of possible paths in a defined time window on a rail line, or part of it, considering a fixed path mix, with market-oriented quality. The proposed simulation-based approach was developed for the rail line Verona–Brennero, located in the Italian part of the European Corridor Hamburg–Napoli. The results were used to estimate the commercial capacity differences between the whole line and three important line sections within it. The analysis also calculated the estimated increase in commercial capacity that could result from a reduction in time spacing between trains.
- Dicembre and Ricci (2011) used simulation to evaluate the theoretical and practical capacity on urban railway corridors. The paper reports on the correlation between capacity, block sections length, typology of services and timetables for high density lines. The analysis has been used to establish the links between a railway system's performances and timetable planning criteria and also the potential trade-offs between appropriate recovery times and buffer times, which influence available capacity.

The research appears to be mainly carried out by academic research and there is no specific information on the use of the results by infrastructure managers and operators to influence decisions on operations and improve the usable capacity.

In 2010, TRL and the University of Birmingham organised a stakeholder workshop as part of a DfT-sponsored research project to review railway capacity in the UK and elsewhere. One idea used during the workshop was that of the "network diagram", demonstrating:

- the overall capacity available (equates to theoretical capacity);
- where capacity is lost;
- the factors that contribute to this loss;
- the associated proportions of the lost capacity; and
- the usable capacity (equates to practical capacity).

Following the workshop, several stakeholders submitted their own capacity breakdowns, giving their views on how capacity is being lost on the GB network. The results shown in Figure 10, clearly demonstrate the divergence of views, but also indicate that there could be opportunities to improve 'usable capacity'.

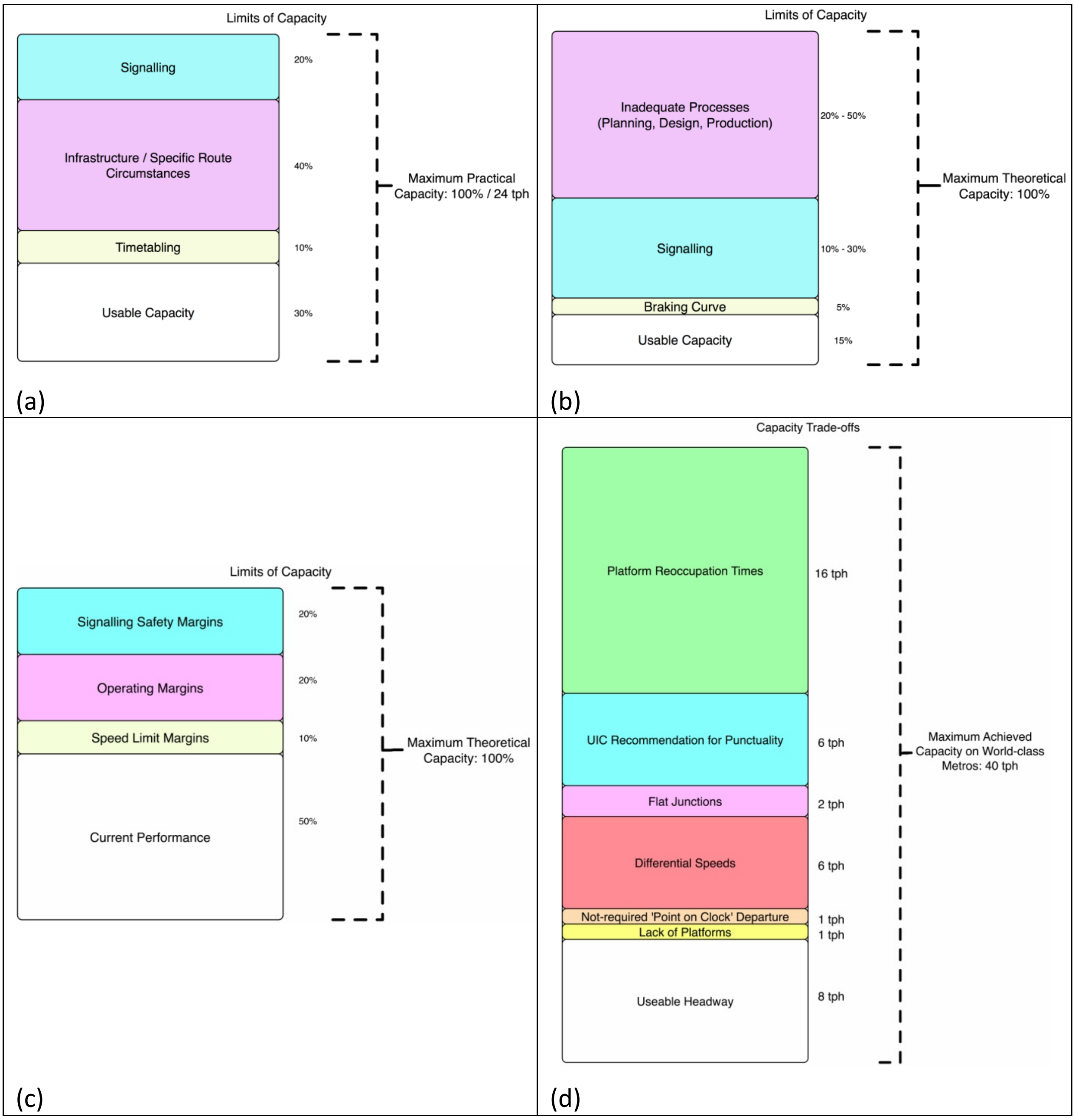


Figure 10 Railway Network Capacity Diagrams

A.3.1 Summary on Capacity Evaluation

The use of CUI and UIC 406 methods for calculating the differences between the actual and compressed timetables for a specific network/route seems to be a particularly popular evaluation technique. These approaches were, however, found to contain some inherent weaknesses, including sensitivity to the length of the section being analysed and the complexity of performing these analysis through nodes. Other techniques primarily compared differences between theoretical, practical (planned) and utilised capacity, through a number of approaches, to determine where capacity is available, how this capacity was lost and what effect using this spare capacity would have on the performance of the network.

The simplified methodology described in the AAR report to identify the routes on the American Railroad system that are over, at or near capacity could be a useful first step in communicating the status of the network and contributing to a better understanding of where capacity could be available and is needed on the network.

A.4 Capacity Metrics

Different categories of metrics exist for measuring how well infrastructure capacity is utilised including throughput (number of trains, tonnes, train-km and tonne-km), level of service (LOS) (terminal/station dwell times, velocity, punctuality/reliability factors and delays) and asset use (block occupation time or percentage usage) (Sameni et al, 2011). Although the most intuitive way to determine capacity appears to be the use of the maximum number of trains operated over the network in a given time period, railway capacity utilisation is a complex trade-off involving various influencing and conflicting factors (Dingler, 2010). Consequently, this makes it challenging to define and measure capacity using a single metric.

The following section summarises a range of metrics, identified in published literature, to calculate infrastructure capacity and capacity utilisation.

Perhaps most importantly for the GB railway sector, the McNulty Rail Value for Money (RVfM) report examined the cost structure of the GB railway sector to identify options for improving passenger and taxpayer value for money (McNulty, 2011). The conclusions of the RVfM assessment highlighted inefficient network capacity allocation as a constraint on the ability of the industry to accommodate extra traffic. The report suggested that capacity be measured as passenger-km per train-km (train capacity) and train-km per track-km (track capacity).

In a series of reports, Dingler (2010), Sameni, Landex and Preston (2011) and Sameni et al (2011) recognised that railway capacity should be defined and measured through the use of multiple metrics, and that analysing trends using a single metric fails to capture the complexity of rail performance. These studies identified metrics to define railway capacity including:

- Throughput: Trains, cars, tonnes, passengers, seats, space (train length)
- Level of service: Terminal dwell, average velocity, delay, cancelled/late trains
- Asset utilisation: Average velocity, capacity utilisation, load factor (crowding)

These analyses looked at Northern American freight operations, levels of heterogeneity, volumes carried, resultant delays and the economic impacts of the changes in capacity associated with these factors. Sameni et al. (2011) built on this research further by developing a profit-generating capacity measure to measure capacity by means of profit. This used the different costs, revenues, delays and utilisations of capacity associated with different operational strategies to calculate and optimise the extraction of value from the railway network.

In a previously performed literature review, Haith (2015) identified four key metrics reported in literature for measuring capacity:

- Sectional running times;

- Headways;
- Traffic intensity; and
- Capacity utilisation.

Sectional running time is the simplest way of calculating capacity utilisation, by examining the transit time between two points on a network, but is generally seen to be inadequate for analysing capacity due to the effects of variable intermediate signalling. To consider the role of signals in determining the level of potential capacity utilisation, it is important to consider the permissible minimum gap or 'headway' between successive trains. 'Technical headways' are the calculated minimum gaps that apply to specific 'block' sections of the network, whilst 'planning headways' are rounded up to the nearest half-minute (in the UK) during the planning process. Headway values can then be used to simply calculate maximum capacity by calculating the maximum number of trains in a given time period (Equation 1; where *C* is the capacity (i.e. maximum number of trains), *T* is the time period and *H* is the relevant headway).

$$\boldsymbol{C = \frac{T}{H}}$$ **Equation 1**

If the number of trains is known, then Equation 1 can be developed to calculate capacity utilisation, as a measure of 'traffic intensity', for a particular stretch of track (Equation 2; where *I* is traffic intensity (%) and *N* is the number of trains in the time period).

$$\boldsymbol{I = \frac{N}{T/H}}$$ **Equation 2**

Haith (2015) identified two popular approaches for calculating capacity utilisation on mixed traffic railways. These are the approaches proposed by the UIC, and widely used in mainland Europe, and in the CUI approach used in Britain. Both 'compress' the timetable until the trains are at minimum headway apart (Figure 4).

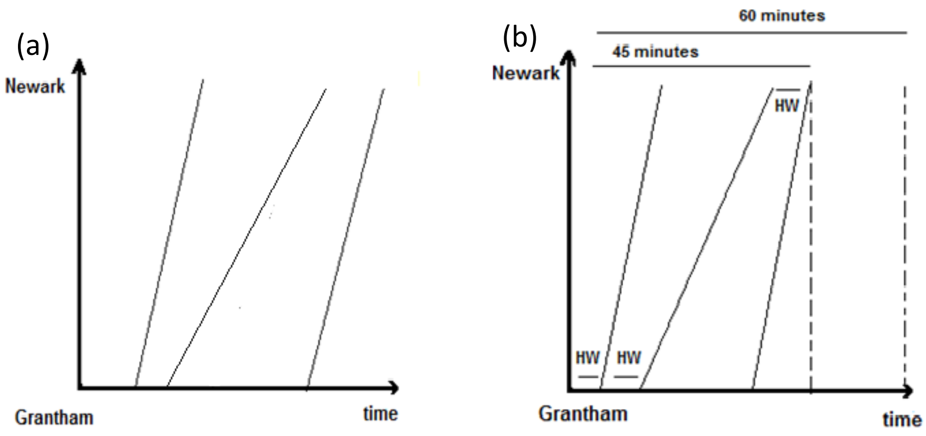


Figure 11 Application of Capacity Utilisation Index (CUI) compression method (Haith et al. 2015)

Figure 11(a) shows the original non-compressed timetable with the second train in the sequence appreciably slower than the other two trains. The compressed state timetable is shown in Figure 11(b), with CUI calculated from the time occupied by the 'compressed' timetable divided by the time period (Equation 3; where A is the time period occupied by the compressed timetable and T is the original time period).

$$CUI = \frac{A}{T} \times 100$$ **Equation 3**

Despite the popularity of the UIC/CUI "compression" approaches, one of its problems is that it is currently largely confined to the calculation of 'link' only capacity utilisation, primarily due to the complexity of calculating capacity utilisation through nodes (i.e. at stations and junctions). Further, issues with the use of CUI and UCI metrics for capacity utilisation lie with its dependence upon the length of the investigated line section and the assessment of nodal capacity (Huber and Herbacek, 2013).

Beck, Bente & Schilling (2013) discussion paper on "Railway Efficiency" looked at several key drivers of efficiency within the railway system and in particular at the functions of infrastructure and operations for a range of railway systems. They looked at the efficiency gaps through key indicators that compared outputs and cost/revenue drivers. The key indicators used for utilisation were for track and train (Figure 12), together with staff productivity and efficiency drivers. The key track utilisation indicator was Million Train-km/Track-km and for train utilisation, Million Transport Units/Track-km, where Transport Units represents the total passenger-km and ton-km combined.

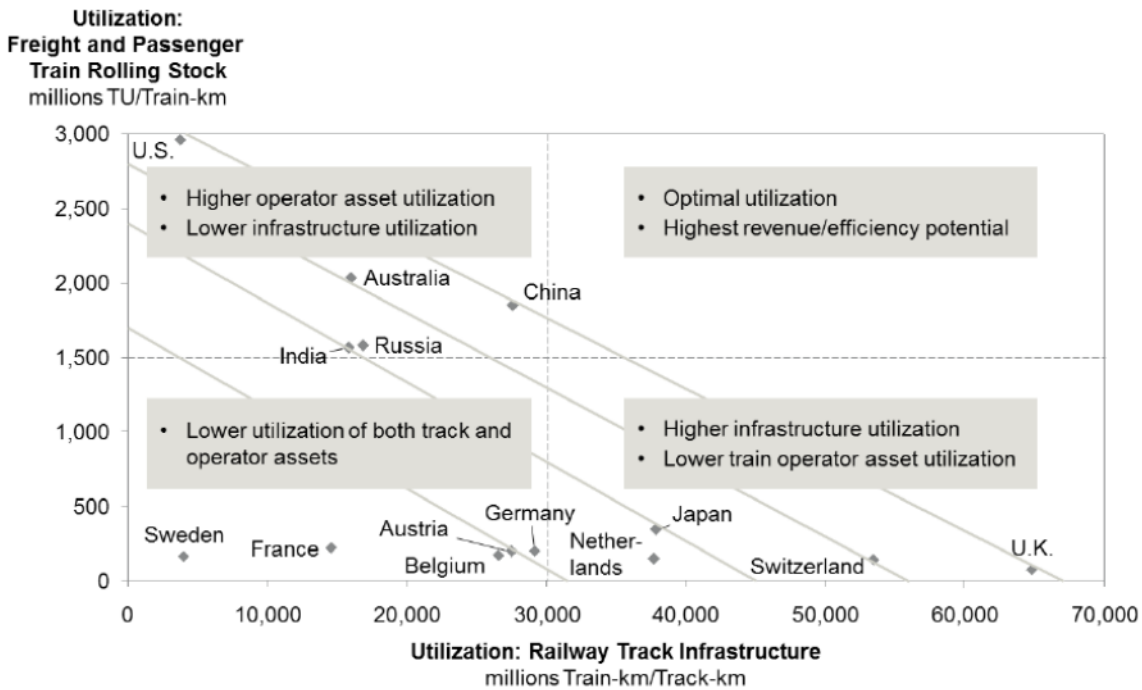


Figure 12 Train operator and railway infrastructure utilisation by country, 2011 (Beck, Bente & Schilling, 2013)

Figure 12 shows that the utilisation of railway track infrastructure in the UK is the highest among the countries investigated, whilst the utilisation of operator assets is low. This suggests that the UK is able to utilise track infrastructure efficiently, but is unable to optimise train utilisation in the same way as, for example the US, Australia and China. A key reason for this may be the geographical differences between large countries (with areas of very low population density) and smaller, more densely populated, countries such as the UK.

Longer trains, travelling longer distances, can significantly increase the utilisation of the train in countries such as the US and China. This graph suggests that, for the UK, the greatest efficiency gains that could be made by improving the utilisation of trains. This would suggest that encouraging increased throughput, in terms of both passengers and freight, is important and is also a key factor to monitor.

Gray (2013) explored the use of a variety of metrics to assess the capacity of a railway and show the impact on performance when utilisation is increased. These metrics were applied to a number of routes in Melbourne through a simulation process and included:

- On-time performance threshold
- Growth of knock-on delay
- Localised timetable stability

The on-time performance threshold considers the five-minute on-time running performance of the network and showed how performance reduced significantly as more trains were scheduled on the route, with a steep downturn in performance when trains are scheduled at close to the technical headway (Figure 13).

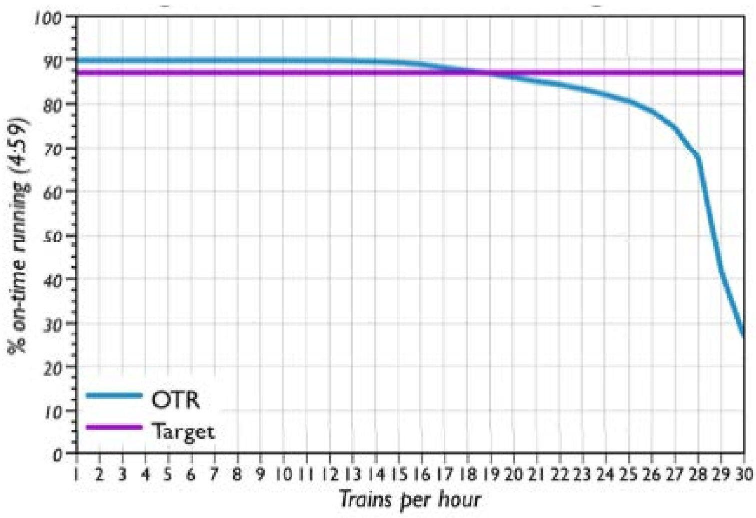


Figure 13 On-time running performance to assess capacity (Gray, 2013)

On-time performance is, however, more indicative of the public performance measure (PPM) currently used by the GB railway network, and throughout Europe, for monitoring punctuality and reliability performance. The use of a performance metric for monitoring route capacity as part of a wider basket of metrics could, however, be very useful for indicating when a route has reached capacity.

Growth of knock-on delay considers the gradient of the on-time performance curve and the average arrival delay. These were less sensitive but showed increasing problems as utilisation increased. Finally, the localised timetable stability metric compared the "sum of the output delays with the sum of the input delays" and if the output delays were less than the input delays, the timetable was considered stable.

A summary of the capacity metrics found during this literature review and their potential application in regards to the definitions used in the literature are presented in Table 17**Error! Reference source not found.**. As can be observed there are several metrics that are specific to a particular capacity application, whilst the majority of capacity metric can be used across multiple capacity applications. It is clear that 'train paths per hour' is the most commonly used metric.

Capacity Metric	Theoretical Capacity	Practical Capacity	Used Capacity	Available Capacity
Train Paths / hour	✓	✓	✓	✓
Passenger-km / year		✓	✓	
Freight Tonnes-km / year		✓	✓	
Train-km / Track-km		✓	✓	
Passenger-km / Track-km		✓	✓	
Freight Tonnes-km / Track-km		✓	✓	
Transport Units / Track-km		✓	✓	
Passenger / hour	✓	✓	✓	
Seats / hour	✓	✓	✓	
Freight Tonnes / hour		✓	✓	
Average Velocity	✓	✓	✓	
Traffic Flow (TPH * Average velocity)	✓	✓	✓	
Train Length	✓	✓	✓	
Load Factor (PiXC)			✓	
Delay Minutes				✓
Cancelled Trains / day			✓	✓
Delayed Trains / hour			✓	✓
Dwell Time				✓
Sectional Running Times		✓	✓	
Journey Times		✓	✓	
Generalised Journey Times		✓	✓	
Technical Headway	✓			
Planning Headway		✓		
Capacity Utilisation Index		✓	✓	✓
Capacity Consumption		✓	✓	✓
Traffic Intensity		✓	✓	✓
On time running threshold			✓	✓
Growth of knock-on delay			✓	✓
Localised timetable stability			✓	✓

Table 17 Capacity Metrics and their application

A.4.1 Summary on Capacity Metrics

From this review it is clear that, although the most intuitive way of determining capacity utilisation is to establish the maximum number of trains operated over the network in a given time period, defining and measuring capacity using a single metric is challenging. This review found a large number of both capacity and capacity utilisation metrics (Table 17) across the literature that have been previously used for measuring the complex trade-off between the various influencing and conflicting factors associated with capacity. It is suggested that this project looks at the combination of a number of capacity metrics that provide a range of useful indicators to ORR for the effective monitoring of capacity.

A.5 IRO Degree course: "Railways Operational Management". Operational Planning Module

A.5.1 Terminology

The IRO Operational Planning degree text states: (Note this text is the copyright of the IRO)

"In fact, in reviewing a network, it is often Utilisation which one is wanting to measure. Utilisation is the actual Usage expressed as a percentage of the Capacity. Whilst these are different things, the issues in measuring them are similar, as Usage may be quite easily quantified, but Capacity has to be defined in order for Utilisation to be quantified."

The definitions inferred from this are simplistically:

- *Capacity: The number of trains that could run*
- *Usage: The number of trains that do run*
- *Utilisation: The ratio between Usage and Capacity*

The simple concepts need to be expanded upon. For instance, a variety of measures of capacity can be found, each offering different degrees of sophistication, and having varying validity depending on the context. Usage can be expressed simply as trains, or may reflect the payload of trains.

A.5.2 Capacity

The fundamental of railway capacity is line headway, that is, the minimum possible interval between successive trains when running at full speed without restriction by signals. This is in turn determined principally by the braking distance from the maximum permitted speed, but also by.

- *Overlap length – set by Group Standards but also related to permitted speed;*
- *Train length;*
- *Sighting Time – or presumably an equivalent system/human response time for ETCS/CBTC;*

This is expressed in the Institution of Railway Signal Engineers text book "Railway Signalling", which presents the relationship between headway and speed. The relationship show assumes in effect that the signalling is perfectly designed to match the permitted speed, and that all trains are running at the full permitted speed. Headways in this case are calculated arithmetically.

In practice, however, as identified by the Institution of Railway Operators degree text:

Whatever the theoretical spacing of signals for the required speed, it may not be possible to locate signals perfectly in practice:

- Signals cannot be placed just beyond bridges, tunnels or cuttings, or round curves that obstruct the view of an approaching driver;
- Signals are not normally placed in the middle of station platforms, to avoid trains being stopped partly against the platform, possibly (in the days before central door-locking) leading passengers to alight where there is no platform;
- Signals might not be placed in tunnels or on viaducts, partly to avoid trains being stopped in such locations that may unnerve passengers, and partly for ease of access for maintenance.

In addition, train speed may vary slightly along a route section, reflecting factors such as gradients and speed restrictions (temporary or permanent) not reflected in the signalling. This will add variation to the time taken to pass through each series of signal blocks forming the separation distance.

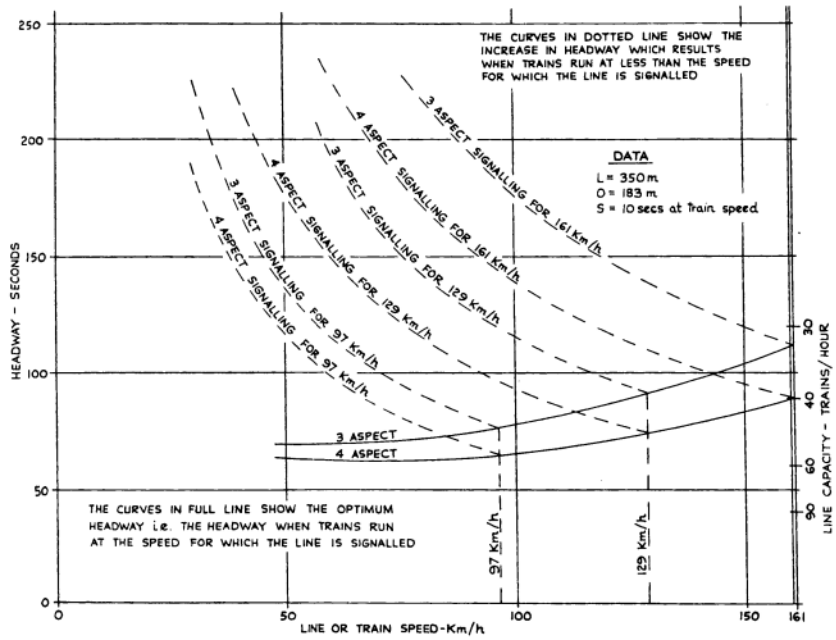


Fig. 2:6 Optimum headway and line capacity and effect of running at a speed less than that for which the line is signalled

[1]Note that the term “Line Speed” is used correctly in this context, meaning the maximum speed permitted by the signalling, and not simply any speed restriction, such as those deriving from curvature, condition of track, etc.

Figure 14: Headway vs Line Speed (reproduced by permission of the IRSE)

The IRSE calculated headways might be referred to as the Theoretical Headway. When practical factors such as those outlined by the IRO are taken into account, the outcome is termed the Technical Headway, and is assessed by simulation modelling.

Network Rail’s National Planning Rules give standards for converting Technical Headway to Planning Headway. The Planning Headway is derived from the Technical Headway, and adds a performance uplift to allow for practical factors such as variation in train running, and robustness. For convenience in planning systems, once a Technical Headway has been uplifted, it is then also rounded up to the next half-minute to give the Planning Headway.

This uplift involves an element of judgement:

- Metro/suburban routes, with same/similar calling patterns and same/similar rolling stock – up to 25%;
- Routes with services travelling 100 miles or less, speed less than 75 mph, mixed traffic – 26% to 75%;
- Routes with services travelling more than 100 miles, speed more than 75 mph, mixed traffic - 76% to 100%.

Crudely these equate to inner suburban, rural or outer suburban, and InterCity respectively.

These uplifts are equivalent to what Leaflet UIC 406 describes as buffer times added to technical headways to achieve “timetable stability”, thus recognising that service performance in the face of adverse events is a factor in capacity. Neither Network Rail nor UIC 406 however distinguish between small uplifts/buffers intended to allow for minor variation in train handling or traction performance, and spare capacity left to assist recovering from perturbation events. A logical approach would be to uplift Technical Headway to an extent that makes individual paths viable, then leave unused paths, “White Space,” to an extent that makes the overall service viable.

Where a flow of stopping trains is the issue, headways derive from the platform reoccupation time plus the platform dwell time. Reoccupation times can be generated from simulation, and are subject to uplift as for line headways. Minimum values for station dwell times to be adopted in timetable compilation are also laid down in Network Rail’s Planning Rules. These are stated to be the value that 75% of trains at a station can achieve, although it is left open as to whether this is an average across the day, or is considered separately for peak and off-peak hours.

The IRO degree text suggests the following are all possible measures of capacity, valid in different contexts:

- *The number of trains that can be passed along a given line at full speed;*
- *The number of trains that can be incorporated into a timetable that is conflict-free, commercially attractive … , and compliant with regulatory requirements;*
- *The number of trains that can be incorporated into a timetable that is conflict-free, commercially attractive, compliant with regulatory requirements, and can be operated within the laid-down performance targets in the face of prevailing levels of Primary Delay ”.*

The text also notes that:

“The more sophisticated the definition, the less the capacity becomes!”

The first definition equates to Line Capacity, and is based purely on Headway – Theoretical, Technical or Planning.

The second definition crucially introduces the realities of planning a comprehensive train service. The requirement to be conflict-free reflects working at junctions, through stations and termini as well as en-route with trains of varying speeds that is compliant with Planning Rules. Other factors represent “softer” objectives of timetabling, aiming to provide, for instance, regular intervals at all stations but still including some fast trains amongst the stopping trains, whereas capacity efficiency is promoted by flighting fast and stopping trains. The IRO terms this "Timetable Capacity".

The third definition supplements this by introducing a performance criterion, as it is now widely recognised in a high intensity service, however conflict-free the plan might be, the risk that one late train may delay others increases. The IRO terms this "Network Capacity". The term "Network Capacity" was adopted by the DfT in the 2007 Rail Technical Strategy in relation to this definition.

Thus the DfT 2007 Rail Technical Strategy also identified System capacity, which takes into account the ability of each train to carry goods or passengers.

RSSB project T915 "Mega City Suburban" of 2010 reviewed capacity concepts and definitions, and presented a diagram sourced from the IRO indicating how capacity decreases as more and more factors are added to the definitions (

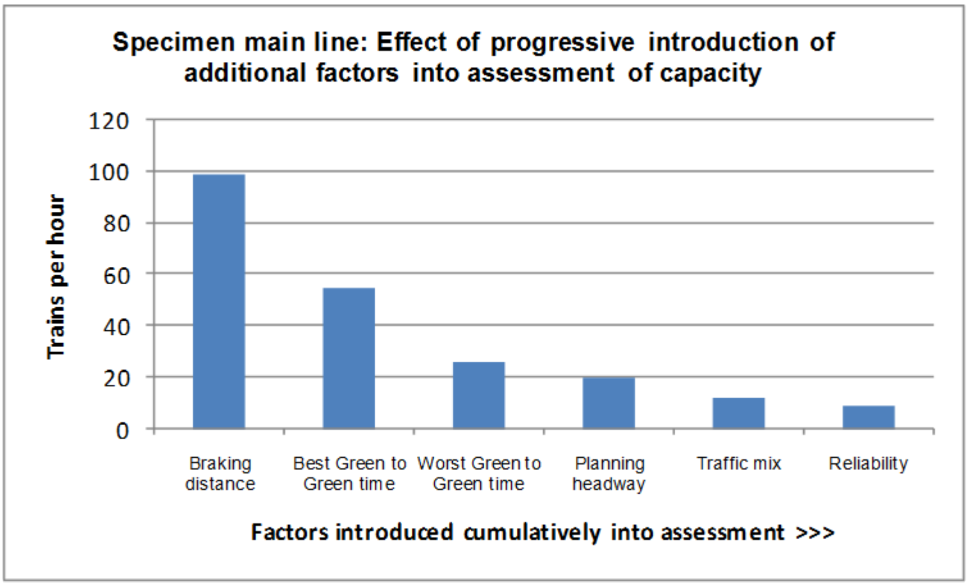


Figure 15: Capacity - how measures relate

Capacity based on braking distance alone represents an ideal case that cannot be improved upon and probably cannot be approached closely even with, for instance, conceptual moving block signalling.

Headway based on the "Best Green to Green time" equates to Theoretical Headway, whilst "Worst Green to Green time" corresponds to Technical Headway deriving from the realities of signal siting. Planning Headway is the Technical Headway uplifted and rounded (the IRO notes that in this example there is little difference between Technical Headway and Planning Headway as one signal section on the route is anomalous). Finally, capacity after considering reliability equates to Network Capacity.

The IRO notes that:

"These definitions are specifically related to the ability of the railway to carry trains, rather than the capacity of the trains to carry passengers or a freight payload, as determined by length of train, seating layout or wagon payload. The capacity of the complete system to fulfil its ultimate purpose is of course a function of both the numbers of trains and the capacity of each train."

Thus the DfT 2007 Rail Technical Strategy also identified System capacity, which takes into account the ability of each train to carry goods or passengers. This “payload” factor could of course be applied to any definition of capacity.

The ITT refers to Notional Capacity, Plannable capacity, Capacity in use and Throughput. Table 18 attempts to set out how these definitions equate to others quoted above, and the factors underlying each.

ITT concept	Equates to	Comments	Measures
Notional capacity	Line capacity as assessed on either: • The theoretical capability of signalling in relation to the Line Speed; or • The technical functioning of the actual signalling system in ideal circumstances of all trains having the same behaviour and running at the speed for which the signalling is optimised.	Neglects influence of “nodes” as it considers only each line in isolation. Needs to be qualified as whether applicable to non-stop or stopping trains	Trains per hour from calculation for simple cases e.g. non-stop, constant speed trains on ideal signalling Trains per hour from simulation for more complex cases e.g. train speed varies en route, signalling block lengths and controls vary en route
Plannable capacity	Line capacity based on Planning Rules headways	Captures uplifts from technical headway to planning headway	Trains per hour from calculation based on 60/headway
	Timetabled capacity	As above but also captures timetabling “hard” realities such as mix of speeds, plus “soft” factors such as requirements for regular interval services at each station	Trains per hour based on timetable exercises.
	Network capacity	As above but also captures performance effects from high utilisation	
	System capacity	As above but also captures payload of trains	
Capacity in use	Usage (measured in terms of trains)	This is an actual figure deriving from timetables	Train numbers broken down by route, function, peak v off-peak etc as necessary
Throughput	Usage (qualified by capacity of each train)	Calculated by factoring Capacity in use by a measure of capacity on train	Capacity on train could be passenger capacity or payload of good but it is difficult to compare the two. Another measure might be train-metres, on the assumption that a train-metre could be either passenger or freight.

Table 18 Capacity definitions

A.6 Other sectors

A.6.1 Gas

The 'entry' and 'exit' capacity operating principles adopted by the GB gas industry gives shippers the entitlement to flow gas on and off the National Transmission System (NTS). Shippers purchase 1 unit of capacity to flow 1 unit of energy on or off the system. This is known as the 'ticket to ride' operating principle, with Quarterly System Entry Capacity (QSEC) auctions used to determine bid allocation for entry/exit capacity (National Grid, 2016). Capacity and energy flow (e.g. utilisation) metrics are measured in kWh/day, similar to the train paths/hour, passengers/hour and tonnes/hour metrics often used by the railway industry.

While any failure by the National Grid to deliver baseline capacity in the long-term (excluding short-term maintenance, emergencies and agreed outages) would be a breach of license terms and incur heavy fines; unlike rail, demand for gas has dropped since 2006, so the pressure on network capacity is currently not so critical.

In relation to capacity in the gas industry, a 'use-it-or-lose-it' (UIOLI) policy is applied to two situations; medium or long-term firm services and short-term interruptible services (EFET Gas Committee, 2002). The primary objective of the UIOLI policy is to ensure that capacity is used efficiently and that a barrier to the development of effective competition does not arise through either restrictions or the provision of inadequate access to unused capacity. A well-designed interruptible UIOLI system can therefore increase capacity availability and can eliminate the need for long-term capacity release.

The firm UIOLI policy primarily relates to medium or long-term contracted capacity that remains unused by the capacity holder, with unused capacity retrospectively determined and subsequently released to alternative users for their future use. This form of UIOLI policy is best suited to situations where the primary capacity allocation mechanism is non-market based, capacity is contracted for periods in excess of one year, demand for capacity exceeds supply or secondary trading of firm capacity is limited.

The short-term interruptible UIOLI policy tends to provide capacity on a daily basis and effectively allows the use of unutilised firm capacity held by network users. In practice, a well-designed interruptible UIOLI policy removes incentives to over-book or withhold long-term capacity, avoiding, or at least diminishing, the problems of implementing firm UIOLI. This allows a certain amount of flexibility in the allocation of capacity in a network and can be used to track and react to changes in demand patterns across the network.

A.6.1.1 Summary

The use of a firm and interruptible UIOLI capacity mechanism for allocating capacity to TOCs could encourage a more flexible, demand-focussed, provision of services for goods and passengers. However, there are a lot of other factors relating to the allocation of capacity in rail which mean that use of such a mechanism may not realise all these benefits in practice.

A.6.2 Water

Water companies are legally obliged to supply water to all customers within their areas, including new developments. National Audit Office report (2007) on 'OFWAT - Meeting the demand for water' focussed essentially on the inherent weaknesses at the time in the information available, both in the demand for water and the level of leakage. Efficiency defined as reduction of leakages was identified as a key issue and OFWAT set leakage targets down to a level where the cost of saving another unit of water through fixing a leak is the same as the cost of providing a unit of water new supply (this prevents charges to customers rising unnecessarily).

Earlier evidence (following the drought in 2006) had demonstrated that companies and consumers can and do respond to non-financial incentives. For example, when Anglian prioritised all visible leaks, consumer demand in the Thames region also reduced to 8% less than the norm for the middle of summer. Consumers in water stretched areas were more willing to conserve water if water companies were seen to conserve water too.

Each company's performance was measured against a range of service categories, including leakage and hose-pipe bans and the overall score feeds into the prices the company can charge.

The recent report by OFWAT (2015), 'Towards Water 2020', highlighted a number of challenges for the water sector going forward, which are particularly affected by the existence of an aging infrastructure, and growing customer expectations for Levels of Services. The challenges identified were:

- Water scarcity
- Environmental water quality
- Resilience
- Affordability
- External influences – climate change, population growth and rising customer expectations.

The policy question being addressed which is relevant to the rail sector is: How to encourage service providers to discover new ways of delivering outcomes to customers while reducing price and improving services? As with Rail, OFWAT is looking for innovation and new ways of approaching issues, i.e. making better use of resources and improving water efficiency and using it across boundaries.

With increasing risk to network capacity (as it starts to decrease, there is risk to continuous supply) and concerns around customers' ability to afford water now and in the future, there is a growing focus on resilience and ensuring a continuous supply in the future.

Severn Trent Water (2015), in response to OFWAT's approach to resilience as part of the Periodic Review, proposed a basket of indicators covering 4 resilience categories: Redundancy, Resistance, Reliability and Response/Recovery. With the focus on enabling long-term sustainability of water resources, it has been recognised that the basket of indicators needs to include forward looking capacity building measures that ensure a long-term view of resilience, with the measures and targets for each company reflecting the priorities of their customers and current resilience levels and needs. Northumbrian Water (OFWAT, 2015), as part of a risk assessment exercise, carried out a theoretical assessment of network capacity compared with full actual pipe capacity in order to determine areas with capacity shortfall, with potential shortfall and no capacity shortfall.

A.6.2.1 Summary

There are a few transferable lessons from the water sector:

- Both suppliers and users respond to non-financial incentives if the right messages are communicated;
- There is concern about future scarcity and this has highlighted the need for innovative ideas to find appropriate solutions; and
- The water companies are beginning to look at ways to improve understanding of capacity issues.

A.6.3 Highways

A.6.3.1 Highway Capacity (USA)

The most widely used Highway Capacity Manual (HCM), published by the US Transportation Research Board (TRB, 2000), defines capacity as "the maximum hourly rate at which persons or vehicles can reasonably be expected to traverse a point or a uniform section of a lane or roadway during a given time period, under prevailing roadway, traffic and control conditions."

- Roadway Conditions refer to the physical aspects of the roadway, such as lane-width, number of lanes, bike lanes, shoulder width, lateral clearance, vertical and horizontal alignments and any other aspect of the roadway;
- Traffic Conditions refer to the characteristics of the traffic stream, such as its composition, vehicles' characteristics and speeds; and
- Control Conditions refer to the types of control (at-grade or grade, unsignalled or signalled junctions), characteristics of control devices (timing, phasing and actuation of the signal system) and traffic regulations (speed limits, etc.).

The manual describes three aspects of capacity:

- Basic capacity: under ideal conditions (most ideal road way, traffic and control conditions that can possibly be attained) with all vehicles travelling at the same speed and the allowed minimum spacing;
- Possible capacity: under prevailing (most frequent/usual) roadway, traffic and control conditions; and
- Design capacity: without the traffic density being so great as to cause unreasonable delays, hazard or restriction to drivers' freedom under the prevailing condition of road way, traffic and control.

The HCM provides methods for estimating the capacity of different types of roadways. Figure 16 presents the speed–volume curves determined from field measurements for ideal conditions: no heavy vehicles, level terrain, and drivers familiar with the roadway. Flow rate is given in number of passenger car per hour per lane (pc/h/ln), and reasonable weather conditions are presumed. These curves end at different capacity values for different free-flow speeds.

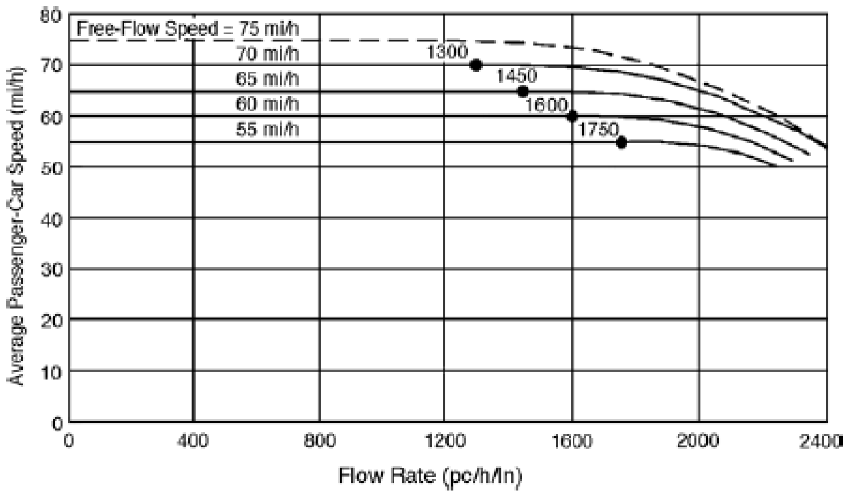


Figure 16: Speed-volume relationships of ideal conditions (TRB, 2000)

There are several situations in which the capacity under ideal conditions is not realistic. Drivers who are unfamiliar with the road tend to drive more cautiously and reduce capacity. Heavy vehicles, particularly on steep gradients, tend to move slower and observe greater distances from other vehicles. Lane width and lateral clearance also affect the driver perception, thus the speed. The capacity of the roadway strongly depends on the number of lanes (Tarko, 2003). To take into account these factors various adjustments have been made available within HCM for different types of road conditions (motorway, two lane rural road, etc.), junctions and upgrade and downgrade road sections. Table 19 to Table 23 show some examples of the adjustments for motorway conditions.

Table 19 Passenger car equivalents on extended motorway segments (TRB, 2000)

Factor	Type of Terrain		
	Level	**Rolling**	**Mountainous**
E_T (for HGVs and buses)	1.5	2.5	4.5
E_R (for recreational vehicles)	1.2	2.0	4.0

Table 20 Adjustments for lane width (TRB, 2000)

Lane width (feet)	Reduction in free-flow speed, f_{LW} (mph)
12	0.0
11	1.9
10	6.6

Table 21 Adjustments for right-shoulder lateral clearance (TRB, 2000)

Right-shoulder lateral clearance (feet)	Reduction in free-flow speed, f_{LC} (mph)			
	Lanes in one direction			
	2	**3**	**4**	**≥5**
≥6	0.0	0.0	0.0	0.0
5	0.6	0.4	0.2	0.1
4	1.2	0.8	0.4	0.2
3	1.8	1.2	0.6	0.3
2	2.4	1.6	0.8	0.4
1	3.0	2.0	1.0	0.5
0	3.6	2.4	1.2	0.6

Table 22 Adjustments for number of lanes (TRB, 2000)

Lanes in one direction	Reduction in free-flow speed, f_N (mph)
≥5	0.0
4	1.5
3	3.0
2	4.5

Table 23 Adjustments for junction density (TRB, 2000)

Junctions per mile	Reduction in free-flow speed, f_{ID} (mph)
0.50	0.0
0.75	1.3
1.00	2.5
1.25	3.7
1.50	5.0
1.75	6.3
2.00	7.5

To assess the degree of congestion on a highway facility the level of service (LOS) is used. It is a qualitative measure describing operational conditions and their perception by drivers. It is intended to capture factors such as speed and travel time, freedom to manoeuvre, and safety. The Highway Capacity Manual defines six levels of service, from A to F, with LOS A representing the best operating condition, LOS E representing the volume being at the capacity level (volume/capacity ratio (v/c) = 1.0) and LOS F representing the volume exceeding the capacity (Table 24). Detailed criteria for LOS for motorway segments are shown in Figure 17 and Table 25. The HCM also provides separate methods applicable to other types of road sections, including multilane motorways and two-lane rural roads; different capacity factors are considered for these roads.

Table 24 General operational conditions of Levels of Service

Level of Service	General Operational Conditions
A	Free flow
B	Reasonably free flow
C	Stable flow
D	Approaching unstable flow
E	Unstable flow (traffic volume is at or near the capacity level)
F	Forced or breakdown flow (traffic volume exceeds the capacity)

Level of Service A

Level of Service B

Level of Service C

Level of Service D

Level of Service E

Level of Service F

Figure 17: Illustrations of level of service (Colorado DoT, n.d.)

Table 25 LOS criteria for basic motorway segments (TRB, 2000)

Criteria	LOS				
	A	B	C	D	E
FFS = 75 mi/h					
Maximum density (pc/mi/ln)	11	18	26	35	45
Minimum speed (mi/h)	75.0	74.8	70.6	62.2	53.3
Maximum v/c	0.34	0.56	0.76	0.90	1.00
Maximum service flow rate (pc/h/ln)	820	1350	1830	2170	2400
FFS = 70 mi/h					
Maximum density (pc/mi/ln)	11	18	26	35	45
Minimum speed (mi/h)	70.0	70.0	68.2	61.5	53.3
Maximum v/c	0.32	0.53	0.74	0.90	1.00
Maximum service flow rate (pc/h/ln)	770	1260	1770	2150	2400
FFS = 65 mi/h					
Maximum density (pc/mi/ln)	11	18	26	35	45
Minimum speed (mi/h)	65.0	65.0	64.6	59.7	52.2
Maximum v/c	0.30	0.50	0.71	0.89	1.00
Maximum service flow rate (pc/h/ln)	710	1170	1680	2090	2350
FFS = 60 mi/h					
Maximum density (pc/mi/ln)	11	18	26	35	45
Minimum speed (mi/h)	60.0	60.0	60.0	57.6	51.1
Maximum v/c	0.29	0.47	0.68	0.88	1.00
Maximum service flow rate (pc/h/ln)	660	1080	1560	2020	2300
FFS = 55 mi/h					
Maximum density (pc/mi/ln)	11	18	26	35	45
Minimum speed (mi/h)	55.0	55.0	55.0	54.7	50.0
Maximum v/c	0.27	0.44	0.64	0.85	1.00
Maximum service flow rate (pc/h/ln)	600	990	1430	1910	2250

Note:
The exact mathematical relationship between density and v/c has not always been maintained at LOS boundaries because of the use of rounded values. Density is the primary determinant of LOS. The speed criterion is the speed at maximum density for a given LOS.

The two most important applications of the highway capacity analysis are: to assess the degree of congestion on a highway facility for a given traffic volume through LOS (operational analysis); and to define the number of lanes required to accommodate a given traffic volume at a desired LOS (design analysis).

To determine level of service of a motorway road section the following steps are often taken:

- Determine flow rate from the given traffic volume and road conditions. For this, adjustments may be required to take into account heavy vehicle (buses, trucks and recreational vehicle), number of lanes, peak hour factor and driver familiarity;
- Determine free flow speed (FFS). This is based on the base free flow speed (design speed) and adjusted for lane width, lateral clearance, number of lanes and junction density;

- Determine level of service (LOS) by comparing the calculated flow rate and free flow speed with those in Table 25.

For design analysis of a new motorway (to determine the number of lanes required) the process is the same as operational analysis above, except the number of lanes is increased (i.e. start with two lanes) until an acceptable level of service is achieved (University of Wisconsin-Milwaukee, n.d.).

A.6.3.2 Highway Capacity (UK)

Highways England (HE), formerly the Highways Agency, currently defines the capacity of its strategic road network using advice notes that determine the traffic flow separately for urban (Highways Agency, 1999) and rural (Highways Agency, 1997) roads. These define maximum capacity as a measure of traffic flow per unit time under favourable road and traffic conditions. Flow rates for urban roads are calculated as the number of vehicles per hour (Highways Agency, 1999), whilst flow rates for rural roads are calculated using the number of vehicles per day (i.e. the AADT, annual average daily traffic).

When monitoring capacity usage, the Department for Transport estimates the number of vehicles per day, or annual average daily flow (AADF), from the data collected during manual traffic counts (DfT, 2014a). This is used in combination with known road lengths to estimate traffic volume (vehicle-km travelled each year) (DfT, 2014b). This approach was also taken by the performance indicators adopted by the National Infrastructure Plan 2014 (H.M. Treasury, 2014), which also established capacity utilisation as the ratio between usage (vehicle-km) and maximum capacity (vehicle-km) of the network.

Highways England Key Performance Indicators, related to capacity, are:

- Network Availability, defined as the percentage of the network available to traffic (lane availability not <97% within one rolling year),
- Incident management: % incidents cleared within one hour (at least 85%)

Both the indicators are related to HE's management of the network (i.e. closures related to maintenance and efficiency of recovery following incidents).

A.6.3.3 Summary

There are similarities in the way capacity is assessed on the highways and on the railways. As with the railways, homogeneity of vehicles (in particular, the speed) can improve the throughput. The achieved capacity is influenced strongly by the driving characteristics of the motorway users and the capacity metrics are related to the availability of lanes to traffic.

A.7 Conclusions

At present detailed and accurate understanding of available capacity, usage and predicted demand is lacking in rail. It is also clear that there is no single view on the key drivers of capacity constraints, and that the changes that would deliver capacity improvements are strongly influenced by the particular characteristics of a line/route. An improved understanding of current capability gaps is required to better match supply with demand

and deliver a service valued by customers. Analyses of the utilisation of the capacity being delivered by the system can help identify crucial bottlenecks.

This literature review has found a significant number of documents relating to the determination of the capacity of a railway network and some papers that discuss the options for metrics.

Many of the papers and documents relating to the assessment of capacity refer to UIC 406 which both notes that there is no single way of determining the absolute capacity of a railway network as the way in which it is used influences the plannable capacity and the subsequent throughput of trains.

Many papers discuss methods of refining the compression method in UIC 406, using a variety of analytical, graphical, probabilistic and simulation methods, but all acknowledge the importance of

- Train and service mix;
- Infrastructure and signalling;
- Performance and reliability parameters; and
- Utilisation of track infrastructure and trains.

The relationship between capacity and performance is brought out and shows that as capacity utilisation increases, performance tends to go down. Abril et al (2007) paper on “An assessment of Railway Capacity” explores the relationship between capacity and reliability.

Gray in his paper on Rail simulation and the analysis of capacity metrics showed that as the capacity use on a line increased, the impact of delays and knock on delays also increased..

The National Rail Freight Infrastructure Capacity and Investment Study of the American Railroad system has proposed the use of ‘Train volume-to-capacity ratio’ for railway corridors (where train corridor volume is represented by the number of trains per day and the capacity by a combination of the number of tracks, type of signalling control system and the mix of train types) to identify corridors operating below, at and above standardised estimates of capacity. The methodology used and measure proposed provides one potential route to identifying capacity measures for the Network Rail network.

A table of the various metrics proposed in literature has been collated and presented in a table. From this review it is clear that, although the most intuitive way of determining capacity utilisation is to establish the maximum number of trains operated over the network in a given time period, defining and measuring capacity using a single metric is challenging. This review found a large number of both capacity and capacity utilisation metrics across the literature that have been previously used for measuring the complex trade-off between various influencing and conflicting factors associated with capacity.

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Appendix B Structure of Stakeholder discussions

Start: Introduction, Background and Objectives of the study on Capacity measures

Q1 Do you concur with the view capacity has been given insufficient weight within railway industry measures and incentives? If so then:

a) Why do you think this has happened?
b) What effect has it had on the industry generally?
c) How has it affected Network Rail?
d) What effect has it had on your organisation?

Q3 What do you understand by the capacity of a railway route?

Q4 What measures of capacity or usage do you and/or your organisation use currently?

Q5 What measures have you seen used elsewhere? Are these relevant to this work?

Q6 Can capacity be measured so that the contributions and performance of different parties within the industry can be considered? If so how?

Q7 If the industry had a capacity/usage measure to set alongside performance and cost:

a) What difference would it make to the industry overall?
b) How would it help you/your organisation?

Q8 Do you think such a measure should be:

a) Regulated output (of Network Rail)?
b) An indicator (i.e. reputational)?

Q9 Do you think that the objectives of this study are realistic? If not, what might be achieved?

Appendix C Specification: Worked Example: Options for Capacity Measures/Metrics

C.1 Introduction

The Capacity Measures study being carried out by TRL for ORR includes the production of a "worked example". This will consist of a simplified model of a real world route section using our software based multi-train simulator, within which options associated with the shortlisted set of capacity measures can be tried out. The objective is to see how the outputs vary with changes in service, planning rules etc so that a suitable set of measures can be proposed.

C.2 Purpose

The purpose of this document is to define the scope, internal and external assumptions and outputs from the "worked example".

C.3 Scope

C.3.1 Geography

The geographic scope of the model will include the South West Main Line from Waterloo to south-west of Woking. The "Windsor" lines via Barnes are excluded. The precise limits of the model are Waterloo to Brookwood (main line) and Worplesdon (Portsmouth line). The fast and slow lines are included together with the following branches:

- Epsom branch from Raynes Park to Epsom and Chessington South
- Richmond line from New Malden as far as Teddington
- Hampton Court branch from Hampton Court Junction
- Guildford New Line from Hampton Court Junction as far as Hinchley Wood

The infrastructure data for the above scope is already available from earlier work for Network Rail with this simulator. Track data (distances, line speeds, permanent speed restrictions, gradients) were sourced from Network Rail "5-mile diagrams

C.3.2 Signalling

The model will be based on current four-aspect, track circuit block signalling as used on South West Main Line. Block sections will be representative of those actually present but may not be placed exactly as in reality.

Driver performance is modelled as follows:

- Acceleration – maximum acceleration (depending on traction characteristics) applied up to cruising speed;

- Cruising speed (average) 5% below line speed. (Adjustable to line speed if desired); and
- Braking – "defensive driving" modelled with characteristics agreed with Network Rail for earlier work (details can be provided).

C.3.3 Rolling Stock

The rolling stock types that will be used in the model are listed in Table 26.

Table 26 Rolling stock types

Service	Type	Class	Detail	Train Length	Max Speed
Fast and outer suburban	EMU	450	8/12 car	160/240m	100 mph
Inner suburban	EMU	455	8-car	160m	75 mph
Waterloo –Salisbury & Exeter	DMU	159	3/9-car	69/207m	90 mph
Freight	Class 4	66	-	775m	75 mph

Detailed performance (acceleration & braking) characteristics for each of the above types were provided by Network Rail for earlier work and are included in the model.

C.3.4 Services Modelled

The services that will be included in the model are listed in Table 27.

Table 27 Services modelled

Run Ref	Origin & Destination	Track	Stops	R/S
1	Brookwood – Waterloo	Fast	None	450 x 12
2	Brookwood – Waterloo	Fast	Woking	450 x 12
3	Worplesdon – Waterloo	Fast	Woking	450 x 12
4	Brookwood – Waterloo	Fast	Woking	159 x 9
5	Woking – Waterloo	See note[6]	All to Surbiton	450 x 12
6	Brookwood – Waterloo	Slow	None	450 x 12
7	Brookwood – Waterloo	Slow	All	450 x 12
8	Hampton Court – Waterloo	Slow	All	455 x 8
9	Epsom – Waterloo	Slow	None	455 x 8
10	Epsom – Waterloo	Slow	All	455 x 8
11	Brookwood – Wimbledon Park	Slow	None	Class 4 Freight
12	Hampton Court – Waterloo	Slow	None	455 x 8
13	Hinchley Wood – Waterloo	Slow	All	450 x 12
14	Teddington – Waterloo	Slow	None	455 x 8
15	Teddington – Waterloo	Slow	All	455 x 8
16	Brookwood – Waterloo	See note[7]	Woking (slow line)	450 x 12

The above runs are a representative selection of the traffic patterns on the route and include stops which are either made by all trains or which are at a key station (Woking). At this stage no attempt has been made to select stops and determine dwell times based on footfall because of the complexity it would add.

The runs will be carried out for both up and down services, assuming these are symmetrical. The interaction between up and down services will not be explored.

These outputs will be calculated for each section of the route from origin to destination, subdivided at the following nodes:

- Woking Junction;
- Hampton Court Junction;
- Berrylands Junction;

[6] Slow to Berrylands Junction then fast

[7] Slow to Woking then fast

- New Malden (slow lines only); and
- Raynes Park (slow lines only).

C.4 Simulation Software

A description of the simulation software is provided in section C.9

C.5 Approach

C.5.1 Notional Capacity Measures

In order to explore "Notional Capacity" options, following headway runs (two trains with the same service pattern running as close together as possible) will be carried out for all service patterns listed in Table 27. The headway will be allowed to "free run" within the model, based solely on the track and signal block layouts and train performance. No margins or other additions from timetable planning rules will be made.

C.5.1.1 Notional - Base Measure Options

The following will be calculated for each run:

- Worst case headway in section
- Arithmetic mean of block headways
- Standard deviation of block headways from mean

The outputs will be collated and analysed to show the impact of options on capacity values at the level of route geography as set out in the following sub-sections.

C.5.1.2 Non-stop vs Stopping Option

Table 28 Notional – Non-stop case

Scenario	Run Ref	Origin & Destination	Stops	R/S	Route Section/Tracks
NN1	1	Brookwood – Waterloo	None	450 x 12	Main Line, Up & down fast
NN2	6	Brookwood – Waterloo	None	450 x 12	Main Line, Up & down slow
NN3	9 (part)	Epsom – Raynes Pk	None	455 x 8	Epsom Branch
NN4	14 (part)	Teddington- New Malden	None	455 x 8	Teddington Branch
NN5	12 (part)	Hampton Court – Surbiton	None	455x 8	Hampton Court Branch

Table 29 Notional –Stopping case

Scenario	Run Ref	Origin & Destination	Stops	R/S	Route Section/Tracks
NS1	2	Brookwood – Waterloo	Woking	450 x 12	Main Line, Up & down fast
NS2	7	Brookwood – Waterloo	All	450 x 12	Main Line, Up & down slow
NS3	10 (part)	Epsom – Raynes Pk	All	455 x 8	Epsom Branch
NS4	15 (part)	Teddington-New Malden	All	455 x 8	Teddington Branch
NS5	8 (part)	Hampton Court – Surbiton	All	455x 8	Hampton Court Branch

Table 30 Notional – Impact of Rolling stock type (Fast Lines)

Scenario	Run Ref	Origin & Destination	Stops	R/S	Route Section/Tracks
NR1.1	2	Brookwood – Waterloo	Woking	450 x 12	Main Line, Up & down fast
NR1.2	4	Brookwood – Waterloo	Woking	159 x 9	

Table 31 Notional – Impact of Rolling Stock Type (Slow Lines)

Scenario	Run Ref	Origin & Destination	Stops	R/S	Route Section/Tracks
NR2.1	7 (part)	Brookwood– Waterloo	All	450 x 12	Main Line, Up & down slow Hampton Court Junction – Waterloo
NR2.2	8(part)	Hampton Ct – Waterloo	All	455 x 8	

C.5.2 Plannable Capacity Measures

In order to explore “Plannable Capacity” the following simulations will be run using all the passenger services identified in Table 27, overlaid in sequence so that the minimum aggregate impact of Timetable Planning Rules can be identified.

The number of trains of each pattern in the sequence has been adjusted to reflect the approximate split between different service frequencies in the timetable.

Table 32 Plannable – Fast Line Sequence – Up

(in order of appearance at waterloo)

Scenario	Seq No	Run Ref	Origin & Destination	Stops	R/S	Notes
PFU	PFU1	5	Woking - Waterloo	None on fast	450x12	Slow to fast at Berrylands
	PFU2	5	Woking - Waterloo	None on fast	450x12	Slow to fast at Berrylands
	PFU3	16	Brookwood – Waterloo	Woking (Plat 1)	450x12	Slow to fast at Woking (east crossovers)
	PFU4	16	Brookwood – Waterloo	Woking (Plat 1)	450x12	Slow to fast at Woking (east crossovers)
	PFU5	3	Worplesdon – Waterloo	Woking (Plat 2)	450x12	From Portsmouth Line at Woking Junction
	PFU6	3	Worplesdon – Waterloo	Woking	450x12	From Portsmouth Line at Woking Junction
	PFU7	4	Brookwood – Waterloo	Woking (Plat 2)	159 x 9	Impact of rolling stock difference
	PFU8	2	Brookwood-Waterloo	Woking (Plat 2)	450x12	Impact of Woking stop
	PFU9	1	Brookwood-Waterloo	None	450x12	Fast Line headway with margin
	PFU10	1	Brookwood-Waterloo	None	450x12	Fast Line headway with margin

Table 33 Plannable – Fast Line Sequence – Down

(in order of departure from Waterloo)

Scenario	Seq No	Run Ref	Origin & Destination	Stops	R/S	Notes
PFD	PFD1	1	Waterloo Brookwood	None	450x12	Fast Line headway with margin
	PFD2	1	Waterloo Brookwood	None	450x12	Fast Line headway with margin
	PFD3	2	Waterloo Brookwood	Woking (Plat 4)	450x12	Impact of Woking stop
	PFD4	4	Waterloo Brookwood –	Woking (Plat 4)	159 x 9	Impact of rolling stock difference
	PFD5	3	Waterloo Worplesdon	Woking (Plat5)	450x12	To Portsmouth Line at Woking Junction
	PFD6	3	Waterloo Worplesdon	Woking (Plat 5)	450x12	To Portsmouth Line at Woking Junction
	PFD7	16	Waterloo Brookwood	Woking (Plat 5)	450x12	Fast to slow at Woking (east crossovers)
	PFD8	16	Waterloo Brookwood	Woking (Plat 5)	450x12	Fast to slow at Woking (east crossovers)
	PFD9	5	Waterloo Woking	None on fast	450x12	Fast to slow at Berrylands
	PFD10	5	Waterloo Woking	None on fast	450x12	Fast to slow at Berrylands

Table 34 Plannable – Slow Line Sequence – Up

(in order of arrival at Waterloo)

Scenario	Seq No	Run Ref	Origin & Destination	Stops	R/S	Notes
PSU	PSU1	10	Epsom – Waterloo	All	455x8	Epsom line headway with margin & dwells
	PSU2	10	Epsom – Waterloo	All	455x8	Epsom line headway with margin & dwells
	PSU3	10	Epsom – Waterloo	All	455x8	Epsom line headway with margin & dwells
	PSU4	15	Teddington – Waterloo	All	455x8	Teddington line headway with margin & dwells
	PSU5	15	Teddington – Waterloo	All	455x8	Teddington line headway with margin & dwells
	PSU6	15	Teddington – Waterloo	All	455x8	Teddington line headway with margin & dwells
	PSU7	8	Hampton Ct – Waterloo	All	455x8	Hampton Ct line headway with margin & dwells
	PSU8	13	Hinchley Wd – Waterloo	All	450x12	Rolling stock differentials
	PSU9	5	Brookwood-Waterloo	All to Surbiton	450x12	Slow line headway with margin & dwells
	PSU10	5	Brookwood-Waterloo	All to Surbiton	450x12	Slow line headway with margin & dwells

Table 35 Plannable – Slow Line Sequence – Down

(in order of departure from Waterloo))

Scenario	Seq No	Run Ref	Origin & Destination	Stops	R/S	Notes
PSD	PSD1	5	Waterloo - Brookwood	All from Surbiton	450x12	Slow line headway with margin & dwells
	PSD2	5	Waterloo - Brookwood	All from Surbiton	450x12	Slow line headway with margin & dwells
	PSD3	13	Waterloo - Hinchley Wd	All	450x12	Rolling stock differentials
	PSD4	8	Waterloo - Hampton Ct	All	455x8	Hampton Ct line headway with margin & dwells
	PSD5	15	Waterloo - Teddington	All	455x8	Teddington line headway with margin & dwells
	PSD6	15	Waterloo - Teddington	All	455x8	Teddington line headway with margin & dwells
	PSD7	15	Waterloo - Teddington	All	455x8	Teddington line headway with margin & dwells
	PSD8	10	Waterloo - Epsom	All	455x8	Epsom line headway with margin & dwells
	PSD9	10	Waterloo - Epsom	All	455x8	Epsom line headway with margin & dwells
	PSD10	10	Waterloo - Epsom	All	455x8	Epsom line headway with margin & dwells

In each case the appropriate additions from the TPR values for the route will be made, to match the service sequence. The aggregate total occupation of the line by this sequence of trains and the potential "Plannable" trains per hour will be calculated.

C.5.3 Freight Scenarios

Although SWML in reality carries very little freight east of Basingstoke and none in the peak, freight runs have been included so that the impact can be evaluated as a "what-if" and considered in deciding the suitable measures.

Table 36 Notional – Comparison of Passenger & Freight – Slow Lines

NR3.1	6	Brookwood – Waterloo	All	450 x 12	Main Line, Up & down slow
NR3.2	11	Brookwood – Wimbledon Park	None	Class 4 freight	Main Line, Up & Down Slow

C.5.4 *“Capacity in Use” – Timetabled*

“Capacity in Use” will not be modelled. Rather, the trains per hour values for the route sections listed above will be calculated by extracting and processing the data for the current working timetable. The number of trains passing through each section during a selected hour will be counted, for the cases tabulated below:

	AM peak	Off-peak	PM Peak
Up Main	✓	✓	x
Up Slow	✓	✓	x
Down Main	x	✓	✓
Down Slow	x	✓	✓

C.6 Initial Analysis

The results from the model runs and calculations defined above will be set out in tabular form for review and analysis. The initial analysis will be aimed at finalising the options and method of calculation for the “Plannable Capacity” measure. The intention of this measure is to show the impact of the Timetable Planning Rules (TPR) when compared with the “Notional” measure. The information provided from the model will show by example what the effect of the various TPR elements (SRT, Headway Margin, Dwell time etc) is and should help to inform a decision as to which elements of the ruleset should be included and therefore how the plannable case should be calculated.

C.7 Sensitivity Tests

Once an initial decision as to the parameters for the “Plannable” case has been made, the sensitivity of the selected measures to variations in parameters can be tested. Only a limited number of variations can be accommodated within the resource available. The following is an initial list of suggestions:

- Change in permanent speed restriction (e.g. at Clapham Junction);
- Change in Timetable Planning Rule – e.g. Headway Margin; and
- Change in Dwell Time.

These can be tested using the most appropriate of the “Notional” and “Plannable” runs outlined above.

C.8 Final Analysis

A comparison between “Notional”, “Plannable” and “In Use” will be made for the following

- Trains per hour by section;
- Train km per hour per section (or aggregated for the route); and
- Train-metres per hour at selected timing points.

C.9 SOFTWARE MODEL DESCRIPTION AND PEDIGREE

C.9.1 Description

The software to be used is a Modelling Environment which means that it is a toolbox of compatible modelling modules that can be configured and customised to the requirements of a specific project. As with other railway models, its heart is the evaluation of train run times considering rolling stock capabilities, passenger loads, alighting and boarding times, signalling constraints, track characteristics etc. Where it differs from other simulators is the use of two levels of model:

a) A static model looking at an individual train run to determine unimpeded speed / time profiles and effective headways (required separation in front of and behind a train); and

b) A full dynamic simulation to explore interaction between simultaneous operation of multiple trains and their ability to satisfy customer demand.

C.9.2 Static Model

This provides the following functionality:

- Representation track layout including:
    - main and branch line segments
    - gradients
    - speed limits
    - grade separated and flat junctions
    - terminal and intermediate stations
    - cross-overs
    - reversing sidings
- Modelling multiple rolling stock types defined in terms of:
    - train consist
    - length of each vehicle
    - tare mass of each vehicle
    - passenger / freight capacity
    - motor tractive effort curves
    - braking characteristics
    - traction control response times
    - braking system response times
    - rolling resistance and drag (separately for tunnel and open sections)
- Modelling multiple signalling types including:
    - 2 or 3 aspect colour light systems

- ETCS level 1 Automatic Train Protection (ATP)
  - ETCS level 2 Automatic Train Protection (ATP)
  - ETCS level 3 Automatic Train Protection (ATP)
  - Automatic Train Operation (ATO) overlays on the above APT systems
  - Metro Communications Based Train Control (CBTC)
- Modelling of nominal station dwell times
- Modelling of predefined routes through the rail network
- Generation, for each route, of normal (unimpeded) speed and time profiles
- Computation, at each point on the predefined routes, of the minimum technical (signalling) headways
- Identification of the most restrictive headway location for each defined route (this defines the design capacity)

Normally a margin will be applied to the design capacity to allow for expected variations in run and dwell times. The magnitude and distribution of the recovery margin can be evaluated using the dynamic modelling facility.

C.9.3 Dynamic Model

This provides the following functionality:

- Re-use of all relevant static model data
- Representation of target service patterns (these can be timetables or target headways by route)
- Variation of inter-station run times based on load variations, random variations or a combination of both
- Variation of station dwell times based on alighting and boarding times, random variations or a combination of both
- Modelling of various Automatic Traffic Regulation (ATR) schemes (these could actually be manual schemes applied by traffic controllers but must be systematic according to pre-defined rules)
- Modelling of defensive driving rules
- Modelling of predefined fixed delays (to evaluate recovery time)
- Generation of time distance plots for each train (waterfall diagrams)
- Generation of plots of departure time variation from timetable at each station
- Calculation of mean and standard deviation of delays at each station

C.9.4 Other Modules

In addition to the core simulation modules, other modules are:

- The Track Builder which converts input data, in a simple form, to a complete representation of the railway network.

- The Timetable Module which constructs a timetable from target frequencies in each railway section.
- A Passenger Flow Module that determines numbers of boarders and alighters to/from each service at each station in predetermined time periods.
- A Profile Output Module that produces charts of train speeds and technical headways over the rail network.
- A Simulation Output Module that produces time / distance (waterfall) diagrams and charts of dwell times and departure headways at each station.

C.9.5 Software Model Pedigree

This software model has been used on a number of railway projects including:

- Evaluation of the costs and benefits of Unattended Train Operation for the Copenhagen suburban rail system (S Bane);
- A study of the maximum capacity that could be obtained for future operations on the YUS Line in Toronto.
- A project for the UK Department for Transport (DfT) looked at the ability of ETCS Level 2 to support high density commuter services such as Thameslink upgrade and Crossrail.
- Further research projects for DfT used PRIME to evaluate migration to ETCS Level 3 and the opportunities for low cost signalling.
- Capacity optimisation for the Copenhagen Metro City Ring project.
- Developing a business case for unattended operation on the Stockholm commuter lines.
- Evaluating the benefits of unattended operation on the Copenhagen commuter line (S Bane).
- Studying the capacity limitations of the central tunnel on the Oslo metro (T Bane) and the effects of signalling upgrades and different levels of automation.
- Comparing signalling options for the extension of the RER Line E in Paris for STIF.
- Assisting Infrabel in evaluating the capacity constraints for ETCS Level 2 and GSM-R deployment at the complex Gent Saint Pieters station area.
- Evaluating alternative track layout options for the Society Grand Paris automatic orbital metro.
- Evaluating performance for alternative service patterns and regulation options for the Society Grand Paris automatic orbital metro.
- Evaluating the capacity improvements to be obtained with ETCS Level 3 on the South West and Greater Anglia Main lines.

Appendix D Detailed Results: Headways in Seconds

	Train	Class 450 12 car				Class 455 8car		Class 159 9car	Class 4 freight
	Line	Fast		Slow		Slow		Fast	Slow
	Stops	Woking	None	All	None	All	None	Woking	None
From	To								
Brookwood	Woking Junction		2.96	3.97	2.96			3.99	3.43
Worplesdon	Woking Junction	2.80							
Woking Junction	Woking	0.40	0.18	0.40	0.19			0.42	0.21
Woking	Hampton Court Junction	10.45	7.86	24.38	8.07			10.45	8.81
Hinchley Wood	Hampton Court Junction		3.29						
Hampton Court	Hampton Court Junction					4.69	3.37		
Hampton Court Junctio	Berrylands Junction		1.62	4.05	1.68	4.37	2.96	1.62	1.86
Berrylands Junction	New Malden		1.33	3.64	1.59	3.15	1.43	1.33	1.72
Teddington	New Malden					9.64	5.44		
New Malden	Raynes Park		0.89	2.92	1.11	2.60	1.19	0.89	1.46
Epsom (Surrey)	Raynes Park					10.84	6.44		
Raynes Park	Wimbledon		1.14	3.17	1.42	3.00	1.51	1.14	3.82
Wimbledon	Waterloo		7.89	15.93	9.51	14.82	9.00	7.90	
Wimbledon	Wimbledon Park								3.61

Table 37 Run times - Down lines (minutes)

	Train	Class 450 12 car				Class 455 8car		Class 159 9car	Class 4 freight
	Line	Fast		Slow		Slow		Fast	Slow
	Stops	Woking	None	All	None	All	None	Woking	None
From	To								
Brookwood	Woking Junction		119.7	144.9	120.4				139.2
Worplesdon	Woking Junction	280.6							
Woking Junction	Woking	220.3	37.2	37	220.5				56.7
Woking	Hampton Court Junction	252.8	99.9	263	100.9				130.1
Hinchley Wood	Hampton Court Junction								
Hampton Court	Hampton Court Junction					228.3	182.5		
Hampton Court Junctio	Berrylands Junction		90.6	220.3	91.3	289.3	211.3		115.1
Berrylands Junction	New Malden		62.3	189.2	71.5	184.8	59.4		130.4
Teddington	New Malden						181.8		
New Malden	Raynes Park		71.3	209.5	88	183.1	112.6		117.5
Epsom (Surrey)	Raynes Park								
Raynes Park	Wimbledon		89.2	315.6	111.1	289.3	106.5		251.9
Wimbledon	Waterloo		111.5	221.6	135.6	199.5	154.6		
Wimbledon	Wimbledon Park								350

Table 38 Limit headways - Down lines (seconds)

	Train	Class 450 12 car				Class 455 8car		Class 159 9car	Class 4 freight
	Line	Fast		Slow		Slow		Fast	Slow
	Stops	Woking	None	All	None	All	None	Woking	None
From	To								
Brookwood	Woking Junction		119.7	144.9	120.4				139.2
Worplesdon	Woking Junction	280.6							
Woking Junction	Woking	220.3	37.2	37	220.5				56.7
Woking	Hampton Court Junction	252.8	99.9	263	100.9				130.1
Hinchley Wood	Hampton Court Junction								
Hampton Court	Hampton Court Junction					228.3	182.5		
Hampton Court Junctio	Berrylands Junction		90.6	220.3	91.3	289.3	211.3		115.1
Berrylands Junction	New Malden		62.3	189.2	71.5	184.8	59.4		130.4
Teddington	New Malden						181.8		
New Malden	Raynes Park		71.3	209.5	88	183.1	112.6		117.5
Epsom (Surrey)	Raynes Park								
Raynes Park	Wimbledon		89.2	315.6	111.1	289.3	106.5		251.9
Wimbledon	Waterloo		111.5	221.6	135.6	199.5	154.6		
Wimbledon	Wimbledon Park								350

Table 39 Mean headways - Down lines (seconds)

	Train	Class 450 12 car				Class 455 8car		Class 159 9car	Class 4 freight
	Line	Fast		Slow		Slow		Fast	Slow
	Stops	Woking	None	All	None	All	None	Woking	None
From	To								
Brookwood	Woking Junction		11.9	12.1	8.5				6.25
Worplesdon	Woking Junction	0							
Woking Junction	Woking	0	0	0	0				0
Woking	Hampton Court Junction	45.4	8.5	51.9	9.44				9.9
Hinchley Wood	Hampton Court Junction								
Hampton Court	Hampton Court Junction					18.5	16.7		
Hampton Court Junctio	Berrylands Junction		16.2	17.2	14.3	60.3	60.4		12.5
Berrylands Junction	New Malden		0	0	0	10.9	0		17.1
Teddington	New Malden						34.9		
New Malden	Raynes Park		0	0	0	0	0		8.1
Epsom (Surrey)	Raynes Park								
Raynes Park	Wimbledon		0	0	0	0	0		0
Wimbledon	Waterloo		9.7	23.15	40.1	38.5	26.1		
Wimbledon	Wimbledon Park								0

Table 40 Standard Deviation - Down Lines (seconds)

	Train	Class 450 12 car				Class 455 8car		Class 159 9car	Class 4 freight
	Line	**Fast**		**Slow**		**Slow**		**Fast**	**Slow**
	Stops	**Woking**	**None**	**All**	**None**	**All**	**None**	**Woking**	**None**
From	**To**								
Brookwood	Woking Junction	3.21	3.21	3.21	3.21			3.25	4.05
Worplesdon	Woking Junction		1.89						
Woking Junction	Woking	2.91	0.35	2.91	0.35			2.92	0.41
Woking	Hampton Court Junction	8.82	7.24	21.96	7.64			8.84	8.62
Hinchley Wood	Hampton Court Junction		2.32						
Hampton Court	Hampton Court Junction					3.76	2.54		
Hampton Court Junctio	Berrylands Junction		1.81	4.28	1.88	4.54	2.83	1.81	1.97
Berrylands Junction	New Malden		1.11	4.81	1.18	4.44	1.17	1.11	1.25
Teddington	New Malden					10.08	4.31		
New Malden	Raynes Park		0.87	2.87	1.07	2.63	1.07	0.87	1.08
Epsom (Surrey)	Raynes Park					13.49	5.94		
Raynes Park	Wimbledon		1.05	3.3	1.41	3.05	1.41	1.05	1.54
Wimbledon	Waterloo		8.39	15.58	10.87	14.48	10.38	8.3	
Wimbledon	Wimbledon Park								5.31

Table 41 Run times - Up Lines (minutes)

	Train	Class 450 12 car				Class 455 8car		Class 159 9car	Class 4 freight
	Line	**Fast**		**Slow**		**Slow**		**Fast**	**Slow**
	Stops	**Woking**	**None**	**All**	**None**	**All**	**None**	**Woking**	**None**
From	**To**								
Brookwood	Woking Junction	**240.1**	123.0	240.2	123.0			**236.3**	**162.9**
Worplesdon	Woking Junction								
Woking Junction	Woking	193.2	93.0	227.3	94.0			226.5	123.7
Woking	Hampton Court Junction	130.7	126.2	**302.7**	128.6			194.0	162.0
Hinchley Wood	Hampton Court Junction								
Hampton Court	Hampton Court Junction					282.9	236.9		
Hampton Court Junctio	Berrylands Junction		92.9	199.8	93.5	173.6	87.2	90.9	162.0
Berrylands Junction	New Malden		74.9	201.4	76.8	170.5	72.7	72.0	101.2
Teddington	New Malden						159.2		
New Malden	Raynes Park		63.8	194.3	79.0	170.5	65.4	62.0	99.6
Epsom (Surrey)	Raynes Park								
Raynes Park	Wimbledon		66.2	176.8	117.5	165.2	102.5	64.4	170.7
Wimbledon	Waterloo		**123.5**	215.1	**162.4**	192.9	143.6	120.1	
Wimbledon	Wimbledon Park								255.6

Table 42 Limit headways - Up lines (seconds)

	Train	Class 450 12 car				Class 455 8car		Class 159 9car	Class 4 freight
	Line	Fast		Slow		Slow		Fast	Slow
	Stops	Woking	None	All	None	All	None	Woking	None
From	To								
Brookwood	Woking Junction	171.1	86.4	152.1	85.4			148.8	115.6
Worplesdon	Woking Junction								
Woking Junction	Woking	193.2	93	227.3	94			226.5	123.7
Woking	Hampton Court Junction	88.2	87.5	224.6	89.8			92.8	113.9
Hinchley Wood	Hampton Court Junction								
Hampton Court	Hampton Court Junction					268.9	195.4		
Hampton Court Junctio	Berrylands Junction		70.4	199.8	76.3	163.3	69.1	71.2	92.7
Berrylands Junction	New Malden		64.6	193.1	71.2	166	68.1	62.5	94.5
Teddington	New Malden						123.5		
New Malden	Raynes Park		56.8	158.7	69.8	160.5	71.6	54.7	91.4
Epsom (Surrey)	Raynes Park								
Raynes Park	Wimbledon		56.4	170	101.8	158.2	93.3	54.4	163.6
Wimbledon	Waterloo		92.8	134.4	101.3	123.1	95	90.7	
Wimbledon	Wimbledon Park								242.8

Table 43 Limit headways - Up lines (seconds)

	Train	Class 450 12 car				Class 455 8car		Class 159 9car	Class 4 freight
	Line	Fast		Slow		Slow		Fast	Slow
	Stops	Woking	None	All	None	All	None	Woking	None
From	To								
Brookwood	Woking Junction	64.2	26.1	63.5	25.2			63.1	31.4
Worplesdon	Woking Junction								
Woking Junction	Woking	0.0	0.0	0.0	0.0			0.0	0.0
Woking	Hampton Court Junction	15.5	14.4	41.0	14.8			28.9	16.3
Hinchley Wood	Hampton Court Junction								
Hampton Court	Hampton Court Junction					14.1	41.5		
Hampton Court Junctio	Berrylands Junction		10.9	20.7	10.3	10.1	9.2	11.5	8.4
Berrylands Junction	New Malden		6.2	8.3	4.0	4.5	4.1	5.7	4.0
Teddington	New Malden						20.8		
New Malden	Raynes Park		4.4	33.2	5.6	10.1	12.8	4.5	6.3
Epsom (Surrey)	Raynes Park								
Raynes Park	Wimbledon		6.2	8.8	9.4	8.5	11.2	6.6	7.1
Wimbledon	Waterloo		15.7	51.6	20.0	47.6	16.5	15.3	
Wimbledon	Wimbledon Park								12.8

Table 44 Standard Deviation - Up Lines (seconds)

Appendix E Extract-Timetable Planning Rules – Wessex – 2017 Timetable

Timing Point (Mandatory in bold; locations not timing points in brackets) (Pink rows are nodes)	Down	Up	Code	Timing Point Notes	Junction Margin	Dwell (min) (* = peak-only value) ("STD" = standard dwell - 0.5s - see sheet 4) DOWN Fast	DOWN Slow	UP Fast	UP Slow	Headway (min) DOWN Fast	DOWN Slow	UP Fast	UP Slow	Headway Notes
SW100 - WATERLOO TO CLAPHAM JNC														
London Waterloo									-	2	2.5	^	^	
(Vauxhall)						-	1	-	1					
Clapham Junc (Main Line)	FL SL	MFL MSL		Platform detail must be shown. *To/from Earlsfield - SW105*		1	1	1.5	1	v	v	2	2.5	
SW105 - CLAPHAM JNC TO WEYMOUTH														
Clapham Junc (Main Line)	FL SL	MFL MSL		Platform detail must be shown. *To/from Vauxhall - SW100*		1	1	1.5	1	2	2.5	^	^	
Wimbledon (Wessex Side)	FL SL UFL USL	FL SL		Platform detail must be shown. *To/from Wimbledon Park (LUL) - SW225*	2	1	1	1	1	v	v	^	^	
Raynes Park	SL	FL SL	S X	Conditional timing point for Slow Lines and trains crossing from Up Slow to Up Fast Lines. *To/from Motspur Park - SW180*	3	-	STD	-	STD	v	v	^	^	Extra 0.5 SRT for down trains to Motspur Park passing (not stopping) Raynes Park
New Malden	FL SL	FL SL		*To/from Norbiton - SW190*	3	-	STD	-	STD	v	v	^	^	Extra 0.5 SRT for down trains to Norbiton passing (not stopping) New Malden
Berrylands	SL	SL	S			-	STD	-	STD	v	v	^	^	Headway for consecutive stopping trains at Berrylands – 3 min
Berrylands Junction					3					v	v	^	^	
Surbiton	FL SL	FL SL		Platform detail must be shown. *To Thames Ditton - SW195*	3	-	1.5*	1.5*	1.5*	v	v	^	^	Minimum Platform re-occupation times for trains travelling in the same direction on restricted aspects at Surbiton – 2 min
Hampton Court Junction	FL SL	FL SL		From Thames Ditton - SW195 To/from Hinchley Wood - SW200	3					v	3.5	^	2.5	Minimum re-occupation times (Hampton Ct Jnc to Woking Jnc) for trains travelling in the same direction: Down Fast – 2 min; Down Slow – 2½ min; Extra 1.0 SRT for down trains to Hinchley Wood passing (not stopping) Surbiton
Esher	SL	SL	S			-	1*	-	1*	v	v	^	^	
Hersham	SL	SL				-	1	-	1	v	v	^	^	Non-standard dwell applies to Class 450 only
Walton on Thames	SL	SL				-	STD	-	STD	v	v	^	^	
Weybridge	FL SL	FL SL	S X	Conditional timing point for Slow Lines, Down Trains crossing from Fast Line to Slow Line and vv, Up Trains crossing from Slow Line to Fast Line. To/from Addlestone Junction - SW255		-	1	-	STD	v	v	^	^	Non-standard dwell applies to Class 450 only
Byfleet & New Haw	SL	SL	S X	Conditional timing point for Slow Lines only and Up trains crossing Fast to Slow Lines		-	STD	-	STD	v	v	^	^	Extra SRT for services joining main line at Addlestone Junction - see original doc for details
West Byfleet	FL SL	SL	S			-	1	-	1	v	v	^	^	Non-standard dwell applies to Class 450 only
Woking	FL SL UFL USL	FL SL		Platform detail must be shown		2	2	2	2	v	v	2	^	Extra SRT for services joining main line at Addlestone Junction - see original doc for details
Woking Junction	FL SL	FL SL			3					v	3	^	^	
Brookwood London End	SL		X	Conditional timing point for Down trains crossing from Fast Line to Slow Line						v	v	^	^	
Brookwood	FL SL	FL SL		Conditional timing point for Slow Lines and trains crossing from Slow Lines to Fast Lines		-	1	-	1	v	v	3	3.5	
SW225 - POINT PLEASANT JUNCTION TO WIMBLEDON														{not clear why fast and slow headway values are provided since route has 2 tracks}
Wimbledon (Wessex Side)	FL UFL USL			*To/from Wimbledon West Crossings - SW105*	2	1	1	1	1	2	2.5	^	^	
Wimbledon Park (LUL)							STD		STD	v	v	2	2.5	
SW180 - RAYNES PARK TO LEATHERHEAD														{not clear why fast and slow headway values are provided since route has 2 tracks}
Raynes Park	SL	FL SL	S X	Conditional timing point for Slow Lines and trains crossing from Up Slow to Up Fast Lines. *To/from Wimbledon - SW105*	3	-	STD	-	STD	2	2.5	^	^	Extra 0.5 SRT for down trains to Motspur Park passing (not stopping) Raynes Park
Motspur Park						-	STD	-	1*	v	v	^	^	
Motspur Park Junction				*To/from Malden Manor - SW185*	2					v	v	^	^	
Worcester Park			S			-	STD	-	STD	v	v	^	^	
Stoneleigh			S			-	STD	-	STD	v	v	^	^	
Ewell West			S			-	STD	-	STD	v	v	^	^	
Epsom				Platform detail must be shown		-	1	-	1	v	v	2	2.5	
SW190 – NEW MALDEN TO SHEPPERTON														{not clear why fast and slow headway values are provided since route has 2 tracks}
New Malden		SL		To/from Raynes Park - SW105	3	-	STD	-	STD	2	2.5	^	^	
Norbiton			S			-	STD	-	1*	v	v	^	^	
Kingston				Show 'Bay' if to/from Bay	3	-	1	-	1	v	v	^	^	Bay platform junction allowance 3 min; 1.5 min between bay arrival and down Teddington service
Hampton Wick			S			-	STD	-	STD	v	v	^	^	
Teddington						-	STD	-	STD	v	v	2	2.5	
SW195 - SURBITON TO HAMPTON COURT														{not clear why fast and slow headway values are provided since route has 2 tracks}
Surbiton		FL SL		*To/From Berrylands - SW105*		-	1.5	1.5	1.5	3	3.5	^	^	See SW105
Hampton Court Junction		SL		Mandatory timing point for Up Trains from Hampton Court on the Up Line only. See also entry on route SW105	STD					v	v	^	^	See SW105
Thames Ditton			S							v	v	^	^	
Hampton Court		DL				-	N/S	-	N/S	v	v	3	3.5	1 min between arrival at platform 1 and departure from platform 2; 2.5 min reccupation time of each platform
SW200 - HAMPTON COURT JNC TO GUILDFORD VIA COBHAM														{not clear why fast and slow headway values are provided since route has 2 tracks}
Hampton Court Junction		FL SL		To/from Surbiton - SW105						2	3.5	^	^	See SW105
Hinchley Wood			S			-	STD	-	1*	v	v	2	3.5	
SW110 - WOKING JNC TO PORTSMOUTH HARBOUR														
Woking Junction		FL SL DFL DSL		To/from Woking - SW105						2	3.5	^	^	
Worplesdon			S			STD	-	STD	-	v	v	^	^	{not clear why fast and slow headway values are provided since route has 2 tracks}
Guildford				Platform detail must be shown. *To/from Ash - SW265. To/from London Road (Guildford) - SW200*		2	-	2	-	v	v	2	3.5	

Options for Capacity Measures/Metrics

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