Research

Defining the case for optimising sectional running times for freight

T1301 - Phase 1

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March 2025

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Executive summary

This project is a follow-up to a previous RSSB research project 'Guidance on limits of freight train trailing length as governed by tractive effort' (T1302), undertaken by Railfreight Consulting and completed in 2023. This project went back to 'first principles' to redefine the available power from locomotives and the resistive forces within a train's consist to provide a more accurate definition of the maximum trailing load for a freight train.

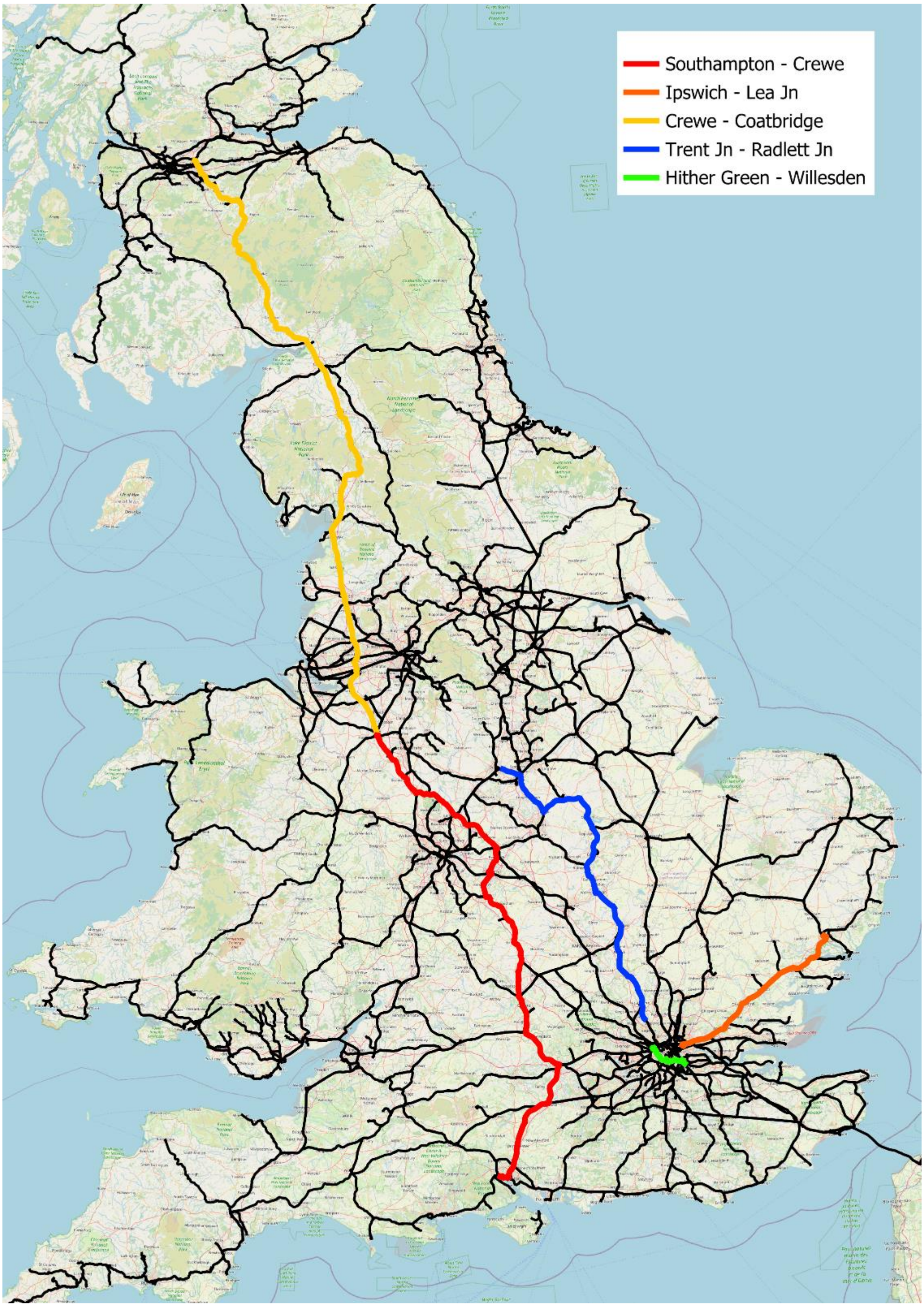
This project 'Defining the case for optimising sectional running times for freight' (T1301) was commissioned to investigate the benefits of applying the T1302 lessons and methodology to improve sectional running times (SRTs) through analysis of five case studies. It was driven by recognition across the rail industry that SRTs have not been systematically updated and maintained over the years.

T1302 has given the industry a much better understanding of the limitations in current SRTs and how their calculation can be improved. In particular, T1302 led to the development of SRTcalc, a tool written in the coding language 'R', which overcomes many of the limitations in previous methods for calculating SRTs. Among other things, it incorporates more up-to-date locomotive data and provides flexibility in how freight train consists are defined. Through this process, the calculation approach to evaluating SRTs can be improved, though it should be recognised that not all SRTs are produced by modelling.

Following stakeholder engagement, five case study locations were chosen (Figure 1):

- Eastleigh to Basingstoke (subsequently extended to Crewe to gain a better appreciation of the potential timing benefits)
- the Great Eastern main line from Ipswich to Lea Junction
- the West Coast main line (WCML) over Grayrigg and Shap summits (subsequently extended from Crewe to Coatbridge to gain a better appreciation of the potential timing benefits)
- the Midland main line from Trent Junction to Radlett
- the West London Line from Latchmere Junction to Willesden (subsequently extended back to Hither Green to gain a better appreciation of the potential timing benefits).

Figure 1 Route map



This grouping enabled analysis of two maritime intermodal routes, one domestic intermodal route, one significant aggregate route, and one complex urban route, which is also a key freight corridor.

The methodological approach was as follows:

- Each route's vertical and horizontal alignment was modelled with line speed restrictions (both local and Class 4, Class 6 maximum speeds).
- Iterations of timing runs were then undertaken:
  - Initially, sample train consists (locomotive type and trailing weight) were run through the model using the appropriate existing Network Rail (NR) SRTs. The resulting run time was compared against existing run times (obtained from NR's TRUST and TABs systems) to validate the model and identify initial areas of inconsistency.
  - The model was run again using new SRTs incorporating the benefits detailed in T1302 to see what improvement in run times could be achieved.
  - Sensitivity runs were undertaken using different locomotive types and trailing loads.
  - These different runs were also used to confirm changes to the locomotive and wagon parameters defined within the T1302 project loading model.
- The modified SRTs were placed into the ATTune timetable modelling system and applied to the 2024 national timetable to define the actual timetabling benefits that could be achieved.

The principal findings of the research are:

- Timings can be improved in all circumstances.
- Heavier trains can be run within the existing timings in all circumstances.
- Electric timings can be significantly improved, and there has been an inconsistent historic approach across different routes to determining the appropriate available tractive effort of these vehicles.
- Every analysed route has some incorrect infrastructure and/or routing assumptions. For example, existing timings are not always updated when infrastructure or routing changes (such as the removal of a PSR).
- Beneficial retiming is generally not possible due to constraining passenger traffic, but sometimes 'stepping up' in front of the preceding passenger train is possible.
- In certain locations and times, a mini freight timing recast should be of value. For example, on the WCML in the early morning, the line is freight only. Therefore, there is potential for improving 'all' freight timings rather than just one, as that will probably conflict with the timings of an 'unimproved' service.
- There is significant opportunity for reducing the delay minutes for each train by using the 'right information'.

The fundamental work on the forces acting on a train developed in T1302 has been reviewed and updated as shown below.

Total train resistance = sum of locomotive and wagon loads (gravity + acceleration + mechanical + curving)

Gravity

$$R_G = g \times \frac{1{,}000}{X} \quad [{}^{N}/_{tonne}]$$

Acceleration

$$R_{AS} = 1{,}000 \times a_S \quad [{}^{N}/_{tonne}]$$

where:

a_S = train acceleration at starting (m/s²), suggested value = 0.025 m/s.

Vehicle	Load case	**Mechanical**	**Curving**
6 axle locomotive	Starting	$(R_{LMS})[\mathrm{N}] = 65.6423 \times \text{locomotive mass [tonnes]}$	$R_{LC(3-axle\ steerable)} = \frac{111{,}500}{(track\ radius\ [m])^2} - \frac{400}{track\ radius\ [m]} + 0.3 \quad [{}^{N}/_{tonne}]$
	Rolling	$R_{LMR\ 6axle\ leading} = K_{LMR4} \times V^2 + K_{LMR5} \times V + K_{LMR6}\ [\mathrm{N}/tonne]$	$R_{LCR(3\ axle\ steerable)} = \frac{K_{LCR2}}{(track\ radius\ [m])^2} - \frac{K_{LCR3}}{track\ radius\ [m]} + K_{WCR4} \quad [{}^{N}/_{tonne}]$
4 axle wagon	Starting	$R_{WMS} = 1.4 \times \left(4.0 + \frac{100}{Q}\right) [{}^{N}/_{tonne}]$	$R_{WCS} = \frac{1.833 \times K_{WCS1}}{R} \quad [{}^{N}/_{tonne}]$
	Rolling	$R_{WMR} = 4.0 + \frac{100}{Q} + K_{WMR3} \times V + \frac{K_{WMR5} \times A_w \times V^2}{1024.081 \times M_w} \quad [{}^{N}/_{tonne}]$	$R_{WCR} = \frac{K_{WCR1}}{R}$

This can be simplified as:

- Gravity and accelerative forces have the same derivation in all circumstances.
- Rolling mechanical forces have the 'Davis equation' format of a quadratic equation with A, B, and C coefficients, where B and C relate to velocity respectively linearly or with a squared relationship:

$Mechanical\ Resistance = A + B \times v + C \times v^2$, where v = the train's speed

For starting mechanical forces, the velocity is zero (starting from a stop) and so the forces are simplified.

These A, B, and C coefficients (sometimes referred to as the wagon parameters*)* have been defined for the most commonly used wagons on the case study routes, as detailed below.

Wagon type	A_W wagon frontal area [m^2]	K_{WMR3} 'B' coefficient [N/tonne]	K_{WMR5} 'C' coefficient [N/tonne]
Intermodal wagon - 60' platform (FEA platform height) loaded with 9'6''	9.443	0.147	22.241
Intermodal wagon - 60' platform (FEA platform height) loaded with 8'6''	8.699*	0.147*	22.241*
Intermodal wagon - 60' platform (FEA platform height) empty	2.391	0.147	22.241
Aggregate box wagon (loaded)	8.361	0.085	18.683
Aggregate box wagon (empty)	8.361	0.085	53.379
Aggregate hopper wagon (loaded)	8.361	0.128	22.51
Aggregate hopper wagon (empty)	8.361	0.128	58.05
Cement tank wagon (loaded) - JPA	7.89	0.106	13.56
Cement tank wagon (empty) - JPA	7.89	0.106	13.56
Petroleum tank wagon (loaded) - TEA	7.89	0.128	24.465
Petroleum tank wagon (empty) - TEA	7.89	0.128	24.465
Covered steel coil wagon (loaded) - IHA	9.13	0.078	16.0
Covered steel coil wagon (empty) - IHA	9.13	0.078	16.0

There is significant variation in the B and C coefficients between wagon types. For example, the B coefficient for an intermodal wagon with a 9'6'' container (0.147) is almost twice that of the steel coil carrier (0.078), and the C coefficient for empty hopper wagon (58.0) is over three times greater than that for the steel coil carrier (16.0).

Therefore, steel coil wagons will have lower resistances, which means at the same trailing weight they will run faster than an empty box wagon. Wagon-specific SRTs should then be considered if the NR and operator systems can accommodate them and if sufficient control on wagon consists can be confirmed. Use of these values can additionally impact wider modelling as well as predictive calculations in TM (or equivalent) systems.

The increased aerodynamic load of the box and hopper wagon leads to them requiring more power to haul unloaded as opposed to loaded at speeds over 40 mph. Sheeting these wagons by covering their open tops will significantly reduce their fuel load.

Articulating the financial benefit of these improvements requires taking some subjective judgements on the number of services improved and the value of each improvement. The quantification undertaken in this report finds an annual benefit of £16m, as detailed below.

Item	Benefit	Effect	Train benefit	Market benefit
1	Enabling existing train weights to travel faster	Reduction in train variable costs, improved asset utilisation	Faster – 3% saving of haulage cost, say £200/train (£6K/train price) Asset utilisation = £250K/train (6.2.1)	5% of 1000 trains accelerated = £3m pa (300 days) 8 services intensified = £2m pa benefit
2	Enabling heavier trains to travel within the existing timings	Reduction in the unit cost of haulage	£78K/train/year (6.2.1.1)	5% of 1000 trains/day = £3.9m pa
3	Supporting market growth	Increase turnover and margin.		5% growth of an £800m market with a 5% margin = £2m pa of value
4	Enabling more accurate pathing to be established	Reduction in TDA and fuel costs	Save £100 on TDA, = £50 saving on actual cost, plus £50 reduction in fuel = £100/train	Applied to 5% of 1000 trains for 300 days = £1.5m pa
5	Electric traction has significant advantages over diesel traction when RTE is the governing factor	As items 1 and 2		2% of 1000 trains accelerated = £1.2m pa (300 days)
6	Improving empty wagons timings	As item 1		2% of 1000 trains accelerated = £1.2m pa (300 days)
7	Identification of existing timing issues	As item 1		2% of 1000 trains accelerated = £1.2m pa (300 days)
			Total benefit	**£16m pa**

The recommendations of this report are:

- The new T1302/1 information should be used to update existing SRTs.
- The new T1302/1 information should be used to produce new SRTs for Class 68, 70, 88, 93, and 99 locomotives. Also, the existing Class 90 and 92 locomotive timings need substantive revision.
- The partially complete corridor assessments of the main lines should be completed:
  - West Coast south of Crewe
  - Great Western between Pilning and Didcot and between Reading West Junction and Paddington
  - Midland main line Trent Junction to Sheffield, Radlett to St Pancras
  - East Coast in its totality.
- Some other key freight routes should be considered, such as North London Line, Doncaster to Immingham.
- This report has not considered the effect of freight train braking, and further opportunities for improvement could arise there. This subject is being addressed by RSSB research project T1348.

Contents

1 Introduction

1.1 Background and project aims

T1301 is a follow-on project from RSSB's project T1302 'Guidance on limits of freight train trailing length as governed by tractive effort'. This report should therefore be read in conjunction with the T1302 final report.

T1302 identified opportunities to improve freight train performance based on improved knowledge of locomotive performance, freight timings, and operational constraints. These aspects include:

Locomotive performance

- improved starting tractive effort for certain locomotive classes
- improved rolling tractive effort for certain locomotive classes
- more realistic wagon resistances for modern wagon types and loadings.

Freight timings

- There is potential to improve historically calculated timings, which were sometimes based on alternative, older, locomotive types.
- Up-to-date timings need to be calculated for new locomotives.
- Consideration should be given to 'junction to junction' timings.

Operational constraints

- Some timings are restricted to accommodate frequently stopping passenger trains on the same route.
- There is an opportunity to enable longer/faster trains overnight in the absence of passenger trains.

T1302 produced a new empirical formula defining the maximum length of a freight train on the GB network based on locomotive and wagon type and the route geography. The project also produced a calculation model for sectional running times (SRTs) for freight trains and applied it to four typical route geographies. This highlighted several possible areas of improvement. RSSB then commissioned project T1301 to take these findings and apply them to a detailed review of five stakeholder chosen locations to draw out learning points that can then be applied to improve the basis of SRT calculation across the network.

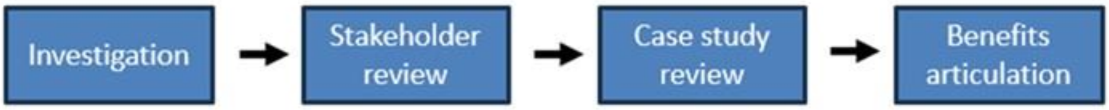
The aims of this project are:

- to take the learnings from T1302 and apply them to five case studies to demonstrate the beneficial opportunities available
- to fully engage with Network Rail (NR) and other stakeholders to provide solutions that are practical for immediate application.

1.2 Overview of project approach

The project was delivered in four stages, illustrated in Figure 2

Figure 2 Project delivery process



The investigation phase reviewed the engineering parameters within the T1302 report and looked at the provenance of the SRTs currently by NR and the various methods that have been used to derive them. The work also produced a prioritised 'long list' of sites to be considered for the case study investigation, in consultation with the stakeholders.

The stakeholder review process discussed the results of the investigation phase and the proposed case study list through two webinars with stakeholders. This was supported with one-to-one meetings with key stakeholders. At the end of this review process, the five case study locations were chosen.

When undertaking the case studies the team initially undertook a rapid validation review comparing planned, modelled, and observed freight running times between key junctions or locations. The learnings from T1302 and the Investigation Phase were then applied to determine through modelling how the SRTs within the case study locations could be improved. Stakeholder review continued during this phase, particularly with NR, to ensure that the suggested improvements were both realistic and practically applicable.

The potential timetable impacts of the improved SRTs were then modelled to see how they could either enable longer trains or faster running or simply improve journey time predictability. These benefits were then worked up to provide an indication of the financial benefits through the adoption of the findings of the research.

1.3 This document

This document is the final output of the T1301 project. It records the work undertaken and the improvement recommendations developed. It should be read in conjunction with the T1302 final report 'Guidance on limits of freight train trailing length as governed by tractive effort'. The structure of this report is as follows:

- **Section 1:** this introduction
- **Section 2:** a detailed explanation of the project's methodology
- **Section 3:** a review of the basis of current situation as used by NR for calculating SRTs
- **Section 4:** new/updated thinking and refinements for calculating SRTs
- **Section 5:** a standalone section where the completed methodology for calculating SRTs using the T1302 and T1301 research is articulated (which, for completeness, brings everything together to complete guidance)

- **Section 6:** a demonstration of the application of the revised methodology and its benefits through a discussion of five case studies and their findings
- **Section 7:** articulation of the benefits of adopting the proposed SRT methodology
- **Section 8:** recommendations and next steps.

2 Methodology

2.1 Investigation/stakeholder review

The findings and recommendations from the T1302 report were reviewed and, in discussion with stakeholders, used to guide a review of current basis and provenance of the SRTs currently used for timetabling. In particular, the project had a significant engagement with the NR national capacity planning team and was able to gain much guidance from them around the historic development of SRTs and the data sets and logic behind them.

From this review, a number of potential opportunity locations were put to the Steering Group for consideration as a case study. Five locations were chosen:

- Eastleigh to Basingstoke northbound (subsequently extended to cover Southampton to Crewe)
- the Great Eastern main line eastbound (Ipswich to Lea Junction)
- the Midland main line southbound (Trent Junction to Radlett Junction)
- the West Coast main line (WCML) Oxenholme to Shap Summit northbound (subsequently extended to cover Crewe to Coatbridge)
- the West London Line northbound (Latchmere Junction to Willesden, subsequently extended to start at Hither Green).

2.2 Case study review

For each location chosen, the following steps were undertaken:

- preparation and data collection
- SRT modelling and iteration
- timetable impact investigation.

These are described in more detail in the following sub-sections.

2.2.1 Preparation

- A geographic model of the case study route was developed, containing:
  - route vertical and horizontal geometry (from NR track shapefile)
  - route line speed and line speed restrictions (both permanent and temporary speed restrictions [PSRs and TSRs] where appropriate) from NR speed restriction files
  - timing point locations (TIPLOCs) from NR BplanGEO (with clean-up as required).
- In parallel, published SRTs were obtained from the NR's BPlanGeo database.
- In parallel, actual running time information from TRUST and train consist and loading data from TABS was obtained, for comparison with the SRTs.

2.2.2 SRT modelling and iteration

- The SRT calculation model developed for T1302 was used to develop proposed indicative running times (IRTs), with the network geography data as an input.
- Timings were initially modelled using the existing assumptions used by NR and compared with the actual running times to validate the model and find immediate areas of opportunity/uncertainty/potential improvement. Use of large data sets of actual running times and associated consists (loadings) of a wide range of services allowed different, statistically significant situations to be explored and so define and calibrate relevant variables for train resistance calculations. This also allowed 'apples to apples' comparisons between observed timings, current SRTs, and proposed IRTS for the same specified number of wagons and trailing weight.
- The model was then run using the methodology recommended in the T1302 report (with the improvements identified through this further T1301 research) using appropriate assumptions for type of wagons, number of wagons, wagon loadings, and train lengths that match real-world operations. The resulting IRTs were then investigated to establish the benefit that could flow from the adoption of that research.
- Iterations of that analysis were then undertaken using amended modelled SRTs to:
  - establish the maximum tonnage that could be moved within the existing timing allowances
  - establish the effect of different locomotive types.

2.2.3 Timetabling impacts

- The modelled SRTs were run in an extract of the national timetable using ATTUne software to see the benefits that could be achieved.
- The output from this work was reviewed to establish opportunities for improvement.

2.3 Benefits

Section 6 of the report takes the opportunities identified through the research and articulates them into monetisable benefits, though some assumptions have had to be made to enable this to happen. This provides indicative financial benefits to support the adoption of the opportunities.

2.4 Stakeholder engagement

2.4.1 Stakeholders engaged during the project

Stakeholders were initially engaged by the project as members of the Steering Group, including:

- NR (freight team, system operator, national capacity planning team, and Southern Region timetabling team) and GB Railways' Transition Team
- freight operating companies (FOCs) DB Cargo, Freightliner, GB Railways, DC Rail, and Colas.

There was also additional engagement with key individuals from the above organisations, and throughout the project, a regular technical meeting was held with timetabling representatives from NR.

The emerging results from the project were briefed out to relevant industry groups such as NR's Freight Development Delivery Group and RSSB's Freight Technical Committee.

2.4.2 Key outcomes from stakeholder engagement

Throughout the course of the project, stakeholders were kept informed about progress, and they supported its development through the project's Steering Group, which met six times. Stakeholders gave specific guidance in the selection of the case studies, wanting a focus on both domestic and maritime flows rather than several bulk flows.

The project had a significant engagement with the NR national timetabling team and was able to gain much guidance from them around the historic development of SRTs and the logic behind them. The team also gave guidance on areas of particular interest and how the developing ideas could be incorporated into 'business-as-usual' work within the timetabling community.

3 Review of existing SRTs and their inputs

3.1 Modelling train timings

3.1.1 Definition of the forces acting on a train

To model train timing performance, the forces acting on the train need to be quantified. Four types of force can be considered, which are:

- gravity: the force required to move the train up a gradient (vertical change)
- curvature: the force required to change the direction of travel around a curve, as a function of the curve radius (horizontal change)
- total mechanical resistance (speed dependent): the aggregate of the resistances within the locomotive and wagons and within the train's external interfaces with the track and air, such as friction within bearings and aerodynamic loading
- acceleration: the force required to overcome inertia (including internal braking forces) and accelerate the train.

3.1.2 Use of the Davis equation to model mechanical resistance

A basic quadratic function is used to model the variation of the mechanical resistance with speed, an approach that has been used for well over a century in multiple countries (see review in the T1302 report). This model has a generic structure of:

$$Mechanical\ Resistance = A + B \times v + C \times v^2\text{, where v = the train's speed}$$

This equation (known as the Davis equation) recognises that the total mechanical resistance force has a number of components: a constant element and elements that increase both with speed and the squared value of speed. The total mechanical resistance of the train is the sum of the locomotive resistances and the cumulative individual wagon resistances and so this varies by locomotive type, wagon type, and train length.

The main types of resistances that align with the A, B, and C coefficients in the Davis equation are listed below:

'A' coefficient (no relationship with vehicle speed):

- bearing resistance
- rolling resistance (non-velocity dependent)
- track resistance.

'B' coefficient (linear relationship with vehicle speed):

- flange friction
- flange impacts
- velocity-dependent rolling resistance between wheel and rail
- wave action of the rail.

‘C’ coefficient (squared relationship with vehicle speed):

- front-end aerodynamic drag
- skin friction on the side of the train
- rear-end aerodynamic drag
- turbulence between vehicles
- yaw angle of wind to the train
- increased aerodynamic drag in tunnels.

3.1.3 Resultant force acting on a train

The resultant force acting on a train can be expressed as the difference between the available tractive effort from the locomotive less the sum of the four resistive forces defined above and any applied braking force:

$$Resultant\ force\ acting\ on\ train = Tractive\ Effort\ (v) - Mechancial\ Resistance\ (v) - Curvature\ Resistance - Brake\ Force - Gradient\ resistance$$

Note that gradient resistance will be negative if the train is going downhill (the train’s weight looks to accelerate it). If the resultant force on the left-hand side of the equation is positive, the train accelerates, if it is negative, the train decelerates, and if it is zero, the train does not change speed. This speed at which the resultant force is zero is known as the ‘balancing speed’ as the tractive effort and resistance forces balance, resulting in no net accelerative force.

3.1.3.1 Calculating train timings

For determining the time taken by a train to pass through a certain section, timing models typically assume acceleration in the highest notch (i.e., utilising the highest available tractive effort at a particular speed) until the train reaches and cruises at the relevant line speed. If the train needs to slow down for a speed restriction, or to stop at the end of the section being considered, then braking at a moderate but reasonable rate is assumed, linked to normal driver braking practice around maintaining line speed but avoiding sharp braking possibly causing wheel slide or excessive brake wear.

NR divide their network into timing points (known as TIPLOCs), and the track between them is known as a timing ‘section’. SRTs are defined for each locomotive class in each timing section at several different trailing loads, and they represent the time allowance required for that loaded train to travel through the section assuming a green aspect or red at the end of a section where it is planned to stop.

Usually there are four SRTs for each consist depending on whether the train is through running (pass – pass), running through and stopping (pass – stop), starting and running through (start – pass), or starting and finishing at a stop (start – stop). The SRTs therefore include an assessment of the train’s acceleration and braking performance.

3.2 Previous and current timing models

Early timing models were first developed and utilised in the 1970s. BR DM&EE's TRATIM (TRAin TIMetabling) was a relatively simple model and consequently quick at generating large volumes of train timings, an important consideration given the limited computing power available at the time. BR Research's more sophisticated GATTS (General Area Timebased Train simulator) gave more insight into network simulation, and its successor VISION (Visual and Interactive Simulation of Infrastructure and Operations on rail Networks) was a more sophisticated model, developed in the 1980s, able to carry out more detailed calculations and was used for power supply calculations. These different models reflected the efforts of different parts of British Rail carrying out different activities in the 1970s. Around 20–25 years ago, there was a move to using the RailSys model developed by Rail Management Consultants Gmbh, which has been subsequently extensively used and updated for NR timetable planning. However, the RailSys model relies on tractive effort data and train resistance characterisations that are developed 'upstream' of it. Exploring the impact of these historic timings can be challenging with current timing models.

More computing power is now available, so more accurate treatments and higher resolution/quality input data can be used. The SRTcalc model, which was developed as part of the previous T1302 project and was used for this project, has greater flexibility as a research tool, as it allows the use of different data sets and different features to be activated or disabled, as well as providing comprehensive outputs and diagnostic indicators.

3.3 Data sets and assumptions currently used in modelling SRTs

Through stakeholder engagement with timetable planning staff at NR and Freightliner, current input data and assumptions for modelling SRTs were obtained, compiled, and assessed. This information had a wide range of quality, current validity, and completeness. In general, all types of input information have been subject to a level of simplification, primarily reflecting historic pressures of computing capacity and the general prioritisation of improving passenger train data for modelling.

The network geography information utilised by NR has various limitations but is generally sufficient for modelling most passenger services, though there is not full country coverage. In some cases, the NR geographic data is not sufficient for freight modelling because of inaccuracies and/or gaps in gradient information (for example correct handling of flyovers). In some cases, the geographic data is not up to date. For instance, speed restrictions not been updated after weak structures have been upgraded. Line curvature data is notably limited, but this only has an impact on resistances at low speed as high track curvature (resulting in high curvature resistance) and medium-to-high line speeds are mutually exclusive.

Train characteristics include train length, tractive effort and adhesion, and locomotive resistances and wagon resistances (which are dependent on wagon type and on loadings). These are discussed in the following sections.

3.4 Train length

A train can be treated as point or a line for modelling purposes (maximum trailing load or timetable calculation). The former is easier to model, but the latter approach takes better account of longer trains taking more time to clear speed restrictions. If using the more accurate 'line' method, it is important to model the correct train length, and it is notable that trains have got longer over time.

This has a large impact, especially as 775 m container trains take longer to clear speed restrictions than current shorter length assumptions for those trains (and much longer than the 'point' assumption, which will usually result in the train being 2 minutes late relative to its timing due to the time taken for the rear of the train to clear the speed restriction before the train can accelerate). The main operational impacts are often observed either when leaving yards or loops with very low line speed limits or at junctions with comparatively low line speed for joining or diverging from the main route.

Current NR practice within RailSys is to treat modelled trains as line sources, but older historical treatment often was to treat them as point sources, so the length of train, including time to clear speed restrictions, was not accounted for. This results in current SRTs being a mix of line and point source depending on when they were calculated. However, current assumption of train length for those treated as line sources may not be long enough in some cases.

3.5 Tractive effort and adhesion

There are a number of factors to consider in the relationship between tractive effort (TE) and rail head adhesion.

3.5.1 Accuracy of the modelled performance

The NR TE data inputs for RailSys modelling are in 1 to 16 km/h increments, with linear interpolation used between data points (apart from the Class 70 data, where the hyperbola functionality in RailSys is used). This is in contrast to the TE data used in the T1302 report, which is all in 1 mph increments (with linear interpolation used between data points). While not making a significant material difference to the available TE for modelling purposes, the more granular data now available does enable more accurate modelling.

3.5.2 Conservative specification of TE

Other key assumptions for the NR RailSys TE data include the use of only 95% of the relevant TE value from the OEM data tables to take account of potential uncertainty in the TE specified by the data tables and what might be delivered in practice. This assumption is sensible for older locomotive types, where the curves are reflective of real measurement, but locomotive OEMs in recent decades have already added a level of conservatism into their official TE curves so that they 'under sell and over deliver' on TE. Potential assumptions on what proportion of the TE values are used for modelling will also vary in practice between the adhesion limited part of the curve and the power limited part of the curve (the majority of the TE curve with approximately hyperbolic curvature to the middle and right of the curves).The adhesion and power limited parts are illustrated in Figure 3 and Figure 4 below.

3.5.3 Alternative definition

For the adhesion limited part of the TE curve (the 'horizontal' left-hand part of the curve at low speed), the assumptions around adhesion, use of the Curtius-Kniffler adhesion limit, and selection of appropriate μ_0 values can address this part of the curve separately. This is also the area where TE delivery is more variable and therefore needs more conservative assumptions in practice. We have therefore used this approach to model this part of the curve, using these assumptions.

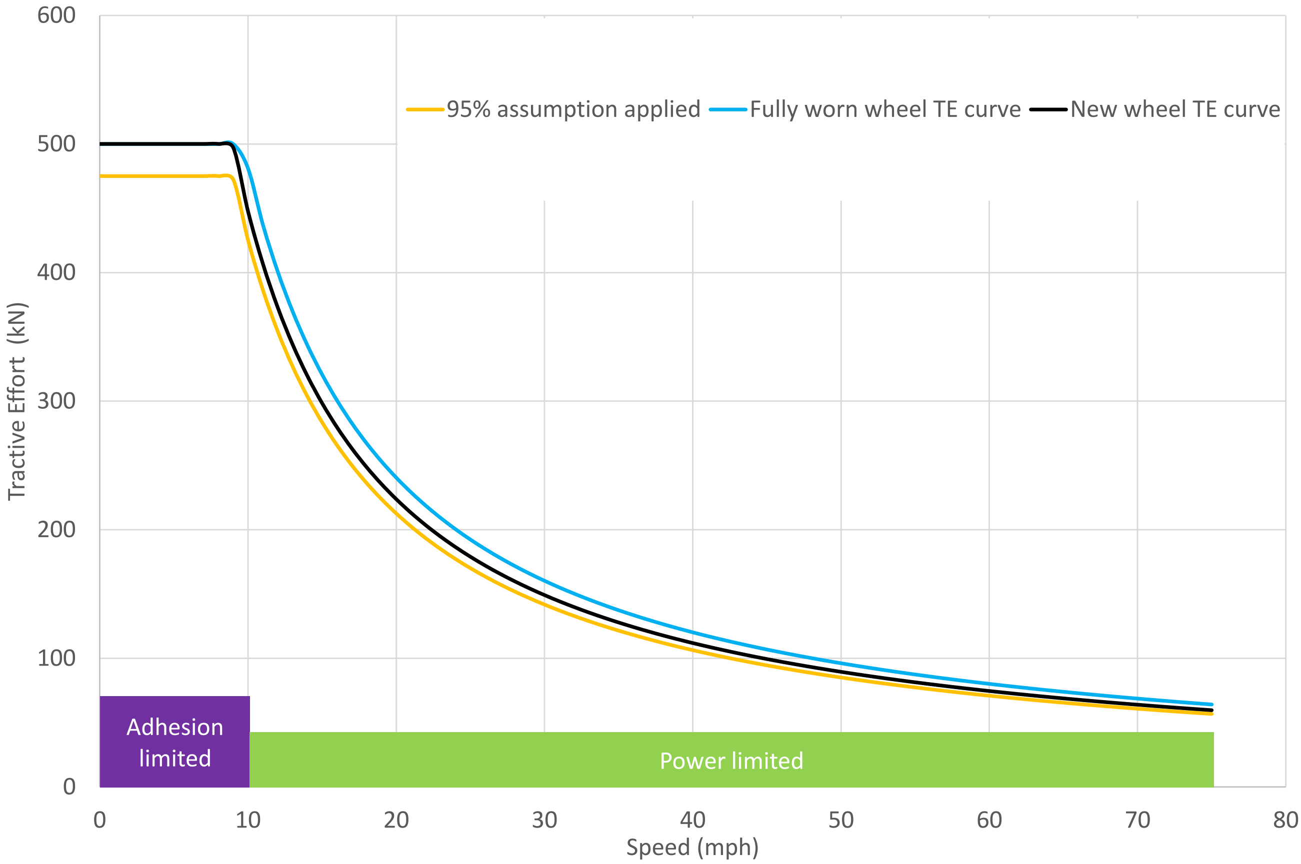
3.5.4 Worn wheels

The power limited part of the TE curve (higher speed curving section) varies with wheel wear, and this can increase (improve) for freight locomotives by up to 7.5% over the working life of the wheelset, hence the usual conservative practice of specifying TE data for 'new wheels'.

3.5.5 Modelling of these factors

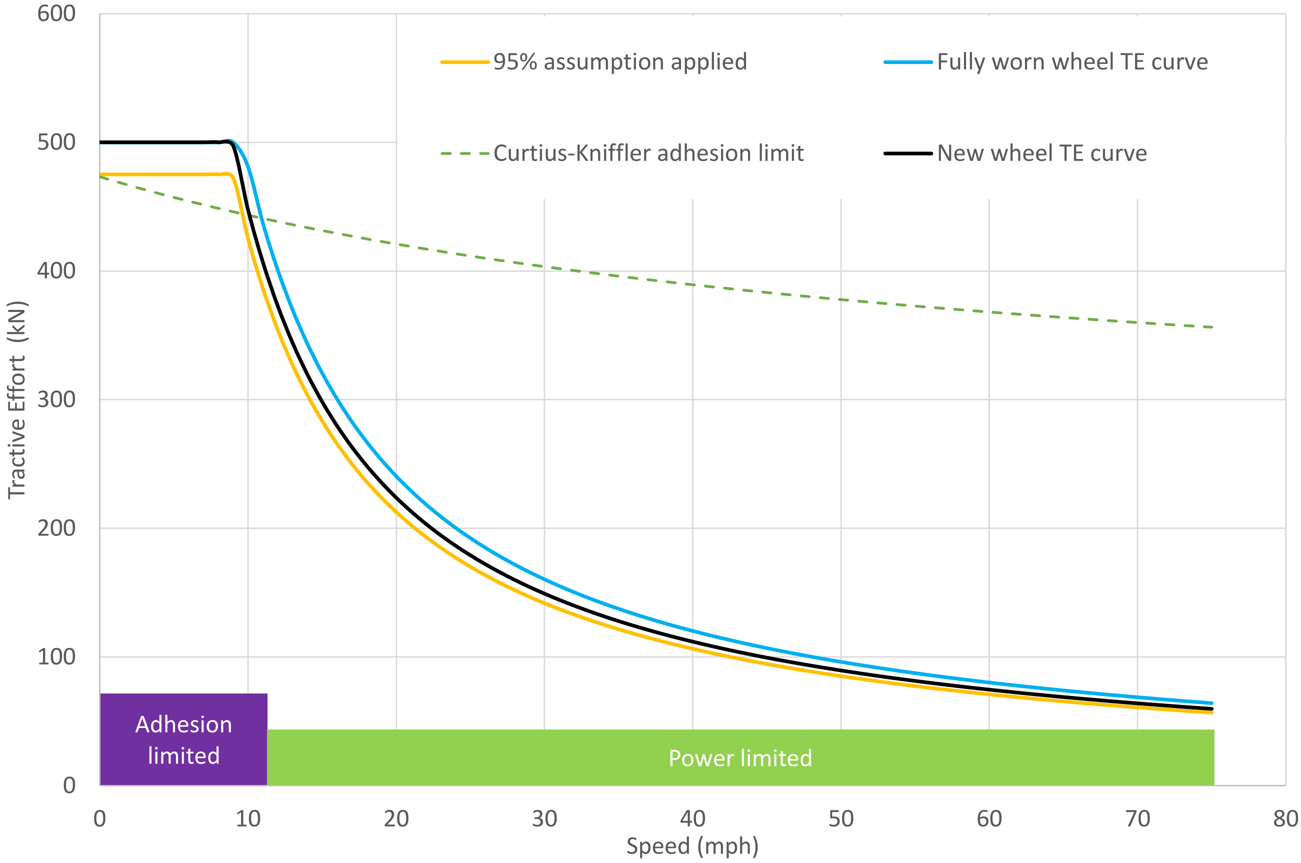
In Figure 3 below, the diverging impacts of the 95% assumption (orange curve) and of fully worn wheels (blue curve) on a nominal locomotive new wheel TE (black curve) is shown. In reality, for modern locomotives, the manufacturer will already have built some conservatism into the black curve, with the real TE performance with new wheel sets likely to be closer to the blue curve (and the real fully worn TE being similarly higher).

Figure 3 Impact on TE of the 95% assumption and of wheel wear during the wheelset life



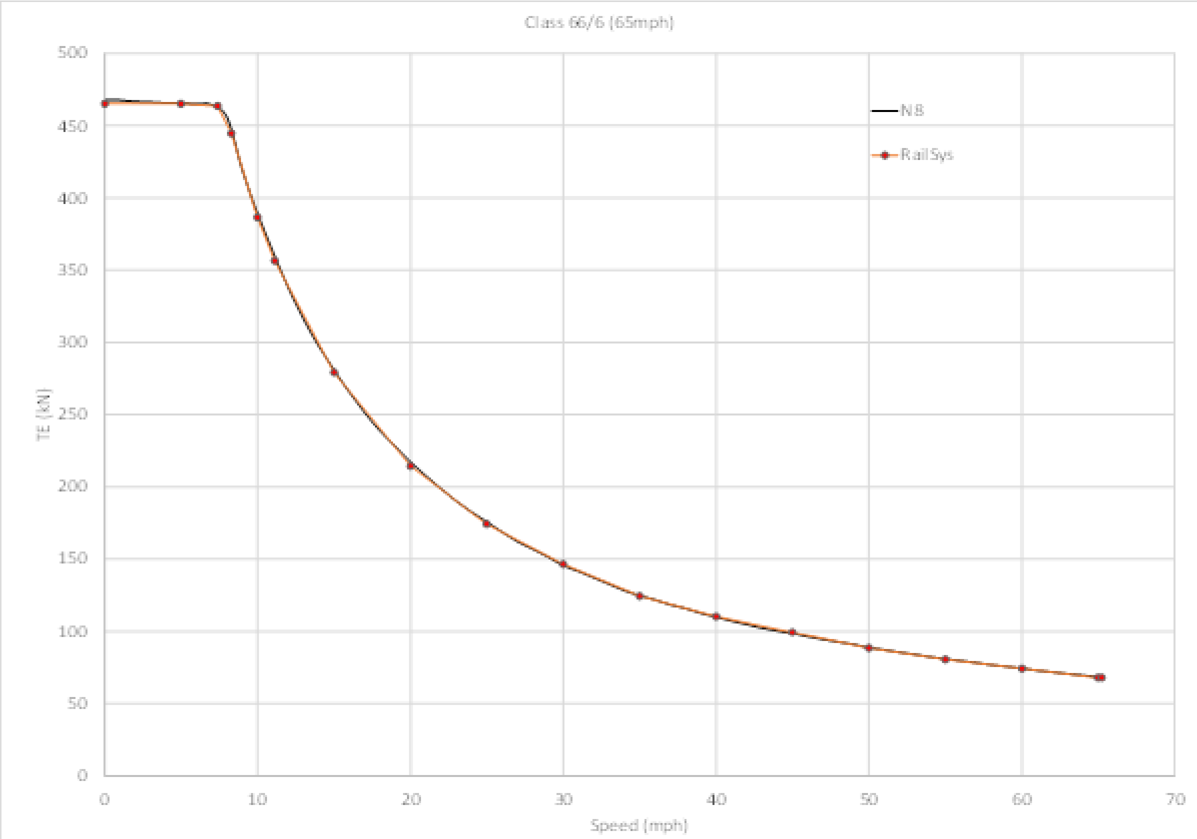
In Figure 4 below, the impact of the 95% assumption and its interaction with the T1302 recommended adhesion approach is based on the Curtius-Kniffler equation (dashed green curve). This separates the expected lower speed deliverable TE from the nominal TE curve(s). This provides a more targeted and appropriate way to handle higher uncertainty in TE delivery at lower speeds on the adhesion limited section of the curve, compared with higher speeds on the power limited section of the curve, where the certainty of delivery is far higher.

Figure 4 Impact on TE of the 95% assumption and its interaction with other adhesion assumptions



An example of a good correlation between the data set used by NR for the Class 66/6 is shown in Figure 5 where the two curves are very closely matched with essentially imperceptible differences.

Figure 5 Comparison of TE curves for the Class 66/6 used by NR in RailSys modelling and in the T1302 report



An example of acceptable data that could be easily improved with more data points is for the Class 92 on AC, which is shown in Figure 6 .

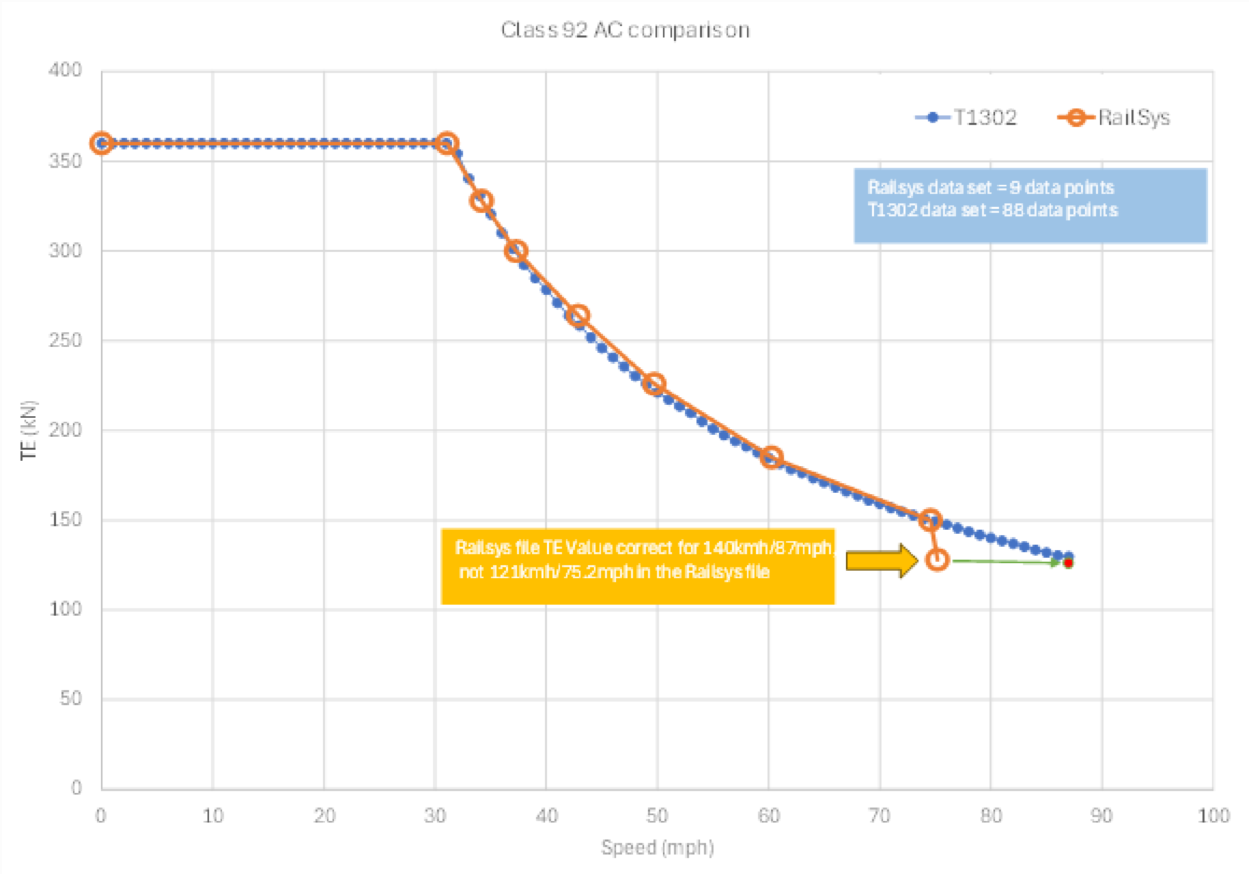
Here, the NR data is generally good from stationary to medium speeds despite only, having nine data points overall. At the top of the speed range, there can often be seen a feature common in multiple older NR TE data sets used for RailSys modelling (those typically originally developed for VISION) whereby an artefact is introduced to significantly reduce the TE at 1 mph below the maximum speed chosen for that particular data set. This has the effect of significantly decreasing potential acceleration as the train approaches the specified top speed.

This appears to be an attempt to model driver behaviour in reducing acceleration as they approach the maximum permitted locomotive speed (for the data set) but is not applied where speeds are limited for other reasons to lower values, such as lower line speeds or lower maximum wagon speeds. Hence, a more consistent approach for added realism would be to apply this more generally when approaching all relevant speed restrictions.

This approach has not been followed in more recent TE data sets in use. In this particular case, the TE data for the Class 92 is available up to 75 mph, which would preclude this data set's use for calculating new Caledonian Sleeper timings (maximum speed of 87 mph), as it has been artificially limited to 75 mph, but the T1302 Class 92 data set (up to 88 mph) would allow these to be calculated.

A better approach to modelling reducing acceleration approaching the maximum permitted train speed or line speeds (both of which can often be lower than the locomotive maximum speed) would be to modify the model's logic so that drivers' actual behaviour in reducing acceleration is included in a uniform transparent way.

Figure 6 Comparison of TE curves for the Class 92 on AC used by NR in RailSys modelling and in the T1302 report

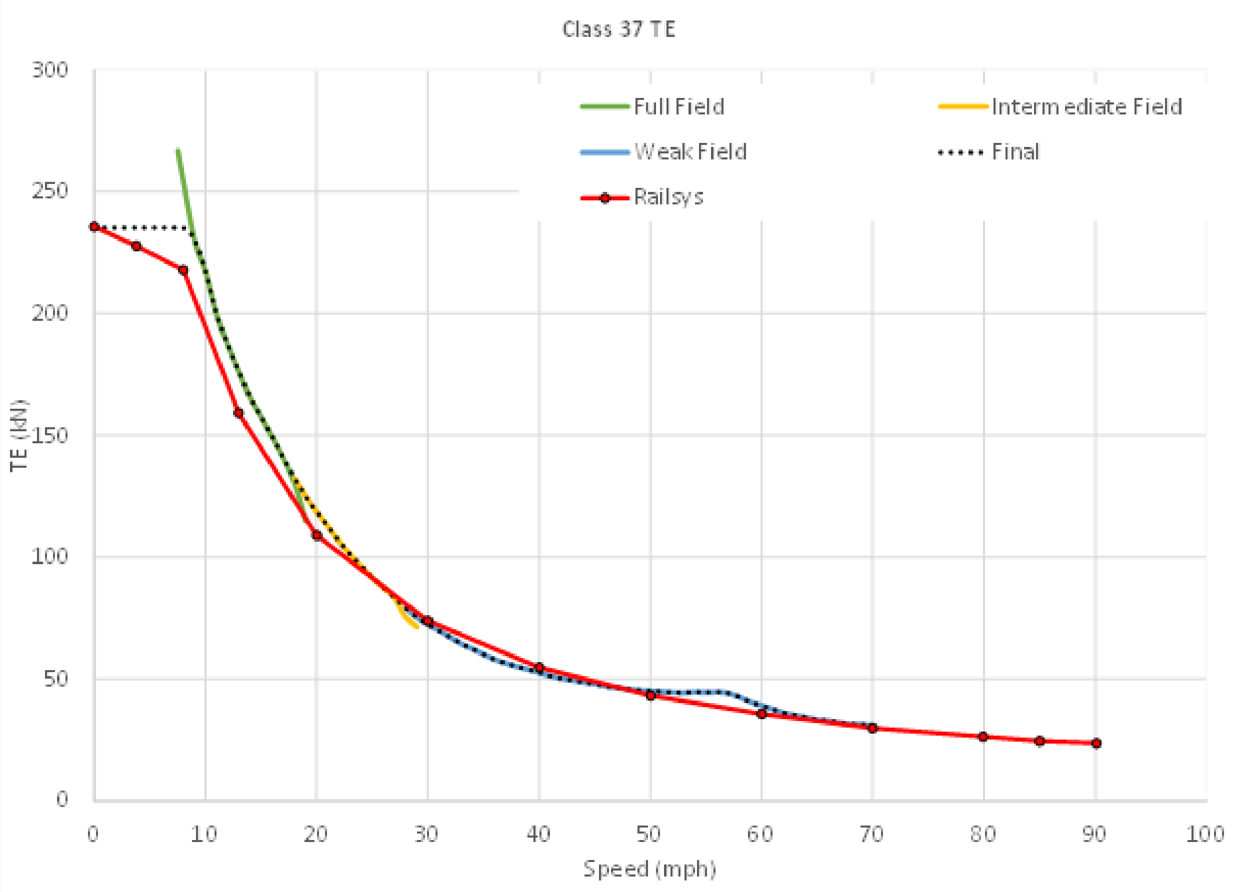


Other locomotive data sets are generally acceptable but have localised differences that could be investigated further and improved with more data points.

For example, in Figure 7 below, the Class 37 data used by NR (red curve with data points as red/black dots) does not have enough data points to capture the complexity of the TE curve shape shown as the black dots. The curve is formed of five distinctive parts due to the use of field weakening of the electrical system on the locomotive.

Furthermore, it appears that a non-standard (for BR) adhesion assumption has been applied to the red TE curve that is used in RailSys. It appears that an adhesion assumption similar to a linear approximation of the Curtius-Kniffler adhesion limit (shown in Figure 4) has been applied to this particular data.

Figure 7 Comparison of TE curves for the Class 37 used by NR in RailSys modelling and in the T1302 report



Other TE curves may have a poorer fit than that shown in Figure 7 and can involve linear interpolation between just two data points. At least five data points are needed to effectively approximate a hyperbola, whereas many of the NR curves have only three data points specified. This leads to poor quality approximations. The final T1302 data is shown as the small black dotted line.

3.5.6 Appropriateness of locomotive specific TE data

An assessment of the TE data for different locomotive classes is shown in Table 1.

Table 1 Assessment of NR TE data used in RailSys modelling for different locomotives

Data quality	Locomotive class	Notes
Good (can easily improve with more data points)	56	Available information around more data points should be added into the TE data files.
	66 (75 mph geared)	
	66 (65 mph geared)	
	68	
	88 (AC electric)	

OK (can easily improve with more data points)	70	Available information around more data points should be added into the TE data files. Hyperbola approximation issue needs to be addressed.
	92 (AC electric)	See Figure 6
OK (localised differences that can be investigated further, also could be improved with more data points)	37	Not enough data points to capture complexity of TE curve shape.
	47	Difference in adhesion assumption at low speed, generally good data quality (good number of data points, matches other Class 47 data sets).
	60	Good data quality for higher speeds, could be improved for lower speeds. It appears NR has used the 1989 data set, whereas T1302 used the 1991 data set.
	59	NR data has lower TE for the virtually all of the curved section, different adhesion assumptions used in the NR data for the 60 mph and 75 mph TE curves for the same class.
Poor (significant further analysis required)	86	Important because it is the basis of many current electric freight paths, and these should be replaced by the correct loco class now being used.
	90	Existing locomotive TE data set was for passenger usage in 1990s and would have allowed Class 86 or 87 locomotives to be substituted. The original multiple working solution specified in the data is no longer used, and one that delivers significantly more TE is used in practice. The Class 90 is discussed below in detail.
	92 (DC electric)	The used TE values above 30 mph are significantly lower than other available data sources and appear to be for just one of the two separate electrical systems on the locomotive (the locomotive has split systems one for each bogie to provide redundancy in the Channel Tunnel).
	73/1 (DC electric)	The file labelled 'diesel' TE file is equivalent to over 3.5 times the power output of the diesel engine fitted to the 73/1 and is closely aligned with the expected electric performance. Otherwise, the NR data does not identify the traction mode. It appears the TE curves for the Class 73 on diesel and electric have been swapped.

	73/1 (diesel)	Labelled as 'electric' in one place, otherwise the NR data otherwise does not identify the traction mode. It appears the TE curves for the Class 73 on diesel and electric have been swapped.
No NR data, but excellent data from T1302 is available	58	Use high-quality 1 mph increment data sets from T1302/1.
	69	
	88 (diesel)	
	93 (electric and diesel)	
	99 (electric and diesel)	
No T1302 data (or other new data) to compare with NR data; further investigation needed	31	Existing NR data sets have been interpolated into 1 mph increments for T1301, but further investigation is needed.
	57	
	67	
	73/9 (diesel)	

We recommend:

- The TE values for locomotive classes 66, 68, 70, 88, 92, 93, and 99 use 100% of the TE curve value instead of 95%
- Use high-accuracy data sets with 1 mph increments from T1302/1.
- Although the TE curves are generally conservative because of the improved adhesion from worn wheels, this advantage cannot be used for modelling, as the modelling has to accommodate the 'worst case' new wheel adhesion limit.
- Class 90 locomotives are specifically reviewed (see the following section).
- The updated T1302 figures are used for more recent locomotive classes, which are currently without TE curves in RailSys (Classes 69, 93, and 99).
- The updated T1302/1 figures are used for locomotive classes where there the quality of the existing TE data in RailSys is poor (Classes 56, 59, 60, 66 [low and high gear], 70, 73, 90, 92).

3.6 Class 90

The current treatment of Class 90s by NR for timetable modelling requires further investigation. Double-headed Class 90 freight services currently use double-headed Class 86 timings. However, Class 90s are significantly more capable than Class 86 locomotives (even with a maximum power draw limitation for double heading). This means Class 90s could be used to (a) run longer or heavier trains in the same timings, (b) run the same loads with quicker timings, or (c) do a combination of both (a) and (b).

Furthermore, both the Class 86 and Class 90 data sets for calculating freight timings have been assessed as low quality by NR. This is due to a number of issues. For lower speeds:

- Both have in-built passenger timetabling assumptions from 1980s.
- The Class 90 TE data currently used for timetabling modelling is limited by an adhesion cap of μ_{max}= 0.23. However, both BR & GEC literature state that the 192 kN value for the starting tractive effort is an explicit adhesion assumption of 0.23, not the rated TE. This assumed adhesion cap would have allowed Class 90s to be easily substituted for a Class 86 (or Class 87) on passenger WCML services, and this remains a sensible assumption for moderate-to-high-speed passenger timetabling today. However, this adhesion cap is not a sensible assumption for freight timetabling, neither in the 1980s nor now.
- The BR maximum-rated TE data for the locomotives equates to μ= 0.255 for the Class 86 and μ= 0.315 for Classes 87 and 90. Thus for Class 86 locomotives, the 0.23 μ_{max} assumption is equivalent to 90% of the maximum rated TE value, while for Class 87 and 90 locomotives, the 0.23 μ_{max} assumption is equivalent to just 73% of the maximum rated TE value, significantly reducing the TE by up to 27% below 50 mph.

For higher speeds for the Class 90:

- Conservative assumptions for TE at higher speeds are based on circumstances that can only occur in passenger running.
- The 'curved' part of the TE curve for Class 90 assumes electrical performance degradation and lower power delivered at the wheel due to significant running time at higher speeds with lower overall traction motor efficiency **and** also field weakening being used with the traction motors. However, traction motor efficiency starts to drop as the locomotive speed increases above at 75 mph, and field weakening (up to five steps can be utilised) starts to be used above 84 mph up to and including the maximum locomotive speed of 110 mph. Since maximum freight train speeds are limited to 75 mph, neither of these scenarios are relevant to assessing the assumed electrical performance degradation, which will be much lower than in real-world Class 90 freight usage. Similar issues are found with the Class 92 locomotive on DC power at higher speeds.

At lower speeds (the flat part of the TE curve), the deliverable TE could be up to **33% higher** for both single and double-headed Class 90s than is currently assumed by NR for RailSys modelling. At higher speeds (the curved part of the TE curve), the deliverable TE could be up to **57% higher** for a single Class 90, and with the newer current limiting solution for double-headed Class 90s, the existing curve is very close to the appropriate values for each locomotive when a pair of Class 90s are used—but without the further power reduction assumptions currently needed. In conclusion, **modelled Class 90 timings could be considerably improved and need to be recalculated**.

A comparison of the Class 90 TE data used by NR in RailSys versus the original GEC assumptions is shown in Figure 8 This shows the significant different between OEM data and the current data set uses. The NR dataset is highly conservative and vastly underestimates real world performance, leading to unrealistically longer timings.

Figure 8 Comparison of Class 90 data used by NR in RailSys versus original GEC assumptions

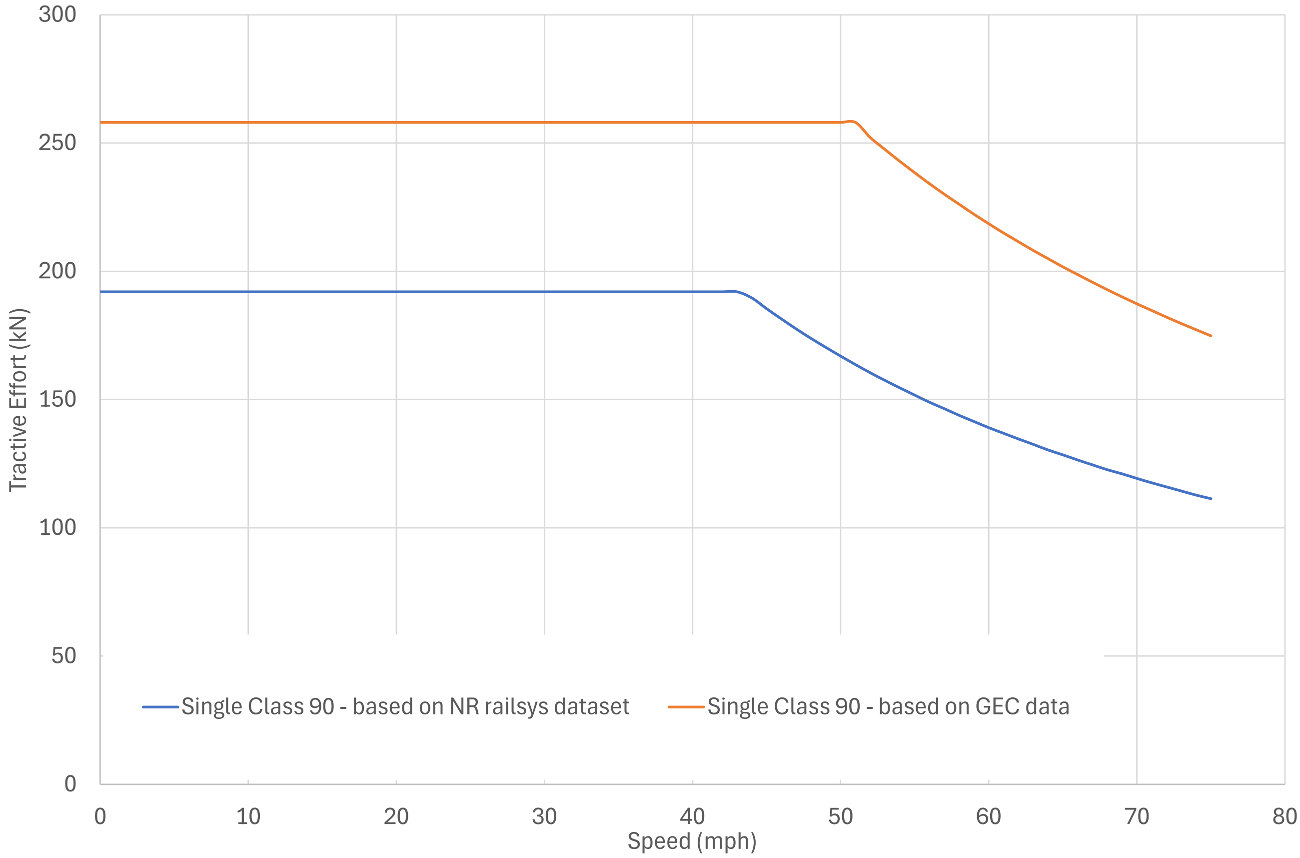
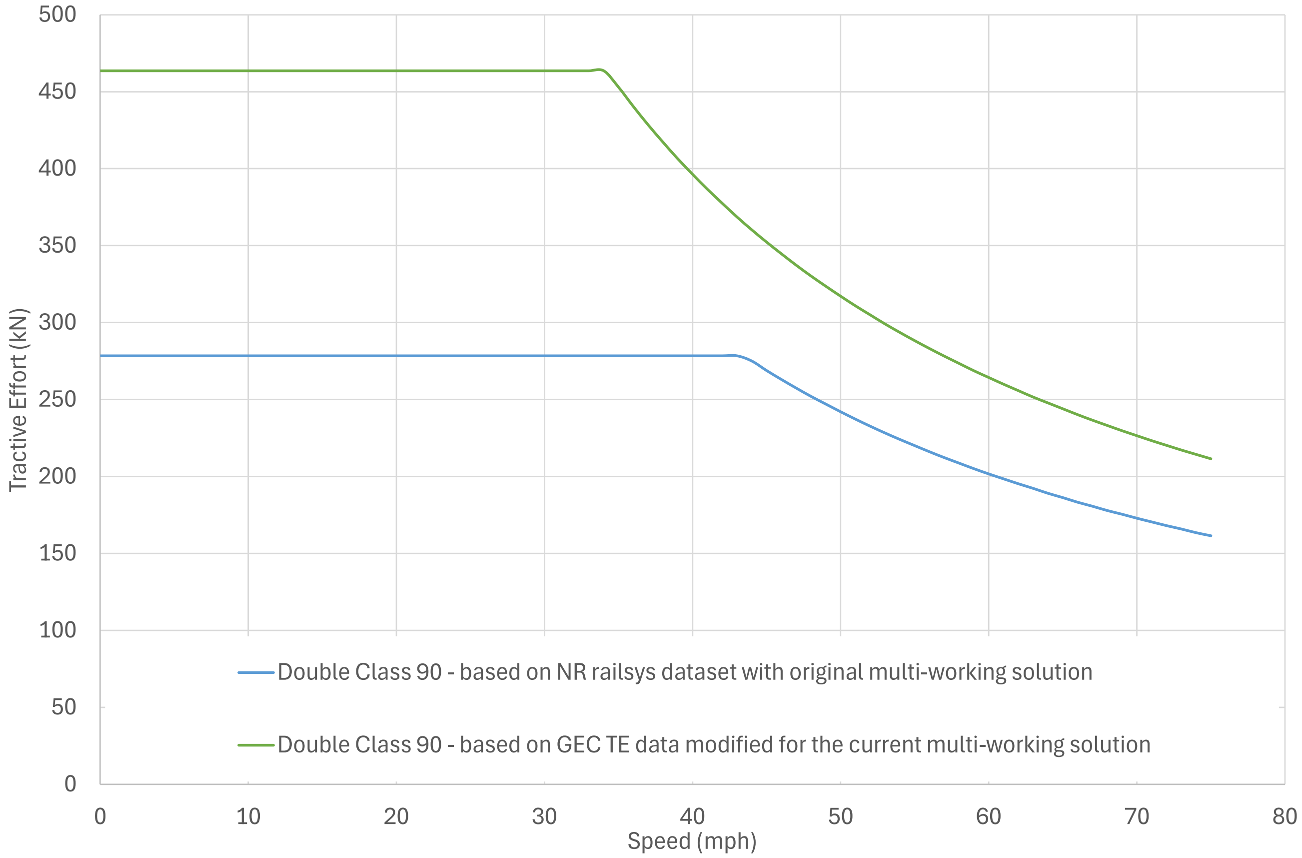


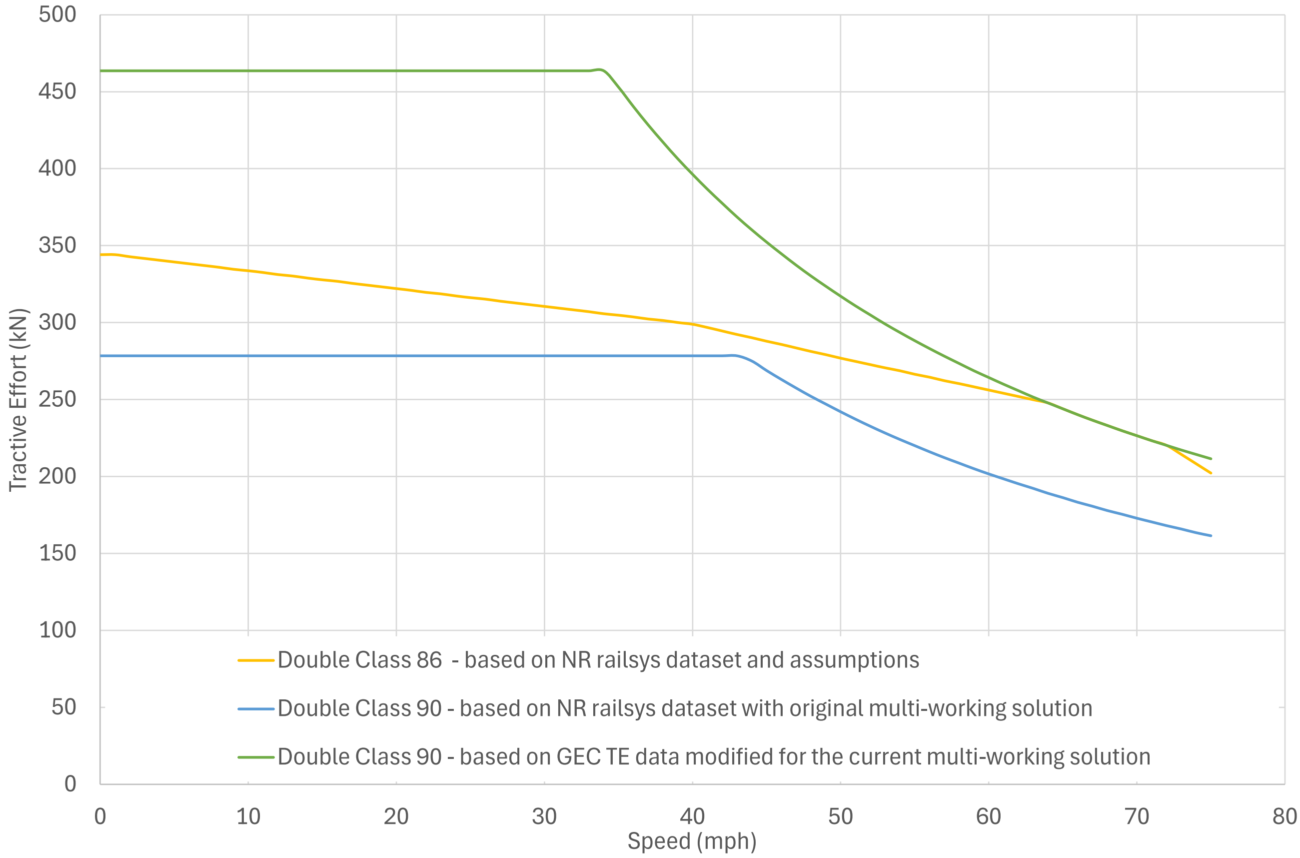
Figure 9 shows the original multi-working solution (where one traction motor is assumed to be isolated on each locomotive), which is captured in the NR RailSys assumptions, and the current improved multi-working solution (where the power is limited where necessary) is applied to the GEC TE data. The mismatch between real-world performance and NR assumptions is further exacerbated, potentially leading to unrealistic longer timings.

Figure 9 Comparison of Class 90 double-heading assumptions for TE



Current Class 90 paths utilise double-headed Class 86 timings. Figure 10 shows a comparison of the double-headed Class 86 default versus both the current Class 90 multi-working solution and using the GEC TE data for the Class 90. The difference between the two curves is not the same as in Figure 9 but it is still large and will lead to unrealistically long timings.

Figure 10 Comparison of the double-headed Class 86 default versus the current 90



3.7 Locomotive resistances

3.7.1 Starting resistances

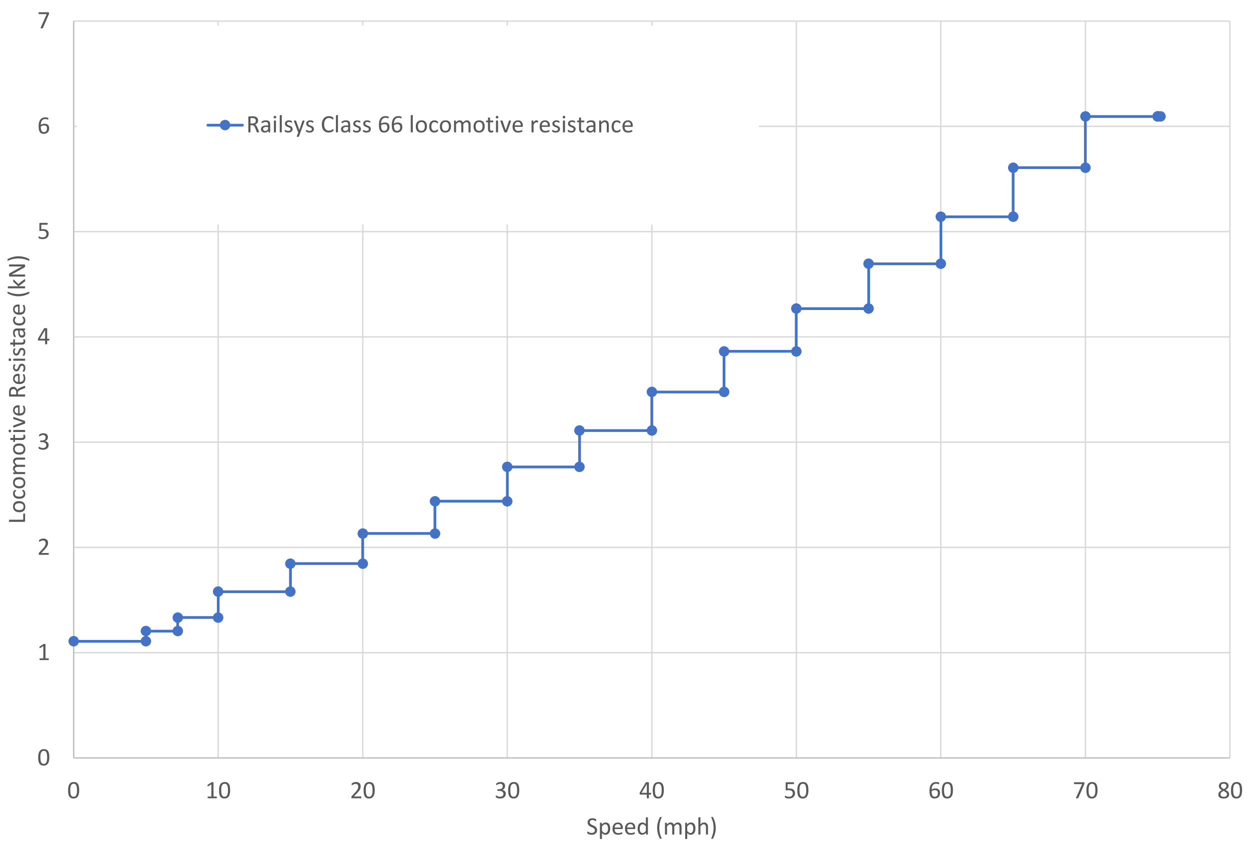
Through engagement with NR and other stakeholders, a review was undertaken of methods used to calculate locomotive resistances, including for specific locomotive types.

Not all locomotive resistance data sets used by NR have locomotive starting resistance included. Those that do use 15 lb/Ton, which is lower than the value of 20 lb/Ton in MT19 (and which was retained in the T1302 report). The 15 lb/Ton value is documented by NR, and this is a step forward from a handwritten note of this value on the available copy of MT19.

3.7.2 Rolling resistances

In the RailSys model used by NR, there are two functional ways of handling locomotive resistance: (i) defined curves (using the A, B, and C coefficient values of the Davis equation), which are used for three locomotive classes; and (ii) linear interpolation between points, which in practice defined a step function with a limited number of data points (which cause artefacts in train resistance calculation – see Figure 11), and which are used for the majority of locomotive classes.

Figure 11 Example of a step function type locomotive resistance curve that is typical of over 85% of those in the NR's RailSys locomotive resistance datasets, in this case for the Class 66 locomotive



We have calculated the velocity related A, B, and C values for underlying curves that were simplified to create the step functions, and the values we calculated showed common patterns across all the locomotive types. These suggest that several common methodologies within each group are being used at different points in time:

- Many older locomotive types have similar values to MT19 (simplified B=0 approach), with many values effectively identical to MT19 values within calculation margins of error.
- Other older locomotive types B≠0 is used (which is the T1302 approach) and values are similar to T1302 values.
- All older locomotives resistance curves produce similar values to MT19/T1302 resistance values.

Table 2 categorises the methods used to calculate resistances for various locomotive classes, and five distinct categories of approaches can be identified. These approaches, which are often inconsistent with each other, are discussed below.

Table 2 Categories of locomotive resistance calculation methods for different locomotive classes

Category	Railsys approach	Formula type	Starting Resistance?	Class (Railsys file)	Loco type listed in MT19?
1	Step Function using defined coordinates	A+C components only (i.e. B=0)	Yes	Class 31	Yes
				Class 56 (75mph)	Yes
				Class 60	Yes - formula misapplied as in MT19
				Class 67 (125mph)	no - locomotive post MT19
				Class 73/1 Electric (75mph)	Yes
				Class 86 Electric (100mph)	no - electric not in MT19 doc., but likely to use same formula
				Class 86 Electric (75mph)	no - electric not in MT19 doc., but likely to use same formula
				Class 90 Electric (both 100 & 110mph)	no - electric not in MT19 doc., but likely to use same formula
				Class 92 Electric both *AC* & *DC* (75mph)	no - electric not in MT19 doc., but likely to use same formula
2		A, B, C		Class 47 (75 & 95mph)	Yes - but not MT19 values used here
				Class 59 (60mph & 75mph)	no - locomotive post MT19
				Class 67 (110mph)	no - locomotive post MT19
				Class 73/9 Diesel (90mph)	no - locomotive post MT19
3			No starting resistance	Class 66(75mph & 65mph)	no - locomotive post MT19
				Class 68 (100mph)	no - locomotive post MT19
				Class 88 Electric (100mph)	no - locomotive post MT19
4	Formula	A+C components only (i.e. B=0)		Class 37 (90mph)	Yes - but not MT19 values used here
5		A, B, C		Class 57 (75mph)	no - locomotive post MT19
				Class 70 (75mph)	no - locomotive post MT19

Category 1 (Class 31, 56, 60, 67, 73/1 electric, 86, 90, 92) uses step function with A+C components only and includes 15 lb/Ton starting resistance. A and C values are the same as the ones produced by the MT19 formula.

Category 2: (Classes 47, 59, 67, 73/9 diesel) uses step function with A, B, and C components and includes 15 lb/Ton starting resistance.

Category 3 (Classes 66, 68, 88 electric) uses step function with A, B, and C components and does not include starting resistance.

Category 4 (Class 37) uses formula with A+C components and does not include starting resistance. The A and C values are not the same as the MT19 formula ones.

Category 5 (Classes 57, 70) uses formula with A, B, and C components and does not include starting resistance.

In conclusion:

- The current NR assumption of locomotive resistances does not work when locomotives are double-headed. The resistance for the second locomotive is much higher than it should be (reduced aerodynamics).
- There is an inconsistent approach to the treatment of locomotive resistance. T1302/1 now provides a more coherent approach (see later sections of this report), which should be adopted, based either on OEM data or a revised analytical approach.

3.8 Wagon resistances equation format

3.8.1 Continued use of historic BR 2 axle wagon approach

This section discusses internal wagon resistance formula and the forces due to gravity that apply due to the train weight (for example, on gradients) or acceleration are handled separately. Everything in this section is therefore a comparison of wagon resistances on level track.

Figure 12 is an extract from the NR RailSys Manual showing the formula for their Type 11 resistance curve.

Figure 12 Formula used by NR for freight wagon resistances

- Type 11 Roller-bearing Axlebox Freight
  - R(V) = RLOCO + CE*(1.0 + 0.07*V) + (13.0 + 0.015*V^2)*NAXLES
- Definitions of units
  - R(V) - resistance force (lb wt)
  - CE - weight of trailing load (tons)
  - V - speed of train (mph)
  - NAXLES - number of axles in trailing load

When placed in the nomenclature of the T1302 report, the NR Type 11 equation appears as:

$$R_{WMR} = M_W \times (1.0 + 0.07 \times V) + (13.0 + 0.015 \times V^2) \times \#\, Axles\ [lbs]$$

Then when rearranged into the MT19/T1302 format with Q = Axle load [Tons], this gives:

$$R_{WMR} = M_W \left(1.0 + \frac{13.0}{Q} + 0.07 \times V + \frac{0.015 \times V^2}{Q}\right) [lbs]$$

Which on a tonnage specific basis gives:

$$R_{WMR} = 1.0 + \frac{13.0}{Q} + 0.07 \times V + \frac{0.015 \times V^2}{Q} \ [{}^{lbs}/_{Ton}]$$

where:

R_{WMR} = specific wagon resistance (lb/Ton)

V = speed (mile/h)

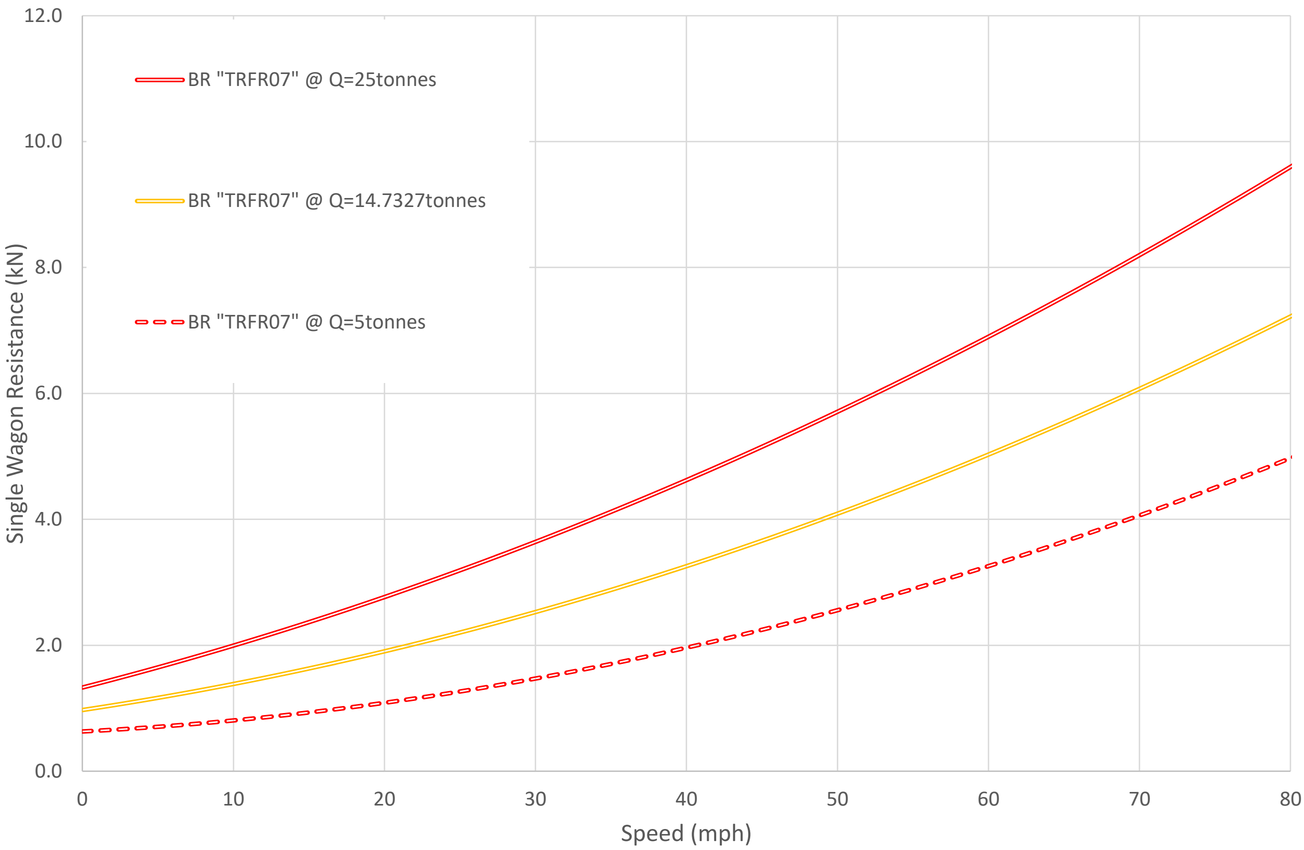
Q = axle load (Ton).

This equation is identical to the two-axle equation that was discussed at length in Section 3.2 of the T1302 report. It is understood that this equation was derived from tests carried out in 1957 with a mixture of short wheelbase wagon types with low axle loads and is consequently due for review. However, the use of two-axle wagons is substantially diminishing. This equation was also incorporated in timetabling calculations by British Rail in the mid-1970s. There is therefore a need to move to the appropriate four-axle equation, rather than using the BR TRFR07/NR Type 11 equation, which is just for two-axle wagons.

3.8.2 Axle loads

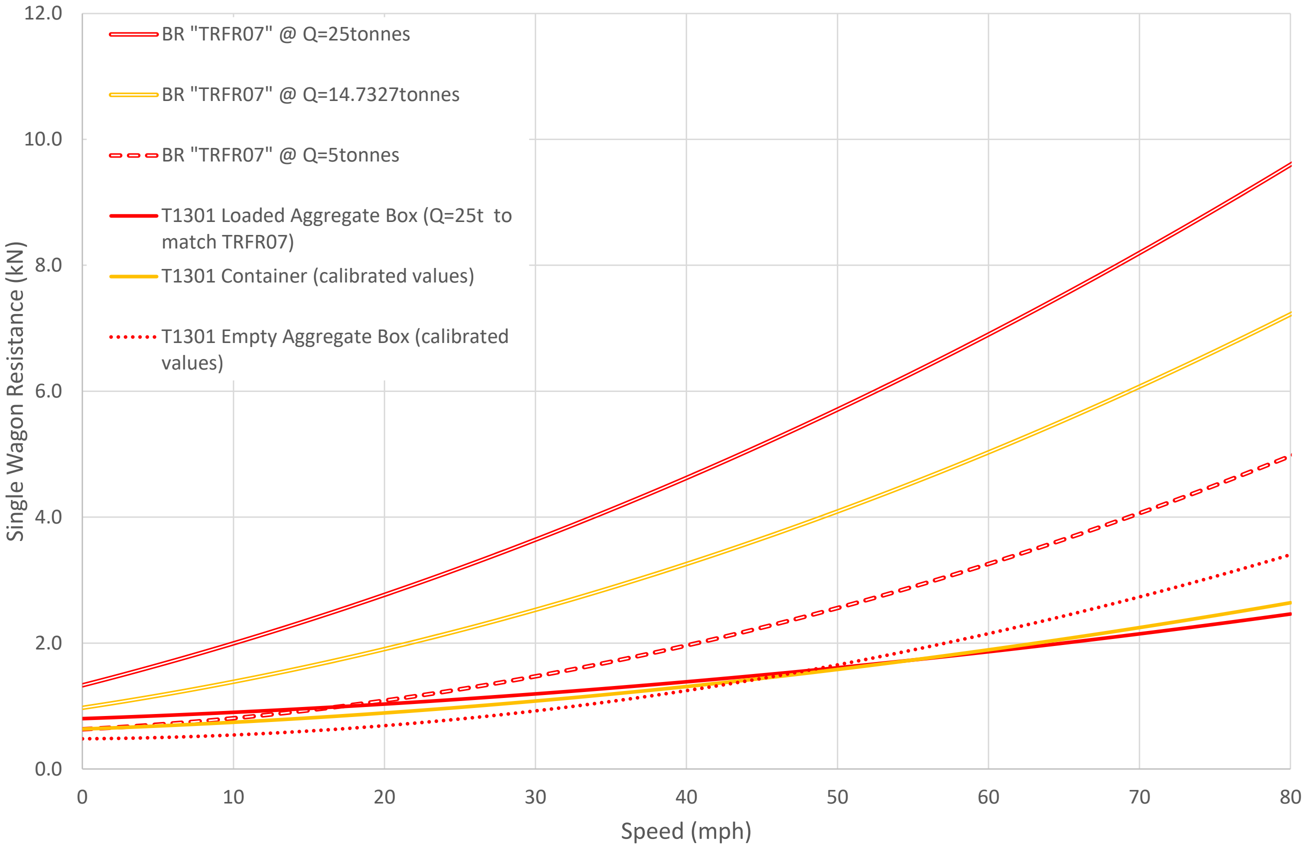
The impact of the three commonly used values of axle load (Q) is shown in Figure 13 below: heavy axle weight (HAW) Q=25 tonnes, container (CON) Q=14.73 tonnes (14.5 Tons), and empty Q=5 tonnes (see discussion of these values in Section 4.3 below). The resistance for a single four-axle wagon under these loads was calculated using the BR TRFR07/Network Rail Type 11 wagon resistance equation.

Figure 13 Comparison of BR TRFR07/Network Rail Type 11 equation for the three key axle load (Q) inputs



The differences between values calculating using BR assumption TRFR07 (as implemented for four-axle wagons) in the NR Type 11 equation and the T1302/T1301 equations for identical wagon resistance equation inputs and assumptions are quite significant, as shown in Figure 14 below. Resistances in the TRFR07/Type 11 equation are higher than the equivalent T1301 values for the same axle loads, being up to 80% higher at low speeds and two to three times higher at high speeds.

Figure 14 Comparison of BR TRFR07/NR Type 11 equation for the three key axle load (Q) inputs with T1302 four-axle equation with the same axle loadings (Q)



The increased wagon resistance (especially at higher speeds) produced when the TRFR07 equation is utilised for 4-axle wagons is unsurprising given the origins of the equation (these are discussed in depth in Section 4.3 of the T1302 report). The key factors driving the differences are:

- The TRFR07/Type 11 equation was derived for two-axle wagons based on late 1950s testing, predating the current significant four-axle wagon use in Great Britain.
- The TRFR07/Type 11 equation assumes a mix of journal and roller bearings (journal bearings have significantly higher resistance than current freight wagon roller bearings).
- The TRFR07/Type 11 equation was based on test running of a mixture of different two-axle wagon types with the aim to include the aerodynamic resistances at the highest end of those possible in order to assess the worst-case resistances.
- TRFR07/Type 11 equation was based on testing done up to 40 mph, hence higher speed resistances are an extrapolation beyond the test speed range.

3.8.3 Typical trailing loads

In the format that the BR TRFR07 equation is presented as the NR Type 11 wagon resistance equation, the user-variable parameters are just:

- total trailing load

- number of axles.

However, SRTs are currently specified for just trailing load, hence the user needs to make assumptions and specify the relevant number of axles in the formula, which is an indirect way of varying the axle load to consider the type of wagon.

SRTs were assessed for the three types of wagon loadings discussed above:

- heavy axle load
- container
- empty.

In recent decades, trailing loads have typically been calculated for increments of 200 tonnes. The older practice from the BR era for specifying trailing load is based on actual train loads by specifying the total trailing load as function of the number of axles and axle load, for example:

$$Trailing\ Load = \#\ Axles \times Q\ [tonne]$$

This approach still persists for many container SRTs, with the trailing load rounded to the nearest 5 tonnes and the number of axles always being even and virtually always divisible by four as well.

The modern 200 tonne increments are equivalent to two fully loaded 100-tonne heavy axle load wagons or 10 empty heavy axle load wagons. Loaded heavy axle load wagons tend to be loaded very close to their maximum permitted levels, so increments of 100 tonnes or multiples thereof is a sensible assumption to use. To reduce the overall number of permutations, calculated increments of two wagons/200 tonnes are used for timing loads. However, the modern 200-tonne increments for timing loads align less well with whole numbers of container wagon, whether the wagons are loaded to either their theoretical maximum or with typical loadings.

The permutations of wagon load and 200-tonne increments of trailing load used for SRT calculations are shown in the Table 3 below. A very limited number of other values are used very infrequently, and these have been excluded for clarity.

Table 3 Wagon assumptions for 200-tonne increment trailing loads used in SRT calculations

Trailing load (tonnes)	Empty wagon	Heavy axle weight ("H"/"HAW") Wagons	Container ("C"/"CON") Wagons	Notes
400	Y			
600	Y			
800	Y	Y	Y	Often no clear identification
1000		Y		
1200		Y		
1400		Y	Limited (Cl. 88, 92)	
1600		Y	Y	
1800		Y	Y	
2000		Y	Limited (Cl. 92)	
2200		Y		
2400		Y		
2600		Y		
2800		Y		
3000		Y		
3200		Y		
3400		Y		
3500		Y		
3600		Y		
3800		Y		
4200		Y		Mainly just on Mendip aggregate flows
4400		Y		
4800		Y		
5000		Y		

The commonly used permutations of wagon loadings with non-200-tonne increments of trailing loads for SRT calculations are shown in the Table 3 below. The main ongoing use is for container SRTs with some residual HAW calculations, for example, the Class 56 SRTs. The Class 56 calculations were the last comprehensive set done by British Rail with fully understood inputs, so they are an important reference data set and are therefore still maintained by NR.

Table 4 Wagon assumptions for non-200-tonne increment trailing loads used in SRT calculations (current container and older BR era HAW calculations)

Trailing load (tonnes)	Empty wagon	Heavy axle weight (“H”/”HAW”) Wagons	Container (“C”/”CON”) Wagons	Notes
715		Y	Y	
975		Y	Y	
1070		Limited	Y	
1235		Limited	Y	
1250		Limited	Y	Often electrically hauled
1475		Limited	Y	
1495		Limited	Y	
1760		Y	Limited	
2020		Y		
2280		Y		
2540		Y		
3065		Y		
3325		Y		

3.9 Current container wagon resistance equation inputs

3.9.1 Axle weight considerations

Most container train SRTs have historically (from the BR era) been calculated assuming a consist with ~75% of the wagons loaded and ~25% empty, and using the same aerodynamic resistance for both loaded and empty wagons. However, the SRTs for a trailing load of 1475 tonnes appear to be the exception, along with two trailing loads historically just used for calculating electrically hauled SRTs (1,070 and 1,250 tonnes), where 100% loaded container wagons are used.

The axle load values (Q) used are:

- Q (loaded) = 14.73 tonnes (14.5 Tons): This is the 99.9% percentile value of current observed average train axle loads.
- Two electrical hauled TLLs (1,070 and 1,250 tonnes): SRTs use a slightly higher Q (loaded) value of 14.83 tonnes (with 100% loaded wagons).
- Q (empty) = 4.9 tonnes: This is the tare Q value of a 1960s FEA container wagon. Modern 60’ container wagons are slightly heavier.

3.9.2 Historical precedent for current modelling practice

An average axle load of 14.73 tonnes equates to a total wagon mass of 58.92 tonnes. This aligns with the sum of maximum historic (pre-1984 road vehicle Construction and Use rule changes) values for a road vehicle carrying a 20’ container and a 40’ container.

This is lower than the maximum mass of containers that could be loaded on the wagon, which is effectively limited to keeping the wagon under RA7 limits. Hence, while it does not recognise the maximum permissible container loads for an individual wagon, it reflects the likely worst case for the train as a whole from an era when a reasonable proportion of container traffic was domestic (current container traffic is predominantly maritime). Typical loadings of average modern containers conveyed by rail are significantly lower, and this presents a challenge in that, if the historic 14.73-tonne axle load assumption is retained, that would result in trains being modelled with fewer wagons than are used in practice. This would result in:

- lower total train resistance for the chosen TLL and hence sometimes faster and unrealistic SRTs
- shorter modelled trains clearing speed restrictions in less time than is required for real trains, again sometimes resulting in faster and unrealistic SRTs.

Historic TLLs, and the associated input assumptions used for SRT calculation, are shown in Table 5 below.

Table 5 Typical existing container train consist assumptions for older TLLs commonly used for SRT calculation

Intermodal container TLL	Loaded wagon axle load (t)	Total wagons	# Loaded wagons	# Empty wagons	Total wagon length (m)	Notes
715 tonnes	14.73	14	11	3	286	
975 tonnes	14.73	20	15	5	408	
1,070 tonnes	**14.83**	**18**	**18**	**0**	**368**	**Electric haulage—slightly higher Q assumption**
1,235 tonnes	14.73	25	19	6	510	
1,250 tonnes	**14.83**	**21**	**21**	**0**	**429**	**Electric haulage—slightly higher Q assumption**
1,475 tonnes	14.73	25	25	0	510	
1,495 tonnes	14.73	30	23	7	612	
1,760 tonnes	14.73	36	27	9	735	

During the 1990s, SRTs began to use TLLs in 200-tonne increments, which led to two additional commonly used TLLs for container SRTs of 1,600 and 1,800 tonnes. This aligns with an increase in axle load from 14.73 to 15 tonnes and still slightly underestimates the number of wagons, and hence train length, leading to the same inaccuracies discussed above due to lower overall wagon resistances and train lengths. For example, many trains running with 1,600-tonne SRTs have 33—36 (and occasionally 37) wagons, rather than the assumed 32 wagons, and the loaded wagons with lower average axle loads than currently assumed.

Table 6 Typical existing container train consist assumptions for newer TLLs commonly used for 200-tonne increment SRT calculation

Intermodal container TLL	Loaded wagon axle load (t)	Total wagons	# Loaded wagons	# Empty wagons	Total wagon length (m)	Notes
1,600 tonnes	15	32	24	8	653	Most commonly used container TLL
1,800 tonnes	15	36	27	9	735	

3.9.3 Recommendations

The existing assumption of ~75% loaded container wagons and ~25% empty container wagons works significantly better than assuming all wagons are fully loaded and should be retained and extended to all container TLL calculations that currently have a 100% loaded wagon assumption.

Generally (with just the exception of the 1,800-tonne TLL), the assumed number of wagons in the train for a given TLL is lower than the number of wagons that often run on services that use the SRTs calculated for those TLLs. This results in lower calculated total train resistance for the chosen TLL and hence faster and sometimes unrealistic SRTs. Also, as the overall modelled train lengths are shorter than real ones, the modelled trains clear speed restrictions in less time than real trains, again resulting in faster and sometimes unrealistic SRTs.

Given the linkage between average axle load (Q) and the number of wagons for a given TLL, it is recommended that lower average axle load assumptions are used to replicate current actual loadings. This will increase the number of wagons for a given TLL, increasing the train resistance and length, making the SRT calculations both more representative of real world, and producing more accurate timing calculations.

3.10 Braking

NR assumes a braking level that is half that of full service or the minimum emergency braking force of 9% *g*, i.e., 4.5% *g*. (Emergency brake force can be up to ~11% *g* for typical wagons.) This is intermediate between the options available to drivers, i.e., Initial (3% *g*) and Service (6% *g*), and it is lower than observed braking behaviour, which typically involves use of both Initial and Service as well as sometimes releasing the brakes during a complete braking event, which results in an average overall braking rate of around 5.0–5.5% *g*. The current NR timetabling assumption for passenger braking is that service braking is half the minimum passenger emergency braking force of 12%, i.e., 6% *g,* and the freight assumption aligns with that 50% approach.

It is likely with the forthcoming widespread introduction of ETCS for freight that more detailed work will be taken on freight braking for timetabling and SRT calculation purposes, hence retaining the current assumption of 4.5% *g* for freight train braking is appropriate in the interim, as it provides a 10–20% conservative assumption on braking, which likely aligns well with more cautious braking in autumn. It is worth noting that 0.45ms^{-2} is approximately equivalent to 1mph s^{-1}, which is the Vision assumption for Class 4 with other freight in vision assuming 0.5mph s^{-1}.

3.11 Use of SRTs in practice

Additional rules are needed to apply SRTs in practice to produce a workable timetable, known as timetable planning rules (TPRs). These include headways (how close a train may be allowed to run behind the train in front) and allowances for the time taken for trains to clear junctions. Manual adjustments may be made to create allowances for longer trains, though these may not fully account for longer trains, for example, assuming 600 m rather than 775 m for container trains.

In general, the historic practice has been to make calculations once and then to use allowances for particular situations to get the most use out of the calculated timings. This stems from historic limitations on computing capabilities. However, situations where trains may be entering a section at different speeds depending on the origin (for example, coming from Southcote Junction or Reading through the Reading West Junction towards Tilehurst) may not be fully captured, and more accurate, direction-specific calculations may be more useful.

Sometimes, adjustments to SRTs are introduced through the Service Plan Review process or adjustments to the TPR rules. In the future, the values introduced using the more robust T1302/1 data will reduce the number of SPRs undertaken, as trains will be running at the maximum weight. However, changes may still be required, and a process for recording change and the reason for should be developed.

4 Refinements to inputs for SRT calculations

The previous T1302 project proposed a new methodology for determining TLLs as well as SRTs, with new formulae and factors set out in Section 5 of the T1302 report. T1301 provided an opportunity to test this methodology with the large body of data made available through the stakeholder engagement and initial analysis undertaken for the case studies. This section of the report presents the outcome of that analysis, identifying where changes to the methodology described in T1302 are required. The required updates are then implemented in the following Section 5, which follows the format of Section 5 of the T1302 report, with the required T1301 revisions.

In Section 3.1.1, we identified four forces resisting the train: gravity, acceleration, curving, and internal resistances. The first three are currently handled well in the approach used by NR, and so this section only deals with changes to internal locomotive and wagon resistances, and an update on locomotive tractive effort/adhesion.

4.1 Locomotive tractive effort and adhesion

Key emerging learnings identified in this project and T1302 include:

- The existing conservative 95% TE assumption is not needed for newer locomotive types.
    - OEMs are already including a conservative assumption on TE in the data sets that they supply.
- TE impacts of new wheel sets are a conservative assumption and should be retained.
- The quality of locomotive TE data sets can be improved, as better data that is now available will improve the quality and accuracy of SRT calculations.
    - TE curve data is now at 1 mph increments in the T1302 report and its associated spreadsheet and with additional TE data sets added as part of the T1301 project.
- Double-heading is not treated consistently or reflects current working practices.
    - Double-heading of electrically hauled services is not accurately reflected in current SRTs, and the complexities of power limits of double-headed services are not understood by all users.
    - These services can haul heavier loads to better timings than are reflected in the current SRTs.
    - Often, there is inconsistency in the input assumptions between NR geographic areas and between calculations undertaken at different times.
    - These issues also align with the impact of not currently accurately taking account of the second locomotive's lower aerodynamic resistance, which accentuates the impacts (see Section 4.2.6).
    - The combined impact of these issues varies by individual route section. There is often minimal impact on downhill sections but significant improvement on moderate or steep uphill sections or when accelerating after clearing a speed restriction.

4.2 Locomotive resistance

This section of the report develops the T1302 analysis around locomotive resistances. Reference is made to the calculation methodology, specific issues with Class 66 locomotives, and some broader technical issues. The conclusion to these issues is given in Section 5, so that section can be taken as a standalone best practice guide.

4.2.1 Calculation methods

Section 3.7 of this report demonstrates that five different approaches have historically been used to calculate locomotive resistance. In Section 5 of this report, we define a simplified common approach that includes starting resistance and correctly handles the A, B, and C components of the Davis equation. It also documents the various input values for future transparency.

Apart from Class 66 locomotives (see below), issues with locomotive resistances data quality and approach do not have a significant impact on overall SRT calculation accuracy. However, it is still worth improving data quality and having a consistent approach to locomotive resistance calculation to enable the correct calculation of SRTs in the future.

The case studies described in Section 6 provide an opportunity to calibrate these resistance coefficients with real data, i.e., ‘reverse engineering’ the A, B, and C coefficients.

4.2.2 Specific Class 66 rolling resistance issues

The overall resistance vs. speed curves for the Class 66 are shown in Figure 15 which compares the current RailSys and T1302 values, and from this it was concluded in T1302 that the current RailSys Class 66 resistance values are too low. The Class 66 has comparatively low resistance coefficients across the speed range with low A, B, and C values. These are substantially lower than Class 59 (both overall and the A and C values). The lower C values would suggest Class 66 aerodynamics are better than that for Classes 68 and 88 and similar to that for the Class 91 and HST power car, which appears intuitively incorrect.

The impact is equivalent to the resistance of up to two container wagons at higher speeds. The green curve in Figure 15 shows the difference between the orange T1302 modelled figures and the historic stepped function figures, expressed as the comparative number of container wagons (using the appropriate wagon resistances). Above 40 mph, this equates to around two wagons.

A second issue leading to low resistance values is that the impact of using the historic step function approach creates big inconsistencies and impacts the Class 66 more than other locomotive types.

Figure 15 Comparison of Class 66 resistance calculations

The conclusion of this analysis is that more accurate rolling resistances are required for the Class 66 in particular, and we define these in Section 5 of this report.

4.2.3 Locomotive starting resistances

Historically, MT19 originally used 20 lb/Ton, which was probably later amended to 15lb/Ton but with minimal documentation. NR have been using 15 lb/Ton for starting resistance, and it is recommended that this value be used, so the value of 87.5230 N/tonne used in the T1302 report is reduced to 65.6423 N/tonne.

This is a default value that should be used in the absence of any other information. Some current locomotive manufacturers are claiming lower starting resistance values in the range 35 to 50 N/tonne for their new locomotive designs, so there is the potential to use such lower values from locomotive OEMs. However, the incremental difference between the revised 65 N/tonne value above and other lower OEM values has a minimal potential impact on the overall performance of the freight train when starting or at very low speed (the further reduction in resistance is equivalent to the resistance of a small fraction of a single wagon).

4.2.4 Stadler locomotives

When reviewing current calculation methods, it was found that different resistance values have been supplied by Stadler and its predecessor (Vossloh) over time. There have also been changes in format of the resistance methodology over time and uncertainty in how to apply the Stadler values. This is because there is limited documentation available. Stadler appears to use a different method to NR, but no significant impact was found on the overall calculation results.

In conclusion, the currently stated Stadler resistance values are similar to other locomotive types but have slightly lower A and B values, reflecting more modern track-friendly bogies and suspension. This assumption does not make a material difference.

4.2.5 Implications of differences in characterising locomotive resistance for real-world performance

The limitations in current locomotive resistance calculations have some implications for real-world performance that will be considered in the case studies in Section 6.

The lack of starting resistance for Class 66s (and other newer locomotives) in existing NR calculations suggests that restarting on a gradient is easier than it should be in practice, reflecting known real-world operational issues, for example, on the West London Line, and T1302 findings. In addition, the existing NR locomotive resistance while moving is also too low, which suggests failure on the gradient is slightly less likely than it should be. This also reflects known real-world issues and T1302 findings.

These implications are investigated in Case Study 5: West London Line (see Section 6.6).

4.2.6 Recommendations for locomotive resistances

The T1302 methodology retained the early MT19 approach of locomotive starting resistance of 20 lb/Ton. The review undertaken for this project found evidence suggesting that this value was subsequently reduced to 15 lb/Ton (though not conclusively documented). NR RailSys calculations currently use 15 lb/Ton (where starting resistance is applied). It is therefore recommended that starting resistance is applied for all locomotives, using a value of 15 lb/Ton (65.6423 N/tonne).

It was found that the T1302 formula and coefficient values often produce similar resistance values to most of the NR RailSys values. Many locomotive resistance values appear to be based upon the MT19 formula, so similar values are not surprising. It is therefore recommended to use the T1302 equation as the default approach, using documented OEM or testing data where available (as recommended in T1302). However, a mechanism is needed not to use unrealistically low data supplied by OEMs.

From the above analysis, three areas of meaningful potential improvements to calculations can be identified:

- Implement lower resistance for second locomotives, primarily due to reduced aerodynamic loading when double-heading.
- Use realistic resistances for Class 66. Current values are very low and do not replicate real-world timings or modelling.
- Modify the calculation approach to apply starting resistance in all cases (mostly not used with newer locomotive types).

4.3 Factors for four-axle wagons

In this section we discuss the calibration of coefficient values for 4-axle wagons. This is based on the equations in Section 5 of the T1302 report for starting and rolling resistances and are shown below for context. We refer to seven of the coefficients or input values within these equations which have been assessed as part of this work. Many have not been changed while there are some minor changes to others and additions of values for wagon types that were not covered in the T1302 report.

4.3.1 4-axle wagon resistance equations

4.3.1.1 Total wagon starting resistance:

$$R_{WTS} = R_G + R_A + R_{WMS} + R_{WCS}$$

where:

R_G = gradient resistance from Section 5.1.1 of the T1302 report

R_A = acceleration resistance from Section 5.1.2 of the T1302 report = 25 N/tonne (as acceleration = 2.5 m/s^2)

4.3.1.2 Mechanical component ($\boldsymbol{R_{WMS}}$)

From Section 4.4.4 of the T1302 report:

$$R_{WMS} = 1.4 \times R_{WMR} \; [{}^{N}/_{tonne}]$$

where:

R_{WMR} = Wagon mechanical resistance from Section 5.4.2 of the T1302 report

which at 0 mph simplifies to:

$$R_{WMS} = 1.4 \times \left(4.0 + \frac{100}{Q}\right) \; [{}^{N}/_{tonne}$$

where:

Q = axle load (tonnes)

4.3.1.3 Curving component ($\boldsymbol{R_{WCS}}$)

From Section 4.4.5.3 of the T1302 report of the T1302 report:

at and above R = 201 m:

$$R_{WCS} = \frac{K_{WCS1}}{R} \; [{}^{N}/_{tonne}]$$

below R = 201 m:

$$R_{WCS} = \frac{1.833 \times K_{WCS1}}{R} \; [{}^{N}/_{tonne}]$$

where:

$K_{WCS1} \; = \; 7{,}390$

R = curve radius (m)

4.3.2 Wagon rolling resistance for four-axles

Rolling resistance for four-axle wagons is determined as follows.

4.3.2.1 Total wagon rolling resistance

Total wagon rolling resistance is:

$$R_{WTR} = R_{WGR} + R_{WAR} + R_{WMR1} + R_{WMR2} + R_{WMR3} + R_{WMR4} + R_{WCR}$$

where:

R_G = gradient resistance from Section 5.1.1 of the T1302 report

R_A = acceleration resistance from Section 5.1.2 of the T1302 report = 0 N/tonne (as acceleration = 0 m/s^2)

4.3.2.2 Mechanical component ($\boldsymbol{R_{WMR}}$)

From Section 4.4.2.4 of the T1302 report:

$$R_{WMR} = R_{WMR1} + R_{WMR2} + R_{WMR3} + R_{WMR4}$$

where:

$$R_{WMR1} = K_{WMR1}\ [^{N}/_{tonne}]$$

$$R_{WMR2} = \frac{K_{WMR2}}{Q}\ [^{N}/_{tonne}]$$

$$R_{WMR3} = K_{WMR3} \times V\ [^{N}/_{tonne}]$$

$$R_{WMR4} = \frac{K_{WMR4} \times K_{WMR5} \times A_w \times V^2}{K_{WMR6} \times M_w}\ [^{N}/_{tonne}]$$

where:

K_{WMR1} = 4.0

K_{WMR2} = 100

K_{WMR3} = 'B' coefficient as defined in Table 19

K_{WMR4} = aerodynamic resistance in tunnels factor, 1 if no tunnel, (N/m^2/mph^2)

K_{WMR5} = 'C' coefficient as defined in Table 20

K_{WMR6} = 1024.081

A_W = wagon frontal area as defined in Table 20 (m^2)

M_w= gross wagon mass (tonnes)

Q = axle load (tonnes)

V = speed (mph)

Using the above, and assuming no tunnels (that is, K_{WMR4} = 1), R_{WMR} simplifies to:

$$R_{WMR} = 4.0 + \frac{100}{Q} + K_{WMR3} \times V + \frac{K_{WMR5} \times A_w \times V^2}{1024.081 \times M_w} \left[{}^{N}/_{tonne}\right]$$

4.3.3 Wagon resistance calibration methodology

4.3.3.1 Options for calibration

There are four potential main methods to calibrate wagon rolling resistance:

1. Measure the deceleration curve of a train using OTMR data as it decelerates while coasting, i.e., with no power or brakes applied. However, in normal running on the GB network, freight trains do not coast for long enough on sections with approximately constant gradient to collect sufficient data across the required wide range of running speeds.
2. Measure the balancing speed of a train and initial acceleration curves using OTMR data for situations where full power is applied on long sections of track with approximately constant gradient. Ideally this would be for trains accelerating from stationary and running at the maximum attainable speed under those conditions (the balancing speeds). Collecting data from trains with differing number of wagons (and container loadings for intermodal wagons) provides the permutations needed for multivariate analysis.
3. Measure locomotive coupling forces with stain gauges and use aligned OTMR data to determine the resistance of an individual train and the TE of its locomotive.
4. Measure the time taken to travel between two timing points with full power applied on long sections of track with approximately constant gradient. Ideally this would be for a mix of trains accelerating from stationary or running at the maximum attainable speed under those conditions (the balancing speed) or both.

For this calibration work, we have used method 4, as sufficient data is available from the analysis of actual train performance to enable accurate calibration. Large amounts of timing and loading data are available for trains with different loading permutations, which is necessary for the multivariate analysis being undertaken.

For similarly loaded heavy axle load wagons, the loading permutations solely derive from the number of wagons in the consist and whether the service has loaded or empty wagons. Intermodal calibration is more complex due to greater variation in the permutation of number of wagons, their length, whether the containers are 8’6’’ or 9’6’’, the fill on the wagons, and the individual container loadings.

The analysis undertaken for the calibration used large data sets generally based on timing and loading data for a year, with many trains in different permutations over a specific section of the route. The ideal situation is a long uphill stretch of route where there are almost constant gradients and where the driver will be using maximum available power and TE. The data was filtered for clear runs (i.e., no signalling delays) and for drivers pushing to maintain schedules (if a train is running early, a driver will need to ease off from full power). The trains that were considered had loadings that match the timing loads wherever possible and were more lightly loaded trains (both in terms of fewer wagons [for all cargo types] and for intermodal variation in container mass and number of containers).

Most intermodal trains run at loads below those modelled for trailing loads and hence often run faster than the SRTs times. These services can be useful for wagon resistance and other calibration work, but for direct comparison with existing SRTs for defined TLLs, this requires the trailing load to approximately match the defined TLL, for which we set a threshold of +/- 20 tonnes, as well as other filtering criteria.

Overall, SRTs need to be suitably conservative and be set for worse-than-average timing outcomes rather than average timing outcomes, and the quantities of timing data assessed as part of these calibrations allowed an understanding of the distribution of real train timings for known loadings.

Curvature resistance is inversely proportional to line speed and is often a very small component of the overall train resistance at higher speeds, especially uphill, hence the calibrated wagon resistance values include a small element of curvature resistance where they have been calibrated on the very straight section used. As such, the wagon resistances derived can be used at medium and higher speeds without needing to include curvature resistance in the overall calculations.

4.3.3.2 Wagon types calibrated

Wagon resistance coefficients and other equation inputs for the T1302 four-axle wagon resistance equation were assessed and calibrated on six sections of route (five case study sections in the main project and one follow-on case study in Wales) for the wagon types shown in Table 7 below.

Table 7 Wagon resistance equation coefficient calibration locations

Case study area	Direction	Wagon types
Eastleigh–Basingstoke	Northbound	Intermodal
Shap	Northbound	Intermodal
Beattock	Northbound	Intermodal
Flitwick–Leagrave (both with and without looping at Sundon)	Southbound	Aggregate box (loaded) Aggregate hopper (loaded) Cement tanks (loaded) Petroleum tanks (empty)
Kettering–Market Harborough (up Desborough Bank)	Northbound	Aggregate box (empty) Aggregate hopper (empty) Cement tanks (empty) Petroleum tanks (loaded)
Margam–Stormy	Eastbound	Petroleum tanks (loaded) Covered Steel wagons (loaded)

Relevant operational learnings from the case studies in the main project are discussed in detail in Section 6. However, the understanding of the wagon resistance equations derived from the case studies is discussed in this section.

We appreciate this is a not a comprehensive list of wagon types, but the project has been limited by the wagon types that could be successfully analysed within the chosen case study areas.

4.3.3.3 Calibration process

The factors assessed for this work were:

- type of wagon for which the calibration assessment is being done
- number of wagons
- wagon mass (payload) M_w and hence axle load Q
- A coefficients K_{WMR1} and K_{WMR2}: applies to all four-axle wagon types, no relationship with velocity
- B coefficient K_{WMR3}: specific to wagon type but not loading, linear relationship with velocity
- C coefficient K_{WMR5}: specific to wagon type and loading, squared relationship with velocity
- wagon frontal area A_w: specific to wagon type and loading.

Many of these values and coefficients are not independent of each other, and there are many feedback loops between them. Hence the coefficients have to be assessed in different ways with different methodologies (sometimes single methods, sometime multiple methods per coefficient), in a specific order, and iteratively.

The assessment and calibration of wagon resistance coefficients and other equation inputs is a five-step process:

1. Ensure there is high certainty in locomotive TE data and adhesion assumptions (see Section 4.1), and in locomotive resistance (see Section 4.2). This is an essential prerequisite.
2. Define the parameters that remain fixed and will not iterate during later calibration and which are generally invariant, for example:
   - type of wagon for which the calibration assessment is being done
     - For intermodal wagons, each train should include a mix of loaded and empty wagons, and there should be significant variation between loaded wagons.
   - number of wagons
   - wagon mass M_w and hence axle load Q
   - wagon frontal area A_w for each wagon type (and loading configuration for container wagons).
3. Assess the coefficients that are dependent on wagon mass/axle load but independent of velocity. These are the A coefficients, K_{WMR1} and K_{WMR2}.
   - These coefficients apply universally to all four-axle wagon types, so this calibration occurs across all wagon types.
   - Step 3 requires calibration across all wagon types and loadings, but once this is completed and values settled upon, further iteration is only needed through steps 3 and 4.
4. Assess the coefficient that is dependent on velocity but independent of wagon mass/axle load. This is the B coefficient K_{WMR3} , which is specific to wagon types but is invariant to loading.
   - Generally, longer wagons have higher values of K_{WMR3} .

- Once values in steps 2 and 3 are settled, steps 4 and 5 occur iteratively for each wagon type and loading case.

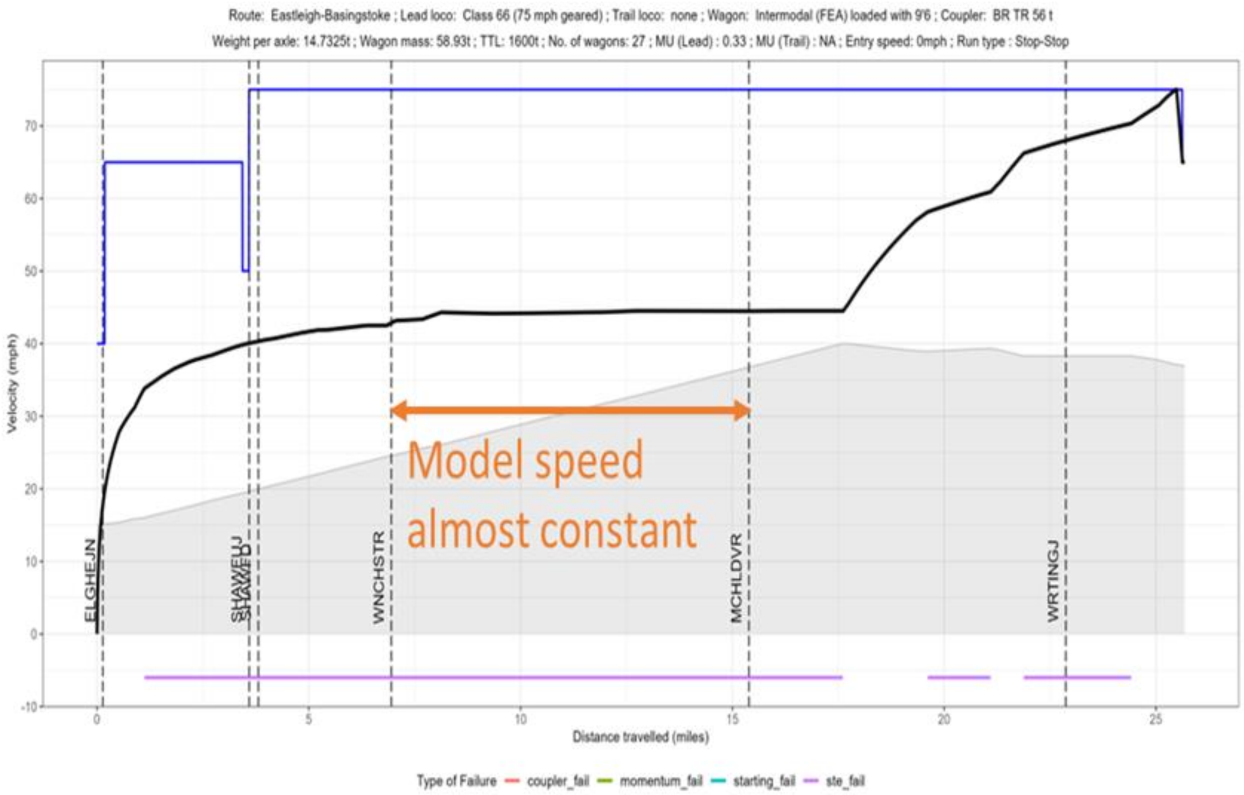
5. Assess the coefficient that is dependent on the square of the velocity but independent of wagon mass/axle load. This is the C coefficient K_{WMR5} , which is specific to wagon type and often loading (for container and open wagon types) but is invariant to wagon mass/axle load.

- Longer wagon typically have higher values of K_{WMR5}.
- For closed type wagons or loads, the C coefficient K_{WMR5} value is invariant with respect to the loading status of the wagon:
  - For example, for tank wagons, the C coefficient (K_{WMR5}) value is always constant for each of type of tank wagon (cement or petroleum) irrespective of whether they are empty or fully loaded, as the aerodynamics are effectively identical. Similarly for container wagons, the key determinant of C coefficient (K_{WMR5}) values is the loading arrangement of the containers rather than the mass of containers and their contents.
- For open type wagons, the C coefficient (K_{WMR5}) value depends on the loading status of the wagon:
  - For example, for aggregate box and hopper wagons, the C Coefficient K_{WMR5} value varies depending on whether the wagons are full or empty.
  - When the aggregate box and hopper wagons are empty, the wagon aerodynamics are much worse due to both higher wagon non-frontal surface area and effectively higher frontal surface area due to the internal side of the rear end of the vehicle being exposed (for both box and hopper wagons). This is similarly the case for exposed internal bulkheads in hopper wagons as well. These factors effectively result in the equivalent of significantly more wagon frontal area.
  - The wagon frontal area A_w for each wagon type is taken from wagon drawings and used in step 1, but the resistance due to the load status of these wagon types is best adjusted through higher C coefficient K_{WMR5} values, as the increase in effective frontal area needs to be determined based on analysis of running data correlated to the increase in surface area.
  - There are also other factors that change, hence the simplest approach is to use higher C coefficient K_{WMR5} values.

4.3.3.4 Example of the calibration process

Figure 16 below shows the model speed profile for a container train starting from stationary at Eastleigh and travelling uphill towards Basingstoke. The train achieves an equilibrium balancing speed between Winchester and Micheldever on the long, constant uphill gradient. We compared the modelled balancing speeds for numerous permutations of consists and equation inputs and coefficients with the average speeds of real services with clear runs with matching loading permutations to those modelled through this section. This allows us to calibrate many of the coefficient values because the range in train consists included different numbers of wagons and axle loadings. In the section illustrated below, the calculated balancing speeds varied by a range of 17 mph depending on the input parameters specified.

Figure 16 Output of calculation of train speed (for a single set of input conditions) for use in wagon resistance calibration



4.3.4 Calibration of wagon resistance equation coefficients

4.3.4.1 Coefficients applicable to all wagons

Step 3 of the methodology discussed above involved calibrating the K_{WMR1} and K_{WMR2} values for associated Q values. This exercise showed that existing recommended values of K_{WMR1} = 4.0 and K_{WMR2} = 100 from T1302 are sufficiently (albeit not perfectly) close to that in found in practice. We therefore recommend retaining the previous values for all wagon types.

4.3.4.2 Coefficients applicable to container wagons

As part of the container wagon calibration, we assessed the current NR RailSys calculation methodology and results, along with calibrating the coefficients and input values used in the T1302 report. The current RailSys approach results in wagon resistances for containers services that are:

- too low at low speeds (faster acceleration at low speeds assumed than is actually possible)
- too high at higher speeds (balancing speeds calculated with existing methodology are often too low, so real trains can run faster than assumed).

In most cases, our modelling can replicate NR SRT calculations for container trains with the assumptions listed in Section 3.3 (apart from where SPR adjustments and manually adjusted rounding have taken place) using NR's input values.

For both the NR RailSys and T1302 approaches, the biggest issue for modelling container services is picking realistic wagon assumptions for the consist (see step 2 above) around the number of loaded and unloaded wagons, with a reasonably high axle load. Ideally the total trailing weight would be matched to the trailing weight for the existing SRT.

Real services tend to have more wagons, a mixture of wagon types (for example, 40', 45', and 60' platforms and different platform heights) and much lower average axle loads than current calculations assume, thereby giving very different train resistances. It is necessary to retain a balance between high axle loads and a high number of wagons.

It is recommended to retain the existing assumption that 75% of wagons are loaded and 25% empty, with T1302 equations, but with slightly lower axle loads than currently used (i.e., 13.17 tonnes instead of 14.73 tonnes). These assumptions calibrated well with real services across a range of loadings when used with lower axle loads and also consequently more wagons overall for a chosen TLL due to the deduction in average loaded wagon axle load.

From this analysis, the typical assumption for a consist of 36 wagons (trailing weight of 1,600 tonnes) is:

- 27 loaded wagons (9'6" assumption), Q=13.17 tonnes (down from 14.73 tonnes)
- 9 empty wagons (Q=4.9 tonnes)

This is based on the assumption that:

$$Trailing\ load = \sum \left(\#\ wagons_{type\ A} \times \#axles_{wagon\ type\ A} \times Q_{wagon\ type\ A}\right) + \left(\#\ wagons_{type\ B} \times \#axles_{wagon\ type\ B} \times Q_{wagon\ type\ B}\right)$$

When modelled this gives slightly slower times than mean or median timings for real services with actual loadings of ~1,600 tonnes, approximately matching 85th to 90th percentile times for services with clear running in those sections. The number of wagons (total, loaded, and empty) matches the existing NR 1,800-tonne assumption but with lower axle load for loaded wagons. Thus, this should represent a suitably but not too conservative approach for container SRT calculations. Most intermodal services run with much lower loads than the trailing load used to calculate the SRTs, so over 99% of intermodal services should be able to meet the times calculated in this way.

The 75% loaded/25% unloaded assumption should be scaled as appropriate to match other required trailing loads for modelling, and Table 8 below shows how these should be calculated. (Existing NR calculation assumptions can be found in Table 5 and Table 6.) For 1,800-tonne intermodal trains, the assumed axle load as to be increased from the default 13.17 tonnes to 14.49 tonnes to keep the overall train length within the 775 m limit.

Table 8 Wagon loading and length values for intermodal container trains for use in calculations for commonly used SRT TLLs

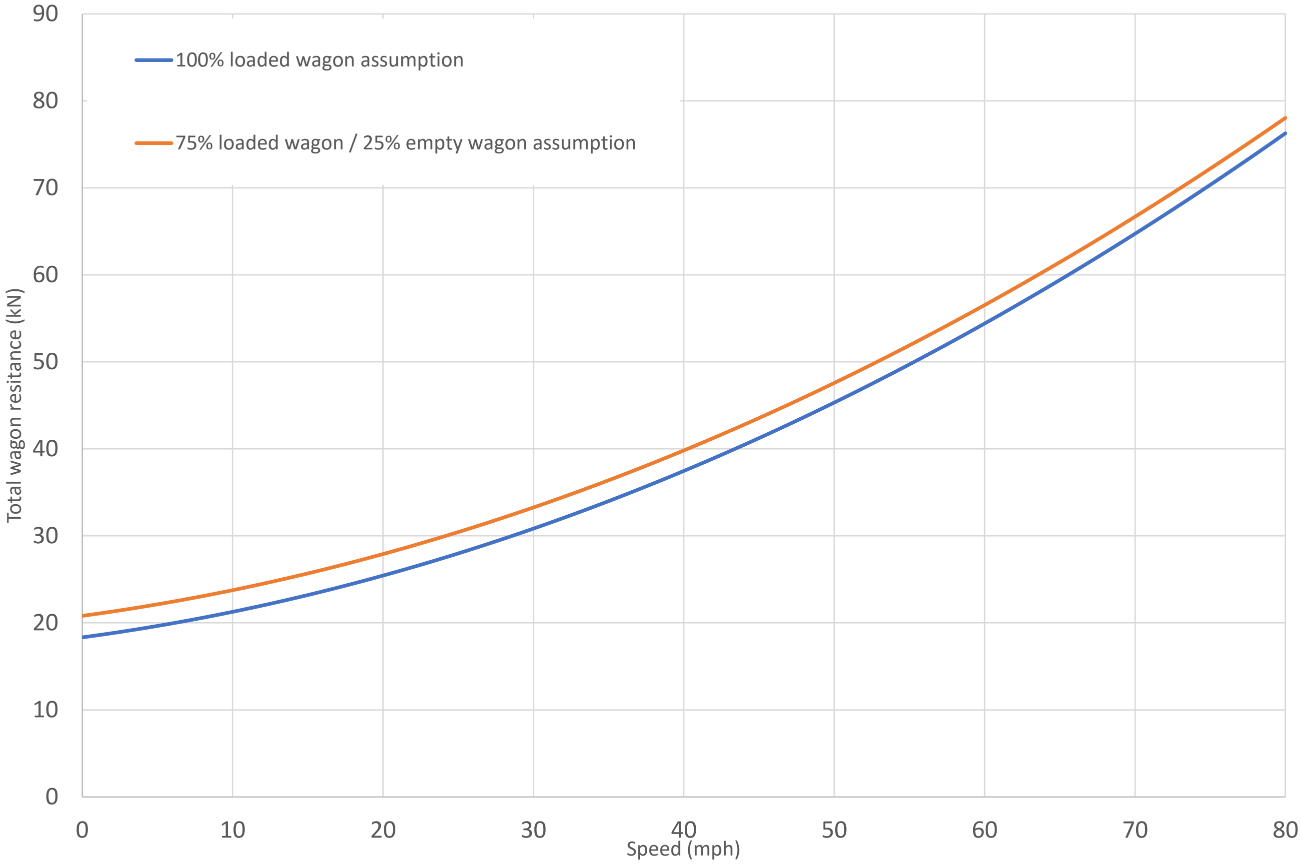
Intermodal container TLL	Total wagons	# Loaded wagons	# Empty wagons	Actual trailing weight (t)	Total wagon length (m)
800 tonnes	**19**	**13**	**6**	**803**	**382**
1,000 tonnes	**23**	**17**	**6**	**1014**	**463**
1,200 tonnes	**27**	**20**	**7**	**1192**	**543**
1,235 tonnes	**29**	**20**	**9**	**1231**	**583**
1,250 tonnes	**28**	**21**	**7**	**1244**	**563**
1,475 tonnes	**33**	**25**	**8**	**1475**	**664**
1,600 tonnes	**36**	**27**	**9**	**1600**	**724**
1,800 tonnes	**37**	**28***	**9**	**1800**	**744**

* With higher axle load (Q) of 14.49 tonnes used here due to overall train length limitations.

From the calibration work undertaken with case study data (see Section 6), it was found that real world 60' container wagon resistances with known loadings are very similar to what would be expected from the T1302 methodology. For 60' wagons, the T1302 approach and values were used. This is expected to be slightly conservative. Investigation of 40' wagon resistances was constrained by some NR timing data (IT) issues with train describer data from one location not being recorded in TRUST as intended, resulting in smaller data sets for these wagons.

The impact of overall wagon resistance of using 100% loaded or 75% loaded/25% unloaded assumption is shown in Figure 17 below for a 1,600-tonne trailing load resulting an increase of between 4% and 9% over the majority of the speed range using the more realistic 75% loaded/25% unloaded assumption.

Figure 17 Comparison of total train wagon resistance for 100% loaded wagons and 75% loaded/25% unloaded assumptions for a 1,600-tonne trailing load



4.3.4.3 Coefficients applicable to loaded and empty heavy axle load box wagons

The MML case study (see Section 6.4) provided an opportunity to undertake calibration of wagon resistances for different wagon heavy axle load wagon types, both loaded (Q value of 25–25.5 tonnes) and unloaded (Q value of 6.05 tonnes), for a range of number of wagons per train. The four-track section of the MML south of Glendon Junction was found to be most suitable for calibration purposes, given the quality of the timing data and the alignment of timing sections with challenging climbing sections. Services with empty heavy axle-load wagons perform far better in practice than current calculation methodologies suggest. The existing wagon formula has been calibrated for high loadings and does not perform well for low loadings, and formula inputs are problematic because the empty wagons are approximated by a few heavily loaded wagons (instead of many wagons with low loadings).

Empty wagon SRTs are sometimes calculated with container assumptions, so these trains will easily recover from delays, but the timetabling calculations are not accurate, and more accurate calculations for the empty wagons have been developed.

4.3.4.4 Coefficients applicable to loaded aggregate box wagons

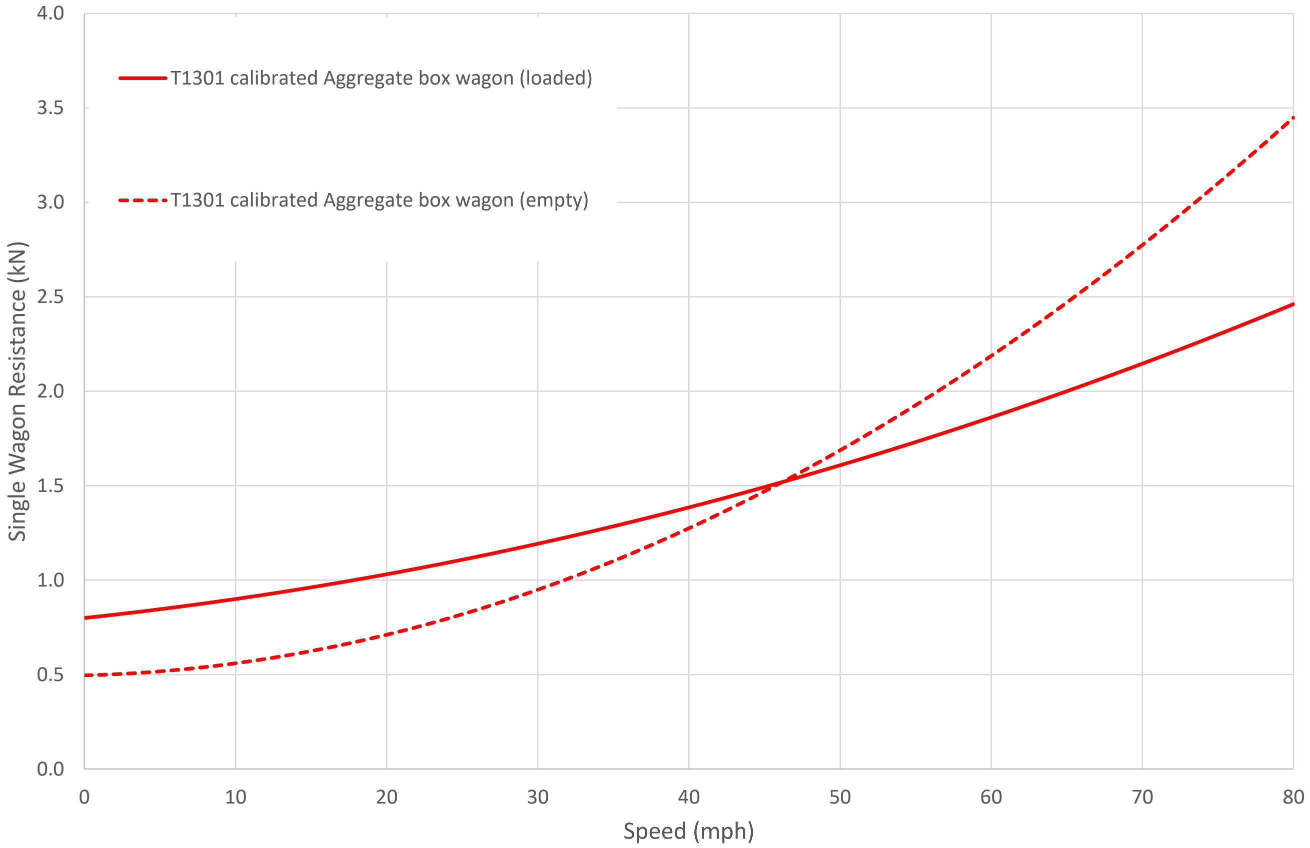
Aggregate trains with loaded wagons (southbound services) are typically looped several times to work with the intensive passenger timetable, hence timing calibration needs to include a variety of through and starting timings depending on the service. Modelled SRTs calculated using the T1302 methodology and coefficients are slightly slower that observed timings (for matching loadings and stopping patterns), so the T1302 total wagon resistance was found to be slightly too high. The timing difference has a linear velocity dependency rather velocity squared or non-velocity dependent, hence indicating a focus on the 'B' coefficient (K_{WMR3}) and the 'C' coefficient (K_{WMR5}) for where the difference might be.

The 'B' coefficient in the Davis equation (defined as K_{WMR3} in the T1302 report) and 'C' coefficient in the Davis equation (defined as K_{WMR5} in the T1302 report) were then iteratively varied to attempt to obtain a better match with real-world wagon resistances. Analysis of the 'B' values for calibration of empty wagon resistances was done in parallel since this parameter should be the same for both loaded and empty aggregate box wagons. The analysis showed that the existing value of the 'C' coefficient (K_{WMR5}) should be retained, while the value of the 'B' coefficient (K_{WMR3}) should be reduced from 0.147 to 0.085. A wider review across multiple wagon types implies a correlation of the 'B' coefficient (K_{WMR3}) with wagon length and/or bogie distance, with longer wagons/bogie spacings resulting in higher values of B coefficient K_{WMR3} .

4.3.4.5 Coefficients applicable to empty aggregate box wagons

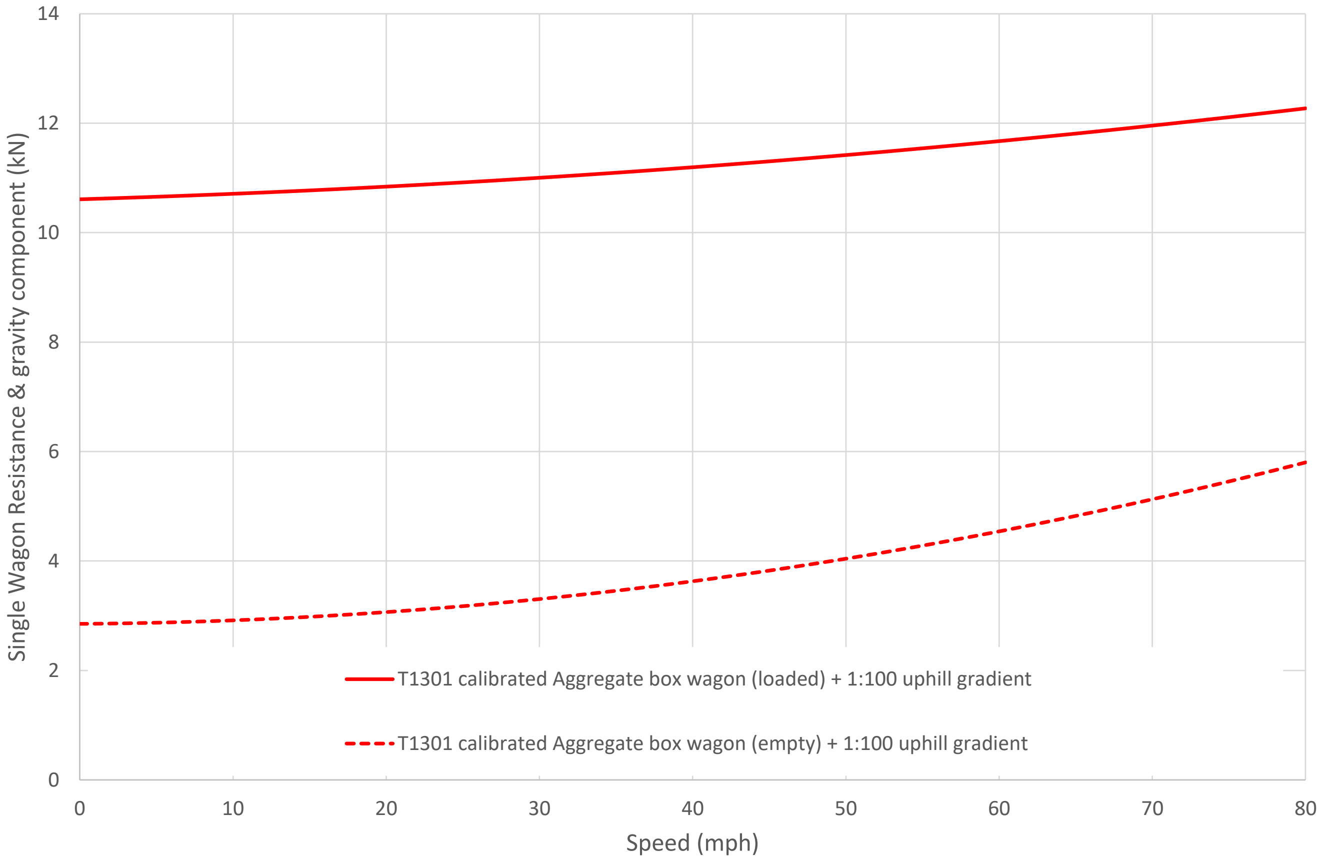
Aggregate trains with empty aggregate box wagons for both 60 mph and 75 mph paths were calibrated northbound between Kettering and Market Harborough (up Desborough Bank). 'B' (K_{WMR3}) coefficient calibration (step 4) was done in conjunction with loaded aggregate box wagons, as the values need to be identical for a wagon type irrespective of loading and while assessing the 'C' coefficient (K_{WMR5}). Similar to the loaded aggregate box wagons, modelled SRTs calculated using the T1302 methodology and coefficients are slower than observed timings (for matching loadings and stopping patterns), so the T1302 total wagon resistance was found to be slightly too high. The timing difference has a linear velocity dependency rather velocity squared or non-velocity dependent, hence indicating a focus on the 'B' coefficient K_{WMR3} and the 'C' coefficient (K_{WMR5}) for where the difference might be. As for loaded aggregate box wagons, the analysis showed that the existing value of the 'C' coefficient (K_{WMR5}) should be retained, while the value of the 'B' coefficient (K_{WMR3}) should be reduced from 0.147 to 0.085. The difference between the wagon resistance for single loaded and empty aggregate box wagons is shown in Figure 18 At lower speeds, the empty wagon resistance is up to 35% lower, but at high speeds, the empty wagon resistance can be up to 40% higher due to the worse aerodynamics of empty wagons. Note that the wagon does not include gravity component, so this comparison is on the level gradient.

Figure 18 Comparison of single wagon resistances for an empty aggregate box wagon and a loaded aggregate box wagon



When the effect of more than a moderate uphill gradient is taken into account, the overall resistance for a loaded wagon is higher than for an empty wagon, but the empty wagon still gets comparatively worse with increasing speed. An example of the impact of gradient is shown in Figure 19 below, where an uphill gradient of 1:100 has been added. At low speeds, the empty wagon has wagon and gravity resistance of 27% of the loaded wagon, but this increases to 47% at higher speeds.

Figure 19 Comparison of single wagon resistances for an empty aggregate box wagon and a loaded aggregate box wagon

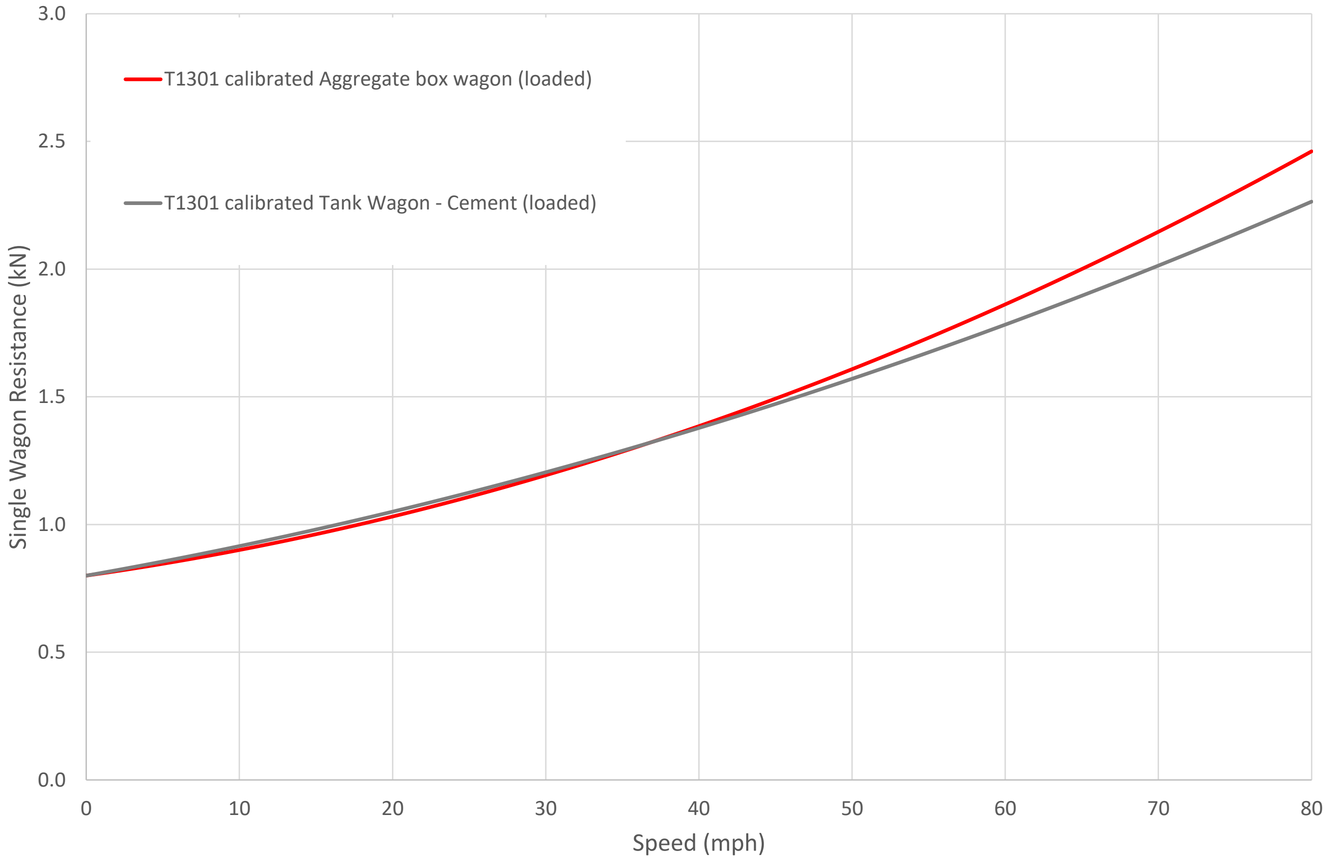


4.3.4.6 Coefficients applicable to loaded and empty cement tank wagons

Theoretically, cement tank wagons should have one of the lowest the lowest loaded gauge profile wagon resistance due to the good aerodynamics of the wagons and the comparatively short length of cement tank wagons (due to their high-density cargo compared with petroleum tank wagons). Loaded cement tanks run 5.7% faster on average than loaded aggregate box wagons (due to the better aerodynamics) with the same value of Q (25–25.5 tonnes). This improvement could theoretically be better than 5.7% due to the greater impact of the 60 mph train speed limit on the cement tank wagons, which run at higher speeds for longer than on aggregate box wagons.

The difference in total wagon resistance between a loaded aggregate box wagon and loaded cement tank wagon is shown in Figure 20 below. While there is very little difference at low speeds, the better aerodynamics of the cement tank wagons lead to lower overall resistance at higher speeds. Hence for most of the speed range, using the loaded aggregate box wagon assumptions is the sensible default, which would enable fewer wagon permutations to be calculated, used, and stored in systems overall. However, if there is significant higher speed cement tank traffic on certain routes, then it might be advantageous to have SRTs calculated for cement tanks, as these would likely allow a couple more wagons per train to run in the path compared with assumptions based on aggregate box wagons.

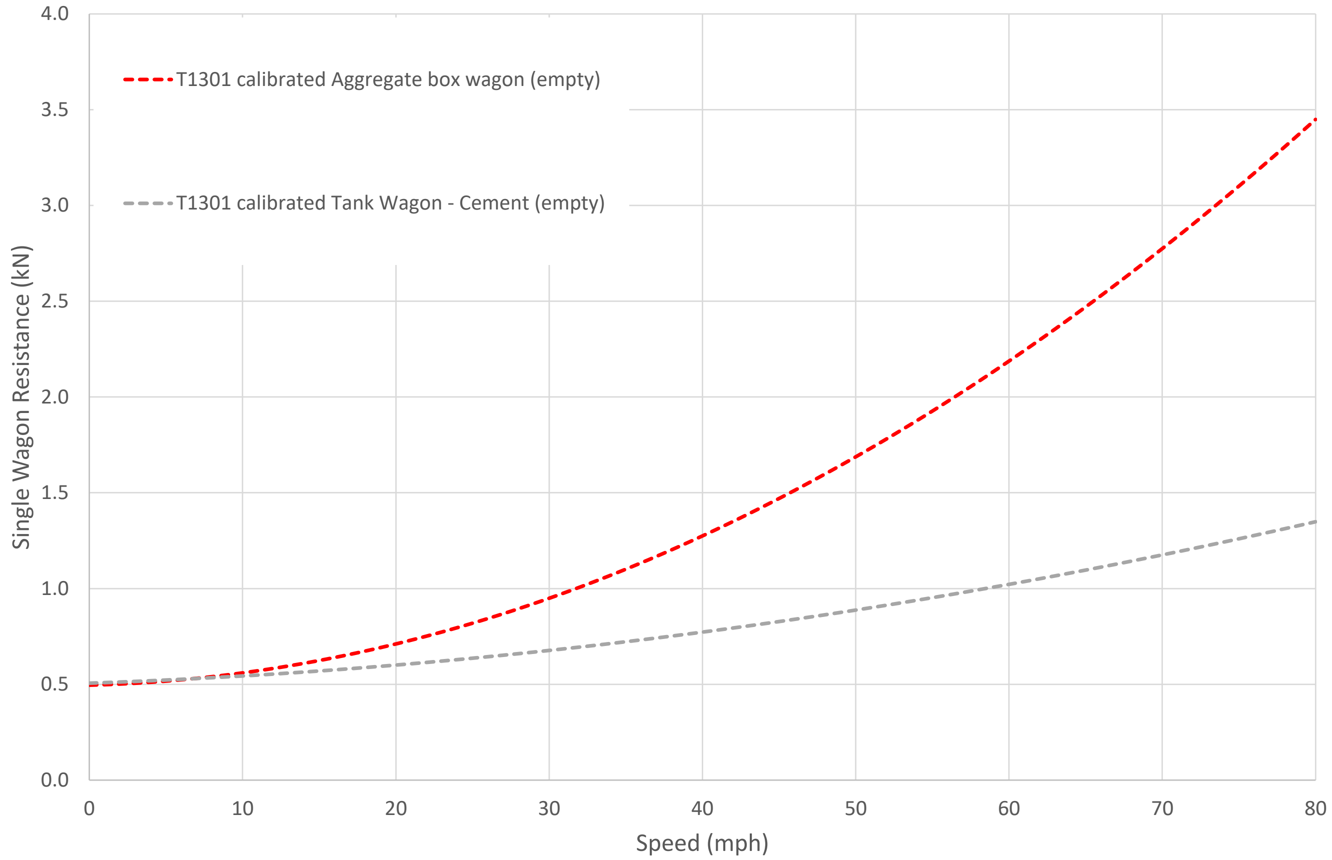
Figure 20 Comparison of single wagon resistances for a loaded cement tank wagon and a loaded aggregate box wagon



There was no recommended value for the 'C' coefficient (K_{WMR5}) for cement tank wagons in the T1302 report (although a value was provided for petroleum tank wagons). Similar to the SRTs for loaded aggregate box wagons calculated using the T1302 methodology, the cement tank wagon coefficients produce times that are slightly slower than the observed timings for these vehicles (with matching loadings and stopping patterns). Thus, the total wagon resistance was found to be slightly too high (with the difference having a stronger velocity dependency than either a dependency on velocity squared or non-velocity), hence indicating a focus on 'B' coefficient K_{WMR3} and potentially 'C' coefficient (K_{WMR5}) for where the difference might be.

The 'B' (K_{WMR3}) and 'C' (K_{WMR5}) values were iteratively varied to attempt to obtain a better match with real-world wagon resistances (which are lower than for loaded aggregate box wagons). Analysis of the 'B' and 'C' values for calibration of empty wagon resistances was done in parallel, since this parameter should be the same for both loaded and empty cement wagons. The analysis showed that the **'B' (K_{WMR3}) coefficient should be reduced from 0.147 to 0.106** and the **'C' (K_{WMR5}) coefficient should be 13.56** (c.f. 18.163 for aggregate box wagons). Similar to that for aggregate box wagons, the reduced value for the 'B' (K_{WMR3}) coefficient implies a correlation of 'B' (K_{WMR3}) with wagon length and/or bogie centre distance, with longer wagons/bogie spacings resulting in higher values of B coefficient K_{WMR3}. Due to the significantly better aerodynamics of the empty cement tank wagons, the overall wagon resistances are much lower at high speeds compared with an empty aggregate box wagon as shown in Figure 21 below.

Figure 21 Comparison of single wagon resistances for an empty cement tank wagon and an empty aggregate box wagon



4.3.4.7 Coefficients applicable to loaded aggregate hopper wagons

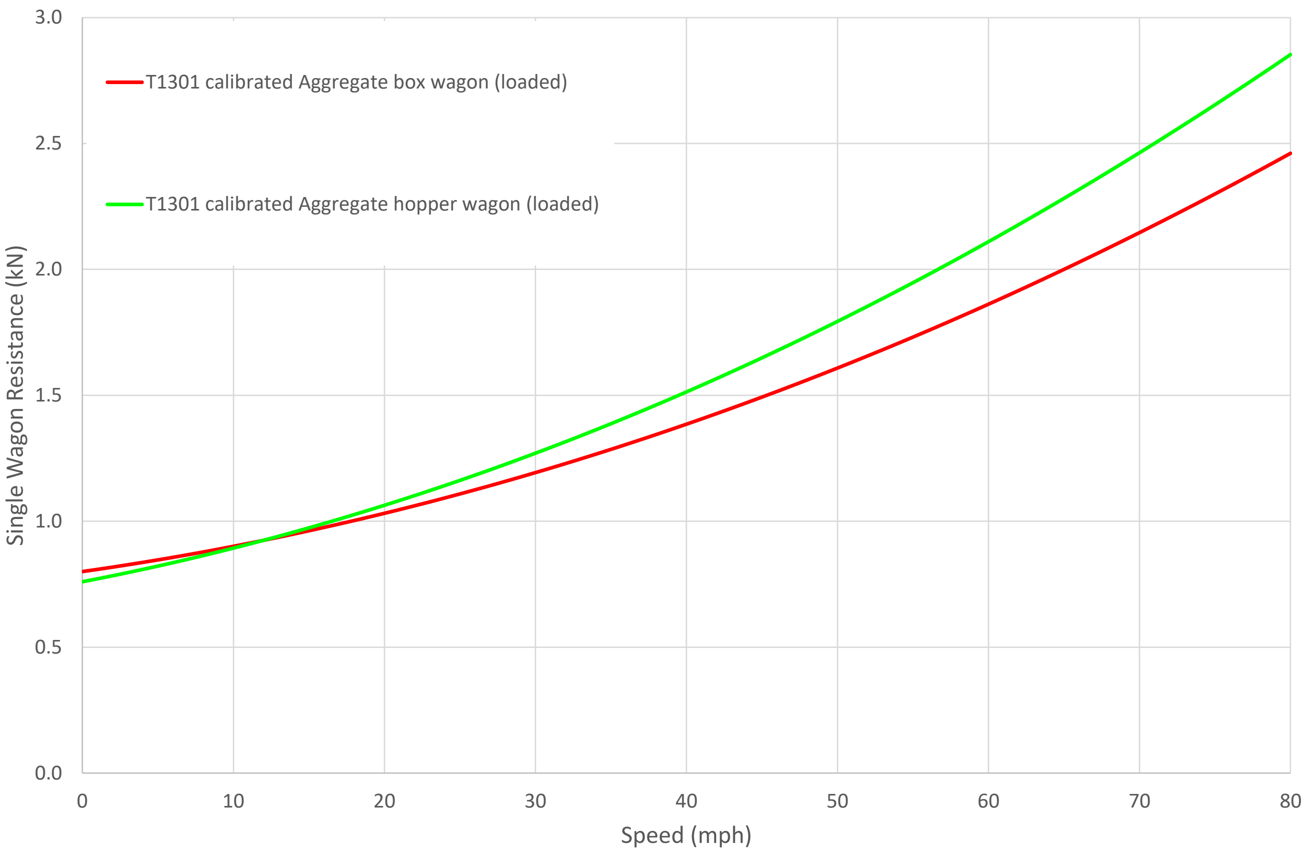
Theoretically loaded aggregate hopper wagons should have higher aerodynamic resistance (i.e., a high overall 'C' value) due to the poorer aerodynamics of the wagons compared with aggregate box wagons. However, loaded aggregate hopper wagons run 4.1% faster on average than loaded aggregate box wagons for the same number of wagons but have a lower value of Q (20-22.5 tonnes). This is a reduction of 10–20% compared with most heavy axle load wagons (depending on individual wagon design). Hence the loaded aggregate box wagon SRT calculation methodology works adequately if Q=25 tonnes is assumed with the matching wagon count. For example, for aggregate box wagons 2,400 tones is equivalent to 24 wagons, not 26/27 wagons as it would be for aggregate hopper wagons (if Q is 22.5 tonnes). Due to the lower value of Q, the total non-velocity dependent resistance ('A') is lower, combined with an expected lower 'B' value based on learning from the calibration of aggregate box wagons, which offsets the impact of the increase in 'C' for the aggregate hopper wagons. Consequently, **the loaded aggregate box wagon calculation results based on trailing tonnage can be used for loaded aggregate hopper wagons**.

There was no recommended value for the 'C' coefficient (K_{WMR5}) for loaded aggregate hopper wagons in the T1302 report. Similar to the loaded box wagons, SRTs calculated using the T1302 methodology and coefficients are slightly slower than observed timings (for matching loadings and stopping patterns). Thus, the total wagon resistance is also slightly too high, with the difference having a stronger velocity dependency than either a dependency on velocity squared or non-velocity coefficient elements.

The 'B' (K_{WMR3}) and 'C' (K_{WMR5}) values were iteratively varied to attempt to obtain a better match with real-world wagon resistances. Analysis of the 'B' values for calibration of empty hopper wagon resistances was done in parallel since this parameter should be the same for both loaded and empty aggregate hopper wagons. The analysis showed that the **'B' (K_{WMR3}) coefficient should be reduced from 0.147 to 0.128** and the **'C' (K_{WMR5}) coefficient should be 22.51** (c.f. 18.163 for aggregate box wagons). Again, the reduced value for the 'B' (K_{WMR3}) coefficient implies a correlation of 'B' (K_{WMR3}) with wagon length and/or bogie centre distance.

In Figure 22 below, the resistance of a single loaded aggregate hopper wagon is compared with a single loaded aggregate box wagon. While fairly similar at low speeds, the resistance of hopper wagon increases at higher speeds.

Figure 22 Comparison of single wagon resistances for loaded aggregate hopper wagon and loaded aggregate box wagon



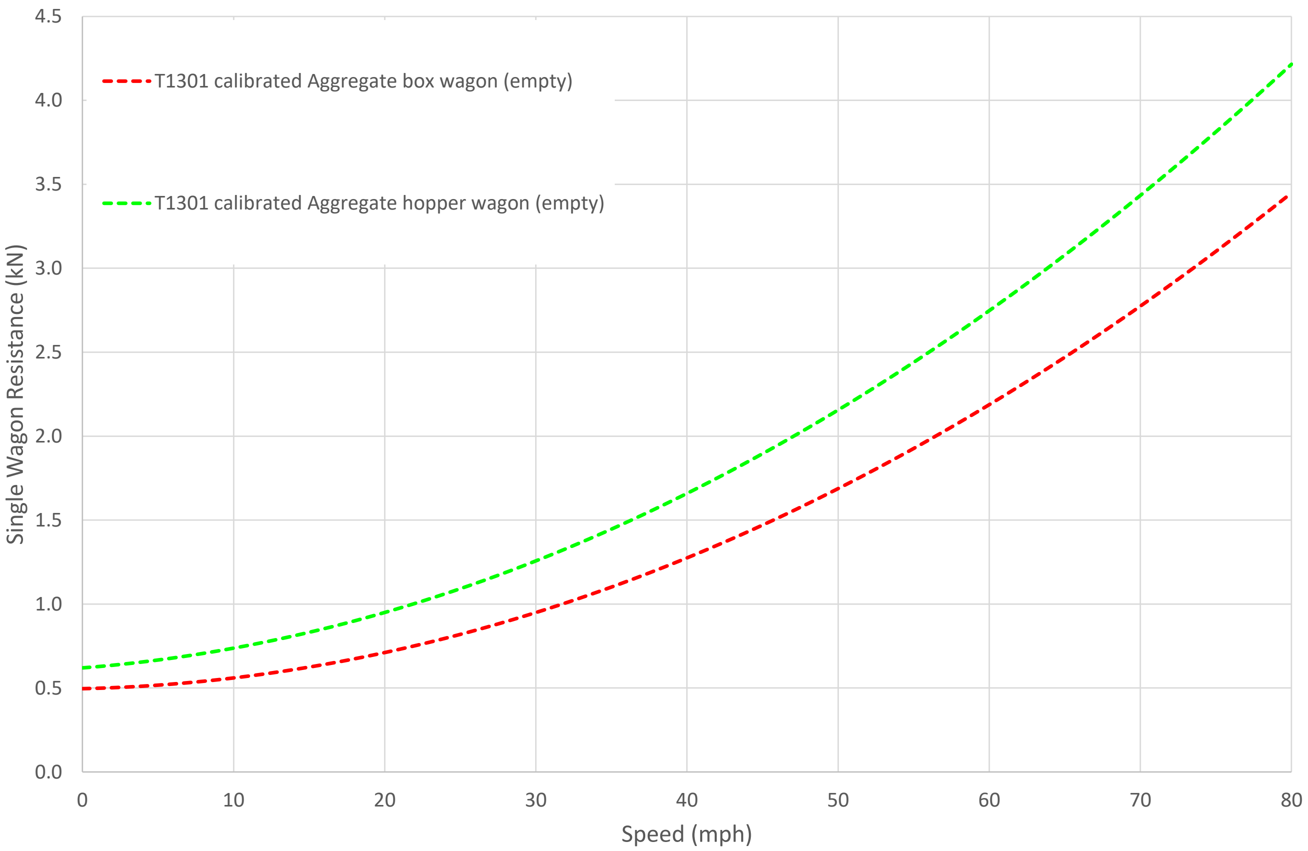
4.3.4.8 Coefficients applicable to empty aggregate hopper wagons

Aggregate trains with empty aggregate hopper wagons for both 60 mph paths (no 75 mph max running unlike for aggregate box wagons) were calibrated northbound between Kettering and Market Harborough (up Desborough Bank). 'B' (K_{WMR3}) coefficient calibration (step 4) was done in conjunction with loaded aggregate hopper wagons, as the values need to be identical for a wagon type irrespective of loading and while assessing the 'C' coefficient (K_{WMR5}). There was no recommended value for the 'C' coefficient (K_{WMR5}) for loaded aggregate hopper wagons in the T1302 report. Similar to the loaded box wagons, SRTs calculated using the T1302 methodology and coefficients are slightly slower than observed timings (for matching loadings and stopping patterns). Thus, the total wagon resistance is also slightly too high, with the difference having a stronger velocity dependency than either a dependency on velocity squared or non-velocity coefficient elements.

The 'B' (K_{WMR3}) and 'C' (K_{WMR5}) values were iteratively varied to attempt to obtain a better match with real-world wagon resistances. Analysis of the 'B' values for calibration of empty hopper wagon resistances was done in parallel since this parameter should be the same for both loaded and empty aggregate hopper wagons. The analysis showed that the **'B' (K_{WMR3}) coefficient should be reduced from 0.147 to 0.128** and the **'C' (K_{WMR5}) coefficient should be 58.05** (c.f. 53.379 for empty aggregate box wagons). Again, the reduced value for the 'B' (K_{WMR3}) coefficient implies a correlation of "B" (K_{WMR3}) with wagon length and/or bogie centre distance.

The difference between the wagon resistance for single empty aggregate hopper and aggregate box wagons is shown in Figure 23 below. At lower speeds, the empty wagon resistance is up to 35% lower, but at high speeds, the empty wagon resistance can be up to 40% higher due to the worse aerodynamics of empty wagons. Note that the wagon does not include gravity component, so this comparison is on the level gradient.

Figure 23 Comparison of single wagon resistances for empty aggregate hopper wagon and empty aggregate box wagon



4.3.4.9 Coefficients applicable to loaded and empty petroleum tank wagons

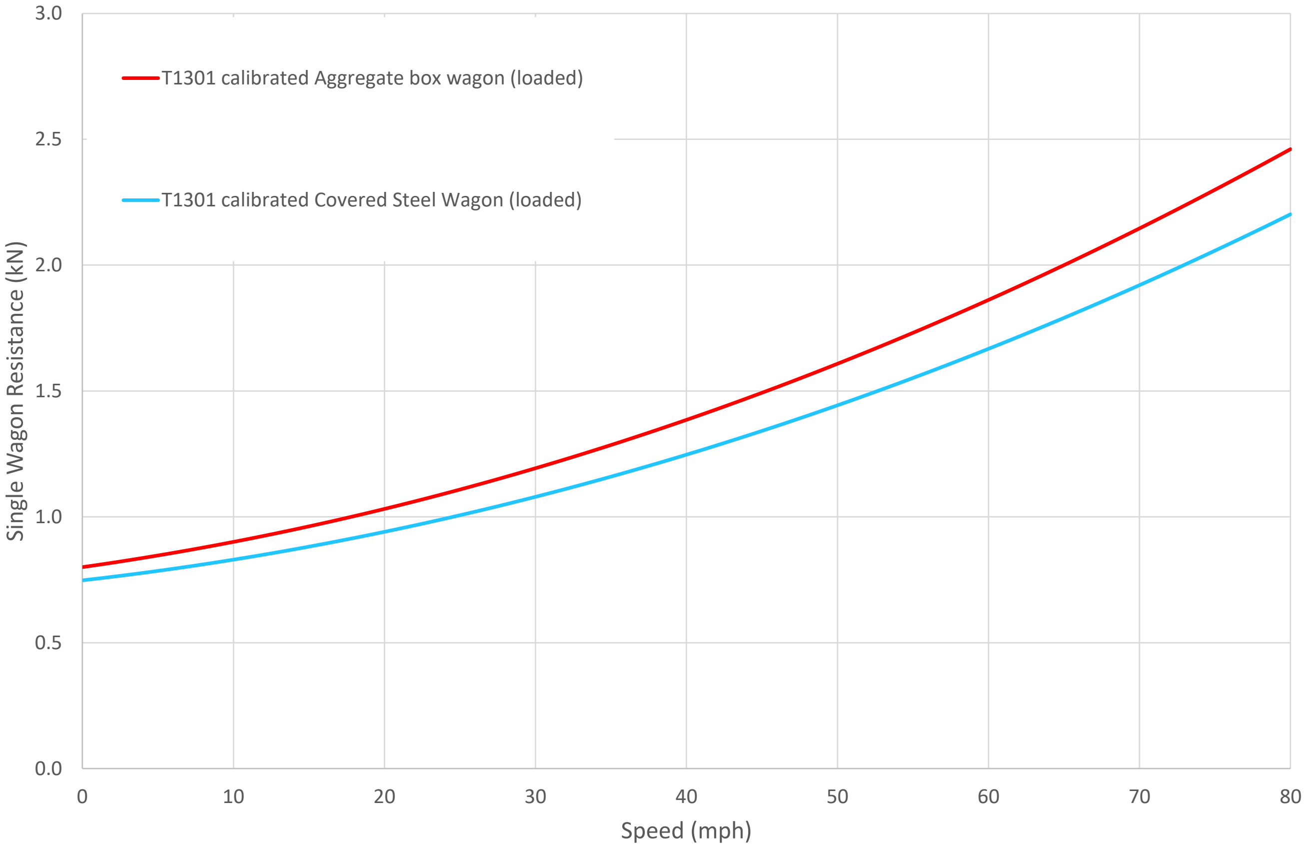
For loaded and empty oil tank wagons, the 'B' ($\boldsymbol{K_{WMR3}}$) coefficient reduced was reduced from the T1302 value of 0.147 to 0.128. No other changes were made.

4.3.4.10 Coefficients applicable to loaded and empty covered steel coil wagons

There were no recommended values for the 'C' coefficient (K_{WMR5}) for cover steel coil wagons in the T1302 report, but values were developed for 'B' ($\boldsymbol{K_{WMR3}}$) and 'C' ($\boldsymbol{K_{WMR5}}$) coefficients as part of the follow-on Wales Route case studies with loaded wagon calibration taking place between Margam and Stormy. These wagons are the shortest commonly used four-axle bogie wagons, and the plastic covers provide relatively clean aerodynamics, albeit with a larger wagon cross-sectional area compared with other non-intermodal wagon types, hence relatively low values of low 'B' ($\boldsymbol{K_{WMR3}}$) and 'C' ($\boldsymbol{K_{WMR5}}$ **)** coefficients were expected as part of the calibration process based on learning from the other wagon coefficient calibrations. The 'B' (K_{WMR3}) and 'C' (K_{WMR5}) values were iteratively varied to attempt to obtain a better match with real-world wagon resistances (which are lower than for loaded aggregate box wagons). Analysis of the 'B' and 'C' values for calibration of empty wagon resistances was done in parallel since this parameter should be the same for both loaded and empty covered steel coil wagons. The analysis showed that the **'B' ($\boldsymbol{K_{WMR3}}$) coefficient should be reduced from 0.147 to 0.078** and the **'C' ($\boldsymbol{K_{WMR5}}$) coefficient should be 16.0** (c.f. 18.163 for aggregate box wagons).

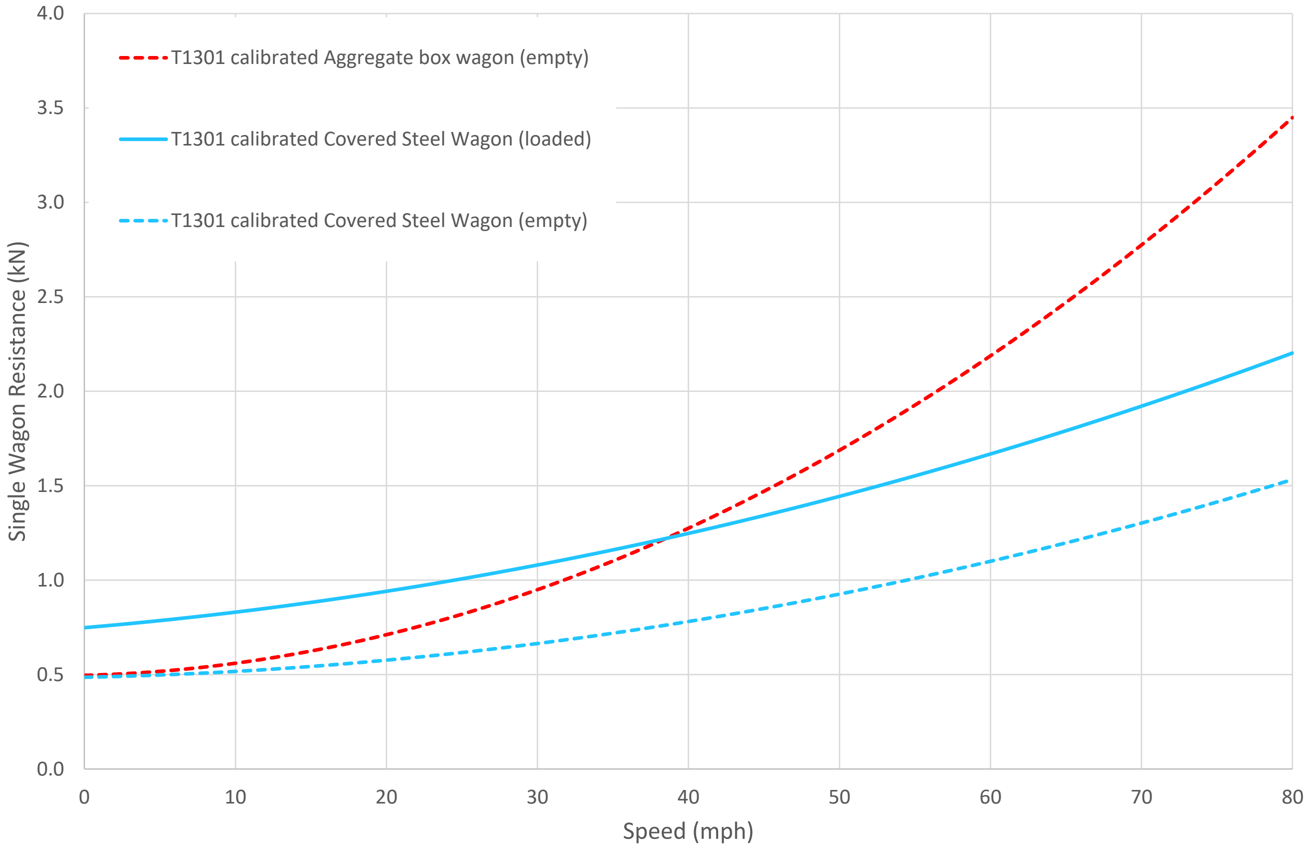
The difference between the wagon resistance for single loaded covered steel and loaded aggregate box wagons is shown in Figure 24 below. While fairly similar at low speeds, the resistance of loaded covered steel wagons is always lower than the aggregate box wagons, and the relative difference increases moderately with increasing speed.

Figure 24 Comparison of single wagon resistances for a loaded covered steel coil wagon and a loaded aggregate box wagon



The difference between the wagon resistance for single loaded and empty covered steel wagons and empty aggregate box wagons is shown in Figure 25 below. At low speed, the resistance of both the empty wagon types is lower than the loaded steel coil wagon. The higher aerodynamic resistance of the empty aggregate box wagon starts rising quickly as speed increases compared with the steel coil wagons, with the load steel coil wagon resistance becoming lower than the empty aggregate box wagon above 40 mph.

Figure 25 Comparison of single wagon resistances for both a loaded and empty covered steel coil wagon and an empty aggregate box wagon



4.3.4.11 Wagon resistance coefficients calibration summary

The outcome of this work has been to calculate a number of new and revised coefficients for different wagon types (including new values for aggregate hopper wagons and cement tank wagons). These new resistance coefficients have been calibrated against real running times for a range of different numbers of wagons per train, for example, 16–24 aggregate box wagons per train. The updated coefficients are shown in Table 9. Note that the values of K_{WMR1} (4.0) + K_{WMR2} (100), which are two of the three components of the A coefficient, are identical for all wagon types (see Section 4.3.4.1) and so these do not appear in Table 9.

Table 9 Wagon resistance coefficients including updates from this work (shown in red)

Wagon type	Axle load—Q (tonnes)	A_W wagon frontal area [m^2]	K_{WMR3} 'B' coefficient [N/tonne]	K_{WMR5} 'C' coefficient [N/tonne]	Notes
Intermodal wagon - 60' platform (FEA) loaded with 9'6''	**13.17**	9.443	0.147	22.241	Platform height 980 mm
Intermodal wagon - 60' platform (FEA) loaded with 8'6''	**13.17**	8.699	0.147	22.241	Platform height 980 mm
Intermodal wagon - 60' platform (FEA) empty	**4.925**	2.391	0.147	22.241	Platform height 980 mm
Aggregate box wagon (loaded)	**25**	8.361	**0.085**	18.683	
Aggregate box wagon (empty)	**6**	8.361	**0.085**	53.379	
Aggregate hopper wagon (loaded)	**22.5**	**8.361**	**0.128**	**22.51**	
Aggregate hopper wagon (empty)	**6**	**8.361**	**0.128**	**58.05**	
Cement tank wagon (loaded)	**25**	**7.89**	**0.106**	**13.56**	Loaded and empty wagon A_W, B and C values are identical
Cement tank wagon (empty)	**5**	**7.89**	**0.106**	**13.56**	Loaded and empty wagon A_W, B and C values are identical
Petroleum tank wagon (loaded)	**25**	7.89	**0.128**	24.465	Loaded and empty wagon A_W, B and C values are identical
Petroleum tank wagon (empty)	**6.6**	7.89	**0.128**	24.465	Loaded and empty wagon A_W, B and C values are identical
Covered steel coil wagon (loaded)	**21.75**	**9.13**	**0.078**	**16.0**	Loaded and empty wagon values are identical
Covered steel coil wagon (empty)	**5.4**	**9.13**	**0.078**	**16.0**	Loaded and empty wagon values are identical

4.4 Synthesis of learnings and recommendations for calculating SRTs

A summary of the key findings from T1301 is given below. While many of the findings support the methodology proposed in T1302, some changes are also proposed. In the following section, a revised methodology is set out that incorporates all of the changes to methodology and values, based on an updated Section 5 of the T1302 report, so as to provide a definitive single source of guidance on SRT calculation.

4.4.1 Locomotive resistances

Starting resistance

- Starting resistance is not currently applied for all locomotive for classes in all cases in existing calculations.
- MT19/T1302 approach to locomotive starting resistances overestimates starting resistances but is fully documented historically.

The recommendation is to:

- Apply locomotive starting resistance in all cases—use 15 lb/Ton (65.6423 N/tonne).
- Potentially use OEM data where available. This will likely be lower than the above value for newer locomotive types, which could potentially be in the 35–50N/tonne range. This will require some engagement with OEM, who may not want to provide data.

Rolling resistance

- As discussed in Section 3.7 of this report, there are many different current NR calculation methodologies for locomotive rolling resistance currently used by NR for SRT calculation, with the mix of methodologies sometimes using smooth curves and sometimes crude step functions (implemented as lookup tables with a minimal number of values).

The recommendations are to:

- Use the T1302 approach that produces smooth curves as the default approach, and use documented OEM or testing data where available (T1302 recommendation).
- Either: Accept OEM data without evidence if the resistance values are up to 15% less than the relevant T1302 resistance values calculated for that locomotive.
- Or: Accept with evidence lower OEM locomotive rolling resistance value if the values are more than 15% lower than the T1302 resistance values calculated for that locomotive.
- Use a lower resistance for the second locomotive when double-heading. However, there is unlikely to be OEM data for non-leading locomotives, which effectively means using the T1302 approach for double-heading.
- Introduce a mechanism not to use unrealistically low data supplied by OEMs (to avoid repeating the Class 66 issue discussed earlier in this section).
- Use realistic resistances for Class 66.

4.4.2 Wagon resistances

The recommendations are to:

- Ideally match total trailing weight to existing SRT trailing weights.
- For intermodal wagons: Retain existing 75% loaded 25% empty wagon approach, with T1302 equations, but using slightly lower axle loads.

- For intermodal wagons: Retain a balance between high Q and high number of wagons so that train lengths are accurately modelled.
- Specific routing needs to be consistently and comprehensively taken into account.

4.4.3 Consequences of revised methodology

- Specific routing needs to be consistently and comprehensively taken into account.

The recommendations are to:

- Calculating Class 70 SRTs at 1,600 and 1,800 tonnes is worthwhile on routes where they are frequently used.
- Calculating accurate double-headed Class 90 SRTs at 1,600 tonnes is worthwhile on routes where they are frequently used.

4.4.4 Application to other case studies

- TE assumptions need to be clearly outlined and applied consistently.
- WCML SRTs require significant adjustment.
- It is important to accurately capture the length of modelled services.

5 Updated methodology for SRT calculations

The RSSB T1302 report 'Guidance on limits of freight train trailing length as governed by tractive effort' proposed new formulae and factors for determining TLLs and hence calculating SRTs. The new methodology was set out in Section 5 of the T1302 report. As explained in the previous section, as a result of the work undertaken in this project (T1301), some further improvements to the methodology can be made. To provide the industry with a single, up-to-date source of guidance on SRT calculation, this section updates the contents of Section 5 in the T1302 report to reflect the new learnings this project. Changes from the T1302 report are indicated in bold red text.

This section is therefore the most up-to-date guidance on SRT calculations and supersedes that set out in the T1302 report.

The components of the revised methodology are 'road mapped' in Table 10.

Table 10 Subsections in Section 5 describing components of the revised methodology

Tractive effort and adhesion	Resistances							
Locomotive	All vehicles		Locomotive		Each wagon (four-axle)		Each wagon (two-axle)	
Section 5.2	Gravity	Accel.	Starting resistance	Rolling resistance	Starting resistance	Rolling resistance	Starting resistance	Rolling resistance
	Section 5.1.1	Section 5.1.2	Section 5.3.1	Section 5.3.2	Section 5.4.1	Section 5.4.2	Section 5.5.1	Section 5.5.2

Each component is discussed in detail below, with specific references back to the relevant subsections in T1302 Sections 3 and 4 of the T1302 report or else to Section 4 of this report where a learning was derived or a decision made.

5.1 Gradient and acceleration (applicable to all vehicles)

5.1.1 Gradient

From Section 3.1.1 of the T1302 report:

$$R_G = g \times \frac{1{,}000}{X} \left[{}^{N}/_{tonne}\right]$$

where:

g = acceleration due to gravity = 9.80665 m/s^2

X = track gradient 1:X, for example, 1:50

5.1.2 Acceleration

From Section 3.1.2 of the T132 report:

$$R_{AS} = 1{,}000 \times a_S \ [{}^{N}/_{tonne}]$$

where:

a_S = train acceleration at starting (m/s^2), suggested value = 0.025 m/s

$$R_{AR} = 1{,}000 \times a_R \ [{}^{N}/_{tonne}]$$

where:

a_R = train acceleration at rolling (m/s^2), suggested value = 0 m/s^2

5.2 Locomotive tractive effort and adhesion factors

The locomotive tractive effort for the trailing load calculation purposes is assumed to be the lesser of locomotive tractive effort from Section 5.2.1 and adhesion from Section 5.2.2 (below).

5.2.1 Locomotive tractive effort

Locomotive tractive effort data and the limiting cases often used for TLL calculations are described in Section 4.3.2 of the T1302 report, and these can also be used for SRT calculation. Recommended starting tractive effort values are presented in Table 11 (values from MT19) and Table 12 (new and updated values). Values in Table 12 updated as a result of T1301 work (see Section 4.1 of this report) are shown in bold red text.

Table 11 Locomotive starting tractive effort values used in MT19

Locomotive class	Locomotive starting TE (kN)
Class 20	172
Class 37/0	236
Class 37/4	250
Class 37/7	252
Class 47	256
Class 56	274
Class 58	274
Class 73/0	165
Class 73/1	160

Table 12 Additional locomotive starting tractive effort values. New or updated values from the ones used in T1302 are shown in **bold red**.

Locomotive class	Locomotive starting TE (kN)
Class 31	**160**
Class 57	**271**
Class 59	506
Class 60	533
Class 66 (75-mph geared)	409
Class 66 (65-mph geared)	465
Class 67	141
Class 68	317
Class 69	273
Class 70	544
Class 73/9	**165**
Class 86	**191**
Class 88 (AC)	317
Class 88 (diesel)	317
Class 90 (single-headed)	258
Class 90 (double-headed)	258
Class 91	**190**
Class 92 (AC & DC)	360
Class 93 (AC)	278
Class 93 (diesel)	278
Class 99 (AC)	500
Class 99 (diesel)	500

Recommended rolling 1-hour and continuous-rated thermal degradation tractive effort values and associated speeds (and 1-hour values where available) are shown in Table 13 and Table 14. The only 1-hour values shown in Table 14 are those used in the Freight Trailing Loads Book (FTLB) '66-H' case (see Section 7 of the T1302 report). Updates to the previous T1302 report (see Section 4.1) are shown in bolded red text in Table 14.

Table 13 Locomotive rolling tractive effort values (1-hour and continuous) used in MT19

Locomotive class	Locomotive rolling TE (kN)			
	1-hour		Continuous	
	TE (kN)	Speed (mph)	TE (kN)	Speed (mph)
Class 20	124	9.7	111	11.0
Class 37/0	157	13.2	147	14.3
Class 37/4	-	-	185	10.2
Class 37/7	-	-	185	10.2
Class 47	149	23.2	137	25.5
Class 56	-	-	240	17.4
Class 58	-	-	240	17.4
Class 73/0	-	-	73	10.0
Class 73/1	-	-	60	11.5

Table 14 Additional locomotive rolling tractive values (1-hour and continuous cases). New or updated values from the ones used in T1302 are shown in **bold red**.

Locomotive class	Locomotive rolling TE (kN)			
	1-hour (just FTLB '66-H' case)		Continuous	
	TE (kN)	Speed (mph)	TE (kN)	Speed (mph)
Class 31	**-**	**-**	**83**	**23.3**
Class 57	**-**	**-**	**140**	**23.7**
Class 59	-	-	291	14.3
Class 60	-	-	336	12.5
Class 66 (75mph-geared)	322	12.1	260	15.9
Class 66 (65mph-geared)	-	-	296	14.0
Class 67	-	-	**90**	**46.5**
Class 68	-	-	258	20.5
Class 69	-	-	239	17.1
Class 70	-	-	427	11.2
Class 73/9	**-**	**-**	**35**	**68.0**
Class 86	**-**	**-**	**85**	**77.5**
Class 88 (AC)	-	-	258	34.3
Class 88 (diesel)	-	-	258	5.3

Locomotive class	Locomotive rolling TE (kN)			
	1-hour (just FTLB '66-H' case)		Continuous	
	TE (kN)	Speed (mph)	TE (kN)	Speed (mph)
Class 90 (single headed)	-	-	244	53.7
Class 90 (double headed)	-	-	244	45.8
Class 91	**-**	**-**	**102**	**96**
Class 92 (AC)	-	-	360	31
Class 93 (AC)	-	-	271	32
Class 93 (diesel)	-	-	258	8.4
Class 99 (AC)	-	-	430	32
Class 99 (diesel)	-	-	430	8.4

We do not believe that the '1-hour and/or continuous' TE values now have any value, as we have a better understanding of TE requirements and locomotive capability, and so we recommend that this 'load case' is no longer included.

Tractive effort data for the following locomotive types in increments of 1 mph is contained within the 'Loco TE Data' spreadsheet associated with this report. This spreadsheet, previously a tab in the T1302 calculation tool, has been updated for this project for the classes shown in bolded red text (see Section 4.1).

- **Class 31**
- Class 37
- Class 47
- Class 56
- **Class 57**
- Class 58
- Class 59
- Class 60
- Class 66 (75-mph geared)
- Class 66 (65-mph geared)
- Class 69
- Class 70

- **Class 73/1 (DC)**
- **Class 73/1 (diesel)**
- **Class 73/9 (diesel)**
- Class 88 (both diesel and electric)
- Class 90 (both single- and double-headed)
- Class 92
- Class 93 (both diesel and electric)
- Class 99 (both diesel and electric)

5.2.2 Adhesion

The following equations were deduced in Section 3.1.1 of the T1302 report:

$$TE_{max}\ [kN] = \mu_v \times locomotive\ adhesion\ mass\ [tonnes] \times g\ \times (1 - gradient\ [as\ decimal])$$

The speed-dependent formula for µ at a given speed μ_V:

$$\mu_v = \frac{K_{MU1}}{(V + K_{MU2})} + (\mu_0 - K_{MU3})\ [V\ in\ mph]$$

where:

K_{MU1} = 4.6612

K_{MU2} = 27.346

K_{MU3} = 0.17045

μ_V = adhesion value at speed V mph

μ_0 = adhesion limit value at 0 mph

V = speed (mph)

Adhesion values at 0 mph (μ_0), that have been retained from MT19 (older locomotive types) are shown in Table 15. Adhesion values at 0 mph (μ_0), for different locomotive types based on locomotive characteristics are set out in Table 16 below for newer locomotive types not covered in MT19 or else revised in this report (indicated in bold red text; see Section 3.1.1 of the T1302 report and Section 4.1 of this report).

Table 15 μ_0 and locomotive weight values retained from MT19 for older locomotive types

Locomotive class	Adhesion weight (tonnes)	Axles	Recommended μ_0 (Main line)	Recommended μ_0 (Secondary)
Class 20	73.87	4	0.24	0.22
Class 37/0	106.69	6	0.24	0.22
Class 37/4	106.00	6	0.24	0.22
Class 37/7	117.01	6	0.24	0.22
Class 47	118.88	6	0.22	0.20
Class 56	125.38	6	0.24	0.22
Class 58	129.01	6	0.24	0.22
Class 73/0	76.31	4	0.22	0.20
Class 73/1	76.81	4	0.24	0.22

Table 16 μ_0 and locomotive weight for newer locomotive types. New or updated values from the ones used in T1302 are shown in **bold red**.

Locomotive	Weight (tonnes)	Axles	Recommended μ_0 (Main line)	Recommended μ_0 (Secondary)
Class 31	**111**	**6**	**0.18**	**0.16**
Class 57	**121**	**6**	**0.23**	**0.21**
Class 59	124	6	0.34*	0.32*
Class 60	130	6	0.36	0.34
Class 66	127	6	0.33*	0.31*
Class 66/6 (low geared)	127	6	0.35*	0.33*
Class 67	**90**	**4**	**0.16**	**0.16**
Class 68	85	4	0.36	0.34
Class 69	**125**	**6**	**0.24**	**0.22**
Class 70	129	6	0.38	0.36
Class 73/9	**77**	**4**	**0.24**	**0.22**
Class 86	**87**	**4**	**0.245**	**0.225**
Class 88	85	4	0.36	0.34
Class 90	84.5	4	0.31**	0.29**
Class 91	**84.5**	**4**	**0.225**	**0.205**
Class 92 (boost mode)	126	6	0.33***	0.33***

Locomotive	Weight (tonnes)	Axles	Recommended μ_0 (Main line)	Recommended μ_0 (Secondary)
Class 92 (normal mode)	126	6	0.29***	0.29***
Class 93	88	4	0.36	0.34
Class 99	113	6	0.38	0.36

Notes:

* Existing value used in FTLB calculations.

** Class 90: Low TE at low speed but high TE at mid and high speeds due to original design assumptions for attainable μ values along with optimising mid and high-speed TE.

*** Class 92: No simple change possible due to hard-coded software configuration and EuroTunnel 34.5-tonne coupler restrictions. Note no difference between main line and secondary route assumption due to the impact of the software configuration.

5.3 Locomotive resistance factors

The recommended approach for both locomotive starting and rolling resistance is to move to using the documented and defined T1302 approaches for locomotive starting resistance and locomotive rolling resistance as the default method and to use suitable data from OEMs or real-world testing if it is available.

The locomotive resistance factors are given in Sections 5.3.1 and 5.3.2 below.

5.3.1 Locomotive starting resistance

Total locomotive starting resistance is given below, followed by a detailed description of the mechanical and curving components:

$$R_{LTS} = R_G + R_{AS} + R_{LMS} + R_{LCS}$$

5.3.1.1 Mechanical component ($\boldsymbol{R_{LMS}}$)

From Section 4.3.4 of the T1302 report with an update from this report reflecting the change from 20 lb/Ton to 15lb/Ton already used by NR for SRT calculations shown in bolded red text:

$$R_{LMS} = K_{LMS1}\ [{}^{N}/_{tonne}]$$

K_{LMS} = Locomotive mechanical starting resistance factor = **65.6423** (N/tonne)

$$K_{LMS1} = \mathbf{65.6423}\ [{}^{N}/_{tonne}]$$

$$\text{Locomotive starting resistance } (R_{LMS})[\text{N}] = \mathbf{65.6423} \times \text{locomotive mass [tonnes]}$$

This is a default value that should be used in the absence of any other information. Some current locomotive manufacturers are claiming lower starting resistance values in the range 40–50 N/tonne for their new locomotive designs, so there is the potential to use such lower values from locomotive OEMs. However, the incremental difference between the revised 65 N/tonne value above and other lower OEM values has a minimal potential impact on the overall performance of the freight train when starting or at very low speed (the further reduction in resistance is equivalent to the resistance of a small fraction of a single wagon).

5.3.1.2 Curving component (R_{LC})

From Section 4.3.3.5 of the T1302 report:

For two-axle bogies (four-axle locomotives):

$$R_{LC(2-axle\ bogie)} = \frac{K_{LC1}}{r}\ [N/tonne]$$

$$R_{LC(2-axle\ bogie)} = \frac{7{,}390}{r}\ [N/tonne]$$

For three-axle bogies (six-axle locomotives) without steerable axles:

$$R_{LC\ (3-axle\ non\ steerable)} = \frac{2 \times K_{LC1}}{r}\ [N/tonne]$$

$$R_{LC\ (3-axle\ non\ steerable)} = \frac{14{,}780}{r}\ [N/tonne]$$

For three-axle bogies (six-axle locomotives) with steerable axles (for example, Class 59 and 66):

$$R_{LC(3-axle\ steerable)} = \frac{K_{LC2}}{(track\ radius\ [m])^2} - \frac{K_{LC3}}{track\ radius\ [m]} + K_{LC4}\ [N/tonne]$$

$$R_{LC(3-axle\ steerable)} = \frac{111{,}500}{(track\ radius\ [m])^2} - \frac{400}{track\ radius\ [m]} + 0.3\ [N/tonne]$$

$$K_{LC1} = 7{,}390\ [N.m/tonne]$$

$$K_{LC2} = 111{,}500\ [N.m/tonne]$$

$$K_{LC3} = 400\ [N.m/tonne]$$

$$K_{LC4} = 0.3\ [N/tonne]$$

where:

r = curve radius (m)

5.3.2 Locomotive rolling resistance

As discussed in Section 3.7 of this report, there are many different calculation methodologies for locomotive rolling resistance currently used by NR for SRT calculation, with the mix of methodologies sometimes using smooth curves and sometimes crude step functions (implemented as look tables with a minimal number of values). The recommendation is to:

- Use the T1302 approach that produces smooth curves as the default approach,
- But to accept OEM data **without** evidence if the resistance values are up to 15% less than the T1302 resistance values calculated for that locomotive, or

- Accept **with** evidence lower OEM locomotive rolling resistance value if the values are more than 15% lower than the T1302 resistance values calculated for that locomotive.

Total locomotive rolling resistance is given below followed by detailed description of the mechanical and curving components:

$$R_{LTR} = R_G + R_{LAR} + R_{LMR} + R_{LCR}$$

5.3.2.1 Mechanical component (leading locomotive)

From Section 4.3.3.3 of the T1302 report, the final combined metric specific locomotive rolling resistance formula for 4-axle locomotives (based on Class 86 measurements by BR) is:

$$R_{LMR\ 4axle\ leading} = K_{LMR1} \times V^2 + K_{LMR2} \times V + K_{LMR3}\ [\mathrm{N}\ /tonne]$$

The final combined metric specific locomotive rolling resistance formula for 6-axle locomotives (based on Class 47 measurements by BR) is:

$$R_{LMR\ 6axle\ leading} = K_{LMR4} \times V^2 + K_{LMR5} \times V + K_{LMR6}\ [\mathrm{N}\ /tonne]$$

5.3.2.2 Mechanical component (non-leading locomotive)

From Section 4.3.3.3 of the T1302 report, all coefficients and values remain the same, except for the V^2 coefficients of K_{LMR7} and K_{LMR8} , which are reduced by ~66%:

$$R_{LMR\ 4axle\ non-leading} = K_{LMR7} \times V^2 + K_{LMR2} \times V + K_{LMR3}\ [\mathrm{N}\ /tonne]$$

$$R_{LMR\ 6axle\ non-leading} = K_{LMR8} \times V^2 + K_{LMR5} \times V + K_{LMR6}\ [\mathrm{N}\ /tonne]$$

where:

K_{LMR1} = 0.00839 N / mph^2 tonne

K_{LMR2} = 0.0698 N / mph tonne

K_{LMR3} = 18.649 N / tonne

K_{LMR4} = 0.00655 N / mph^2 tonne

K_{LMR5} = 0.0607 N / mph tonne

K_{LMR6} = 19.157 N / tonne

K_{LMR7} = 0.00284 N / mph^2 tonne

K_{LMR8} = 0.00222 N / mph^2 tonne

m_L = mass of locomotive tonnes

V = speed mph

5.3.2.3 Curving component (R_{LCR})

From Section 4.4.5.3 of the T1302 report:

For two-axle bogies (four-axle locomotives):

$$R_{LCR(2-axle\ bogie)} = \frac{K_{LCR1}}{r}\ [^N/_{tonne}]$$

$$R_{LCR(2-axle\ bogie)} = \frac{7{,}390}{r}\ [{}^{N}/_{tonne}]$$

For three-axle bogies (six-axle locomotives) without steerable axles:

$$R_{LCR\ (3\ axle\ non\ steerable)} = \frac{2 \times K_{LCR1}}{r}\ [{}^{N}/_{tonne}]$$

$$R_{LCR\ (3\ axle\ non\ steerable\ bogie} = \frac{14{,}780}{r}\ [{}^{N}/_{tonne}]$$

For three-axle bogies (six-axle locomotives) with steerable axles (for example, Class 59 and 66):

$$R_{LCR(3\ axle\ steerable)} = \frac{K_{LCR2}}{(track\ radius\ [m])^2} - \frac{K_{LCR3}}{track\ radius\ [m]} + K_{WCR4}\ [{}^{N}/_{tonne}]$$

$$R_{LCR(3\ axle\ steerable)} = \frac{111{,}500}{(track\ radius\ [m])^2} - \frac{400}{track\ radius\ [m]} + 0.3\ [{}^{N}/_{tonne}]$$

$$K_{LCR1} = 7{,}390\ [{}^{N.m}/_{tonne}]$$
$$K_{LCR2} = 111{,}500\ [{}^{N.m}/_{tonne}]$$
$$K_{LCR3} = 400\ [{}^{N.m}/_{tonne}]$$
$$K_{LCR4} = 0.3\ [{}^{N}/_{tonne}]$$

where:

r = curve radius (m)

5.4 Wagon factors for 4-axle wagons

The wagon loadings, number of wagons, and the equation coefficients in this section are all interlinked and calibrated against real running times for matching consists, hence complete sets of linked calculation inputs and assumptions need to be used to calculate realistic timings. For example, container services usually contain a mix of both occupied and empty slots on wagons along with axle loads that are substantially lower than the maximum for the wagons, which results in a train that is substantially longer than would be assumed based on maximum axle loadings and full filled slots on wagons, resulting in a longer train and higher overall wagon resistances.

This section has been expanded from the equivalent section in the T1302 report to add default general train assumptions, including the number of wagons and axle loading to use for calculations (see Section 4.3).

Table 17 summarises the recommended wagon loading and length values for calculation purposes of typical wagons in a variety of categories use on the GB network. The same table structure is used in other following tables for other wagon characteristics.

Table 17 Recommended wagon loading and length values for selected wagon types for use in SRT calculations

Wagon type	Wagon loading status	Total wagon mass (t)	Axle load—Q (t)	Wagon length (m)
Intermodal wagon - 60' platform (FEA) loaded with 9'6''	Loaded, with 9'6" containers	52.68	13.17	20.1
Intermodal wagon - 60' platform (FEA) loaded with 8'6''	Loaded, with 8'6" containers	52.68	13.17	20.1
Intermodal wagon - 60' platform (FEA) empty	Empty, no containers	19.7	4.925	20.1
Aggregate box wagon (loaded)	Loaded	100	25	14.0
Aggregate box wagon (empty)	Empty	24	6	14.0
Aggregate hopper wagon (loaded)	Loaded	90	22.5	15.2
Aggregate hopper wagon (empty)	Empty	24	6	15.2
Cement tank wagon (loaded)	Loaded	100	25	16.2
Cement tank wagon (empty)	Empty	20	5	16.2
Petroleum tank wagon (loaded)	Loaded	100	25	18.3
Petroleum tank wagon (empty)	Empty	26.4	6.6	18.3
Covered steel coil wagon (loaded)	Loaded	87	21.75	12.9
Covered steel coil wagon (empty)	Empty	21.5	5.4	12.9

For general SRT calculation purposes (as discussed in Section 4.3 of this report), a small subset of wagon assumptions should be used:

- Default wagons assumption for container train timings, i.e., with 'C' or 'CON' specified, should be (also see Table 18 below):
  - Intermodal wagon - 60' platform (FEA) loaded with 9'6'' for TLLs up to and including 1,600 tonnes – for ~75% of the wagons; see Table 18 below for the recommended number of wagons and train length.
  - Intermodal wagon - 60' platform (FEA) empty – for ~25% of the wagons; see Table 18 below for the recommended number of wagons and train length.
- Default wagons assumption for loaded heavy axle load timings, i.e., with 'H' or 'HAW' specified, should be:
  - aggregate box wagon (loaded).
- Default wagons assumption for empty heavy axle load timings, i.e., with 'H' or 'HAW' and trailing loads of 400, 600, and also usually 800 tonnes (800-tonne TLLs are used for both very long empty heavy axle load trains and short loaded ones, with the former much more common) specified, should be:
  - aggregate box wagon (empty).

Table 18 summarises the recommended container train number of wagons, wagon loadings, and total wagon length values for calculation purposes.

Table 18 Wagon loading and length values for intermodal container trains for use in calculations for commonly used SRT TLLs

Intermodal container TLL	Total wagons	# Loaded wagons	# Empty wagons	Actual trailing weight (t)	Total wagon length (m)
800 tonnes	19	13	6	803	382
1,000 tonnes	23	17	6	1014	463
1,200 tonnes	27	20	7	1192	543
1,235 tonnes	29	20	9	1231	583
1,250 tonnes	28	21	7	1244	563
1,475 tonnes	33	25	8	1475	664
1,600 tonnes	36	27	9	1600	724
1,800 tonnes	37	28*	9	1800	744

* With higher axle load (Q) of 14.49 tonnes used here due to overall train length limitations.

Wagon resistances and input assumptions have been derived and calibrated for many wagon types that cover the vast majority of freight traffic on the GB network. However, it was not possible to derive and calibrate values and assumptions for the following remaining wagon types:

- 40’ or 45’ container wagons
- covered biomass hoppers
- 90-tonne low sided NR ballast wagons, such as ‘Falcon’ JNAs
- non-covered steel slab wagons
- timber wagons
- car transporter wagons.

These would require further case studies in different areas to the ones covered so far and should be considered for future work.

The four-axle wagon resistance factors are given in Sections 5.4.1 (starting) and 5.4.2 (rolling) below.

5.4.1 Wagon starting resistances for 4-axles

Starting resistance for four-axle wagons is as follows.

5.4.1.1 Total wagon starting resistance

$$R_{WTS} = R_G + R_A + R_{WMS} + R_{WCS}$$

where:

R_G = gradient resistance from Section 5.1.1

R_A = acceleration resistance from Section 5.1.2 = 25 N/tonne (as acceleration = 2.5 m/s^2)

5.4.1.2 Mechanical component (R_{WMS})

From Section 4.4.4 of the T1302 report:

$$R_{WMS} = 1.4 \times R_{WMR} \, [^N/_{tonne}]$$

where:

R_{WMR} = Wagon mechanical resistance from Section 5.4.2

which at 0 mph simplifies to:

$$R_{WMS} = 1.4 \times \left(4.0 + \frac{100}{Q}\right) [^N/_{tonne}]$$

where:

Q = axle load (tonnes)

5.4.1.3 Curving component (R_{WCS})

From Section 4.4.5.3 of the T1302 report:

at and above R = 201 m:

$$R_{WCS} = \frac{K_{WCS1}}{R} [^N/_{tonne}]$$

below R = 201 m:

$$R_{WCS} = \frac{1.833 \times K_{WCS1}}{R} [^N/_{tonne}]$$

where:

$K_{WCS1} = 7{,}390$

R = curve radius (m)

5.4.2 Wagon rolling resistance for four-axles

Rolling resistance for four-axle wagons is determined as follows.

5.4.2.1 Total wagon rolling resistance

Total wagon rolling resistance is:

$$R_{WTR} = R_{WGR} + R_{WAR} + R_{WMR1} + R_{WMR2} + R_{WMR3} + R_{WMR4} + R_{WCR}$$

where:

R_G = gradient resistance from Section 5.1.1

R_A = acceleration resistance from Section 5.1.2 = 0 N/tonne (as acceleration = 0 m/s^2)

5.4.2.2 Mechanical component (R_{WMR})

From Section 4.4.2.4 of the T1302 report:

$$R_{WMR} = R_{WMR1} + R_{WMR2} + R_{WMR3} + R_{WMR4}$$

where:

$$R_{WMR1} = K_{WMR1}\ [^{N}/_{tonne}]$$

$$R_{WMR2} = \frac{K_{WMR2}}{Q}\ [^{N}/_{tonne}]$$

$$R_{WMR3} = K_{WMR3} \times V\ [^{N}/_{tonne}]$$

$$R_{WMR4} = \frac{K_{WMR4} \times K_{WMR5} \times A_w \times V^2}{K_{WMR6} \times M_w}\ [^{N}/_{tonne}]$$

where:

K_{WMR1} = 4.0

K_{WMR2} = 100

K_{WMR3} = ‘B’ coefficient as defined in Table 19

K_{WMR4} = aerodynamic resistance in tunnels factor, 1 if no tunnel, ($N/m^2/mph^2$)

K_{WMR5} = ‘C’ coefficient as defined in Table 20

K_{WMR6} = 1024.081

A_W = wagon frontal area as defined in Table 20 (m^2)

M_w= gross wagon mass (tonnes)

Q = axle load (tonnes)

V = speed (mph)

Using the above, and assuming no tunnels (that is, K_{WMR4} = 1), R_{WMR} simplifies to:

$$R_{WMR} = 4.0 + \frac{100}{Q} + K_{WMR3} \times V + \frac{K_{WMR5} \times A_w \times V^2}{1024.081 \times M_w}\ [^{N}/_{tonne}]$$

Table 19 summarises the recommended wagon K_{WMR3} values for calculation purposes of typical wagons in a variety of categories use on the GB network. See Section 4.3 for the derivation of these values. The same table structure is used in other following tables for other wagon characteristics.

Table 19 K_{WMR3} values for selected wagon types. New or updated values from the ones used in T1302 are shown in **bold red**.

Wagon type	K_{WMR3} 'B' coefficient [N/tonne]
Intermodal wagon - 60' platform (FEA) loaded with 9'6''	0.147
Intermodal wagon - 60' platform (FEA) loaded with 8'6''	0.147
Intermodal wagon - 60' platform (FEA) empty	0.147
Aggregate box wagon (loaded)	**0.085**
Aggregate box wagon (empty)	**0.085**
Aggregate hopper wagon (loaded)	**0.128**
Aggregate hopper wagon (empty)	**0.128**
Cement tank wagon (loaded)	**0.106**
Cement tank wagon (empty)	**0.106**
Petroleum tank wagon (loaded)	**0.128**
Petroleum tank wagon (empty)	**0.128**
Covered steel coil wagon (loaded)	**0.078**
Covered steel coil wagon (empty)	**0.078**

Table 20 summarises the recommended wagon K_{WMR5} and A_w values for calculation purposes of typical wagons in a variety of categories in use on the GB network summarises the recommended values for typical wagons in use on the GB network.

Table 20 K_{WMR5} and A_W values for selected wagon types. New or updated values from the ones used in T1302 are shown in **bold red**.

Wagon type	K_{WMR5} 'C' coefficient [N/tonne]	A_W wagon frontal area [m^2]	Notes
Intermodal wagon - 60' platform (FEA) loaded with 9'6''	22.241	9.443	Platform height 980 mm
Intermodal wagon - 60' platform (FEA) loaded with 8'6''	22.241	8.699	Platform height 980 mm
Intermodal wagon - 60' platform (FEA) empty	22.241	2.391	Platform height 980 mm
Aggregate box wagon (loaded)	18.683	8.361	
Aggregate box wagon (empty)	53.379	8.361	
Aggregate hopper wagon (loaded)	**22.51**	**8.361**	
Aggregate hopper wagon (empty)	**58.05**	**8.361**	
Cement tank wagon (loaded)	**13.56**	**7.89**	Loaded and empty wagon values are identical
Cement tank wagon (empty)	**13.56**	**7.89**	Loaded and empty wagon values are identical
Petroleum tank wagon (loaded)	24.465	7.89	Loaded and empty wagon values are identical
Petroleum tank wagon (empty)	24.465	7.89	Loaded and empty wagon values are identical
Covered steel coil wagon (loaded)	**16.0**	**9.13**	Loaded and empty wagon values are identical
Covered steel coil wagon (empty)	**16.0**	**9.13**	Loaded and empty wagon values are identical

5.4.2.3 Curving component (R_{WCR})

From Section 4.4.5.3 of the T1302 report:

$$R_{WCR} = \frac{K_{WCR1}}{R} \left[{}^{N}/_{tonne}\right]$$

where:

$K_{WCR1} = 7{,}390$

R = curve radius (m)

5.5 Wagon factors for two-axle wagons

The two-axle wagon resistance factors are given in Section 5.5.1 (starting resistance) and Section 5.5.2 (rolling resistance) below. There are no changes from the T1302 report.

5.5.1 Wagon starting resistances for two-axles

Starting resistance for two-axle wagons is as follows.

5.5.1.1 Total wagon starting resistance

$$R_{WTS} = R_G + R_A + R_{WMS} + R_{WCS}$$

where:

R_G = gradient resistance from Section 5.1.1

R_A = acceleration resistance from Section 5.1.2 = 25 N/tonne (as acceleration = 2.5 m/s^2)

5.5.1.2 Mechanical component (R_{WMS})

From Section 4.4.4 of the T1302 report:

$$R_{WMS} = 1.4 \times R_{WMR} \; [{}^{N}/_{tonne}]$$

where:

R_{WMR} = Wagon mechanical resistance from Section 5.5.2.2

which at 0 mph simplifies to:

$$R_{WMS} = 1.4 \times \left(4.38 + \frac{57.8}{Q}\right) [{}^{N}/_{tonne}]$$

where:

Q = axle load (tonnes)

5.5.1.3 Curving component (R_{WCS})

From Section 4.4.5.3 of the T1302 report:

At and above R = 201 m:

$$R_{WCS} = \frac{K_{WCS1}}{R} [{}^{N}/_{tonne}]$$

Below R = 201 m:

$$R_{WCS} = \frac{1.833 \times K_{WCS1}}{R} [{}^{N}/_{tonne}]$$

where:

$K_{WCS1} = 7{,}390$

R = curve radius (m)

5.5.2 Wagon rolling resistance for two-axles

Rolling resistance for two-axle wagons is as follows.

5.5.2.1 Total wagon rolling resistance

$$R_{WTR} = R_{WGR} + R_{WAR} + R_{WMR1} + R_{WMR2} + R_{WMR3} + R_{WMR4} + R_{WCR}$$

where:

R_G = gradient resistance from Section 5.1.1

R_A = acceleration resistance from Section 5.1.2 = 0 N/tonne (as acceleration = 0 m/s^2)

5.5.2.2 Mechanical component ($\boldsymbol{R_{WMR}}$)

From Section 4.4.5.3 of the T1302 report:

$$R_{WMR} = R_{WMR11} + R_{WMR12} + R_{WMR13} + R_{WMR14}$$

where:

$$R_{WMR11} = K_{WMR11}\ [{}^{N}/_{tonne}]$$

$$R_{WMR12} = \frac{K_{WMR12}}{Q}\ [{}^{N}/_{tonne}]$$

$$R_{WMR13} = K_{WMR13} \times V\ [{}^{N}/_{tonne}]$$

$$R_{WMR14} = \frac{K_{WMR4} \times K_{WMR15} \times V^2}{Q}\ [{}^{N}/_{tonne}]$$

where:

K_{WMR11} = 4.38

K_{WMR12} = 57.8

K_{WMR13} = 0.19

K_{WMR4} = aerodynamic resistance in tunnels factor, 1 if no tunnel, (N/m^2/mph^2)

K_{WMR15} = 0.025772

Q = axle load (tonnes)

V = speed (mph)

Using the above, and assuming no tunnels, R_{WMR} simplifies to:

$$R_{WMR} = 4.38 + \frac{57.8}{Q} + 0.19 \times V + \frac{0.025772 \times V^2}{Q}\ [{}^{N}/_{tonne}]$$

5.5.2.3 Curving component ($\boldsymbol{R_{WCR}}$)

From Section 4.4.5.3 of the T1302 report:

$$R_{WCR} = \frac{K_{WCR1}}{R}\ [{}^{N}/_{tonne}]$$

where:

$K_{WCR1} = 7{,}390$

R = curve radius (m)

5.6 Braking

NR assumes a braking level of 4.5% *g* for freight trains (see discussion in Section 3.10). While this value is unrealistic in practice (slightly lower and more conservative), it does have the merit of being a clear, conservative assumption that is well documented, so we recommend retaining this assumption.

From Section 3.10:

$$B_F = 4.5\% \times g \times Mass_{train}\ [N]$$

where:

g = acceleration due to gravity = 9.80665 m/s^2

$Mass_{train}$ = mass of train

6 Learnings from case studies

6.1 Introduction to the case studies

Five case studies were agreed with the stakeholders at the project Steering Group meetings. Although each case study followed a similar approach, each study had a specific focus that reflected the points of interest identified during stakeholder engagement. The case studies and their motivations are listed below.

Case study 1: Wessex Main Line, Eastleigh–Basingstoke, subsequently extended to Southampton to Crewe

Investigate the wagon resistances on a long challenging gradient from Winchester to Basingstoke. Apply these principally to intermodal traffic and take the opportunity to evaluate the effect of different train loadings and axle weights. Then evaluate intermodal train performance on a key intermodal corridor that this section forms part of.

Case study 2: Midland Main Line (MML)

Investigate the potential improvement on a route with heavy bulk aggregate flows (enabling study of aggregate wagon resistances) and a dense high speed and local passenger service. Observations show that SRTs for empty aggregate wagon services appear unrealistic.

Case study 3: West Coast Main Line (WCML)

Investigate the potential benefit on Anglo-Scottish domestic intermodal trains through the most challenging geography on their route (Grayrigg and then Shap as well as Beattock), where observed performance is significantly better than timetabled performance. Also investigate the differential benefit of electric and diesel locomotives, and four- and six-axle locomotives and the opportunity to run faster or longer trains.

Case study 4: Great Eastern Main Line (GEML)

Investigate the potential benefits of running with electric locomotives on the busy route into London. Establish if trains can either run faster, longer, or both, and consider with care their entry and exit from the GEML.

Case study 5: West London Line (WLL)

The West London Line is a strategic freight corridor, being the most eastern freight crossing of the River Thames. The route is complex and has interfaces with several different passenger networks. It also has a significant gradient from Shepherds Bush to Willesden, which currently limits train length to 2,000 tonnes. The study looks to determine opportunities for improved pathing, timing and train weight.

6.2 Case study 1: Eastleigh–Basingstoke (extended to Southampton to Crewe)

6.2.1 Outcome of SRT modelling

Although the case study focused on Eastleigh–Basingstoke, modelling was undertaken for trains running between Southampton and Crewe so that implications for real services could be understood. The modelled time for the whole trip, using T1302 assumptions, was 3 hr 59 mins, a 5.5% reduction in journey time.

The performance improvements can be attributed to:

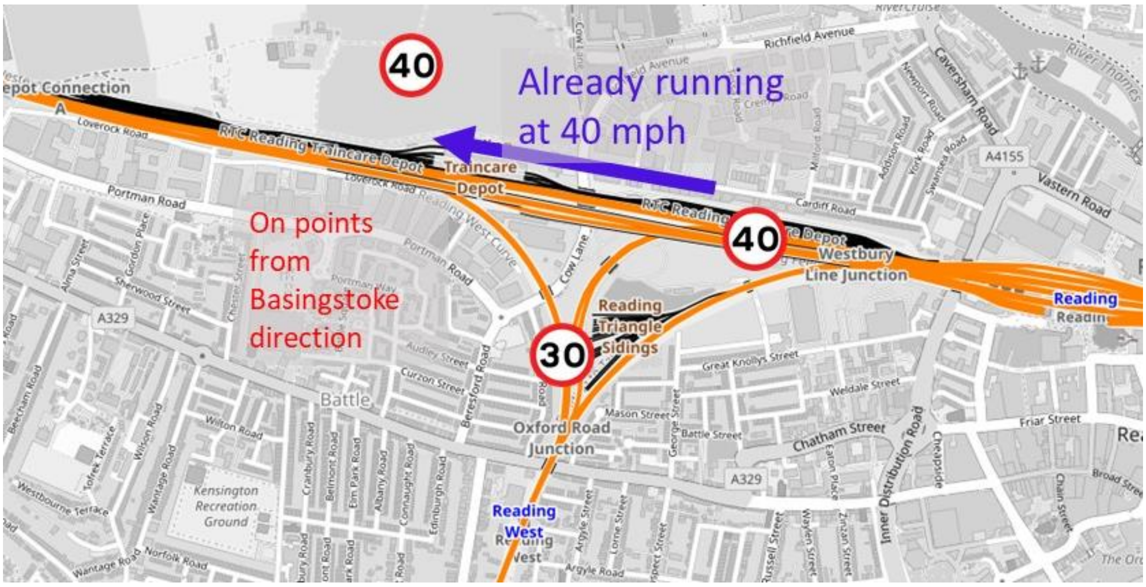
- greater realism of T1302 assumptions (while retaining an overall conservative approach)
- inaccuracy of some of the existing SRTs.

The performance improvements are particularly notable in sections with challenging geography (for example, Eastleigh–Basingstoke). These improvements are due to the more accurate formulas derived in T1302 and validated/calibrated in this case study.

6.2.2 Investigation of local timing differences

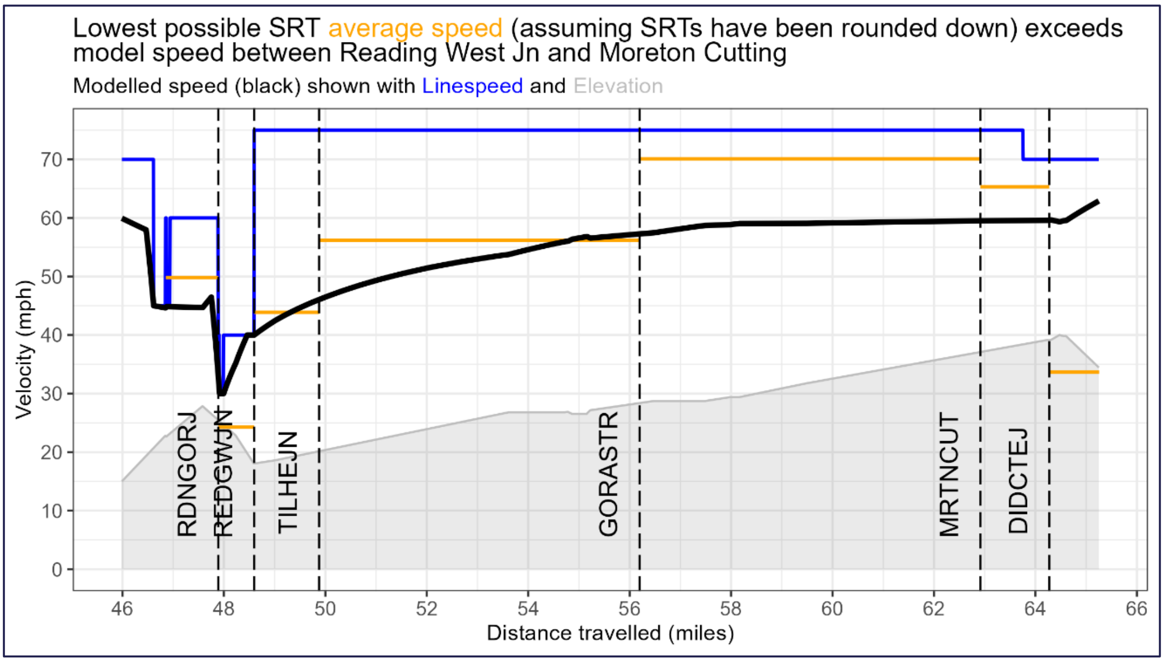
The improvement in performance is not uniformly observed, partly due to inconsistency in rounding rules. However, inconsistency also arises from inaccuracy of SRTs. For example, the modelled timings (using realistic assumptions about consists and traction performance) are slower than the existing SRTs between Reading and Didcot. When this discrepancy was investigated, by looking at the Sectional Appendices for the area, it was found that trains routed from Basingstoke towards Didcot are limited to 30 mph at the bottom of the triangle and 40 mph just before joining the main line (see Figure 26). However, when routed from Acton to Didcot, trains are already at 40 mph across the top of the triangle.

Figure 26 Effect of different speed limits entering a section



Basingstoke trains are therefore at a lower speed when entering the GWML than a train pathed from Acton and so are incapable of matching the performance (and SRTs) of an ex-Acton service in subsequent sections. Both trains accelerate at similar rates, but the model ultimately reaches a slightly lower speed peak speed on the climb to the west (due to the lower entry speed); see Figure 27 .

Figure 27 Modelled speed vs. minimum average speed implied by current SRT



This chart clearly shows that between Tilehurst East Junction (TILHEJN) and Moreton Cutting (MRTNCUT), the achieved is always around 10 mph behind the required average speed to meet the SRTs. When compared with the existing SRTs in Table 21, each train will pick up nearly 3 minutes of delay.

Table 21 Modelled time vs. existing SRT from Reading West to Didcot

Section start	Section end	Existing SRT	Modelled time (mins)	Difference (mins)
Reading West Jn	Tilehurst East Jn	1.5	1.78	0.28
Tilehurst East Jn	Goring and Streatley	6.5	7.22	0.72
Goring and Streatley	Moreton Cutting	5.5	6.83	1.33
Moreton Cutting	Didcot East Jn	1	1.37	0.37
			Total delay	**2.70**

The modelled timings before Goring and Streatley are 1 minute slower than the current SRTs. However, investigation of timetable planning rules suggests that an adjustment of 1 minute has been made to the current timetable, which reflects the increased time required. However, after Goring and Streatley, there is an additional 2-minute adjustment (when rounded) required to modelled times to reflect the lower entry speed at Reading West. No adjustment is currently made to reflect this. In these final two sections, the geography is more challenging making entry speed (or 'momentum') more significant. Services typically lose at least 2 minutes on the Reading to Didcot section, confirming the findings of the modelling when the existing 1-minute timing allowance has been considered.

A similar situation was found between Oxford and Wolvercote Junction, where SRTs for trains via both the Platform 4 line and the through lines (the normal freight routing) are assumed to be the same. This is despite the Platform 4 line being limited to 40 mph just prior to Oxford station. Consequently, trains would require longer to reach Wolvercote Junction than trains on the through lines. A wider more general point is specific routing needs to be consistently and comprehensively considered when establishing SRTs.

6.2.3 Potential for further reductions to SRTs

Services on this route frequently run with Class 70 or with Class 66 but a trailing load under 1475 tonnes. Modelled SRTs for these combinations are compared with the modelled Class 66, 1,600 tonne timings in Table 22.

Table 22 SRT improvements from smaller loads or different traction

Consist	Time (Southampton–Crewe, currently 4hrs 13 mins)	Reduction from current SRTs	Relative to Class 66, 1,600 tonnes
Class 66 1,600 tonnes	3 hrs 59 mins	5.45% (13 minutes)	-
Class 66 1,475 tonnes	3 hrs 52 mins	8.29% (20 minutes)	2.84% (7 minutes)
Class 70 1,600 tonnes	3 hrs 46 mins	10.54% (26 minutes)	5.09% (13 minutes)

This shows the net 5.45% reduction to SRTs that is possible using the T1302 methodology.

If SRTs are calculated at the typical 'median' service weight of 1,475 tonnes, then a further 7-minute saving can be achieved. (For example, rather than higher axle weight assumptions.) Using a Class 70 rather than a Class 66 saves a further 13 minutes, so calculating Class 70 SRTs at 1,600 and 1,800 tonnes will be within the existing timing allowance.

In summary:

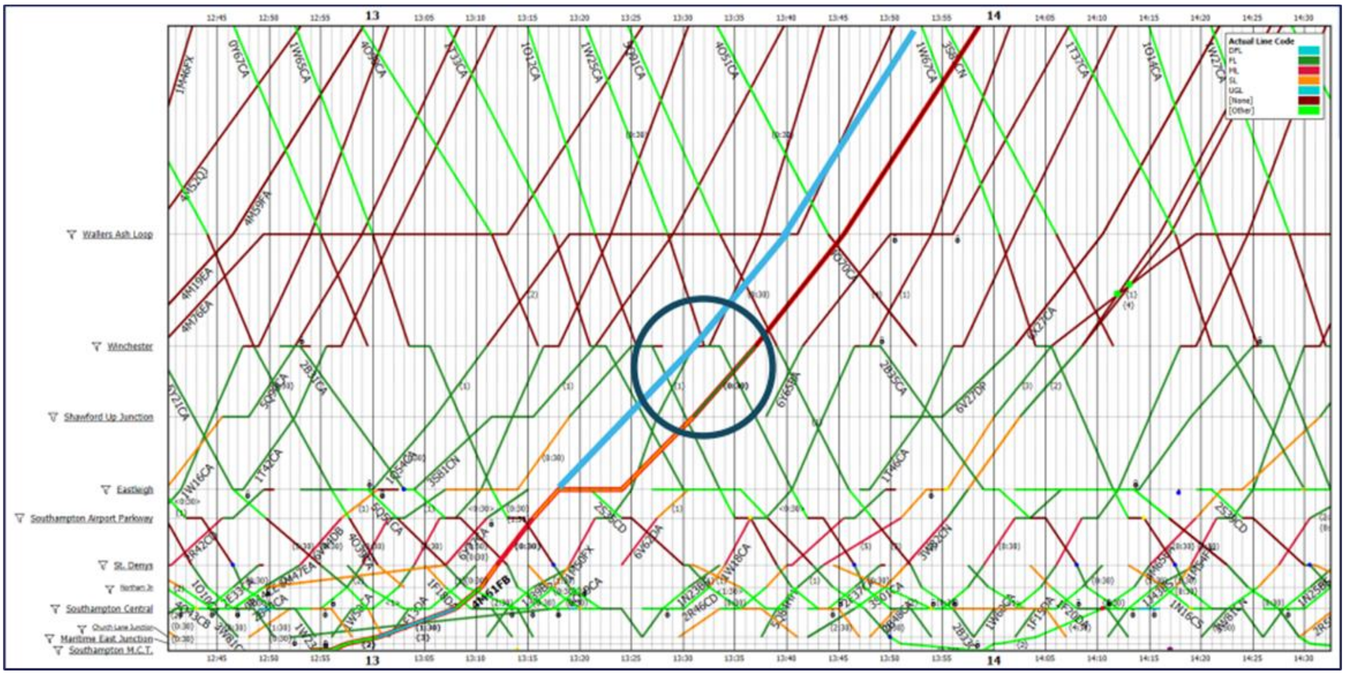
- 5% improvement (Class 66, 1,600 tonnes)
- 3% further improvement (Class 66, 1,475 tonnes)—note 8% reduction in load = 8% improvement in timing
- 11% total improvement (Class 70, 1600 tonnes)—almost half an hour, double the benefit of a Class 66.

These improvements include the absorption of the specific local issues identified, which leads to higher SRTs in several sections, such as 3 minutes lost up to Didcot from Reading West Junction.

Timetable modelling was undertaken using the modelled SRTs to see if the path could be improved. The route is complex, with interfaces with the South-West Main Line (SWML), Great Western Main Line (GWML), a single-track line between Three Spires and Leamington Spa, and then the WCML.

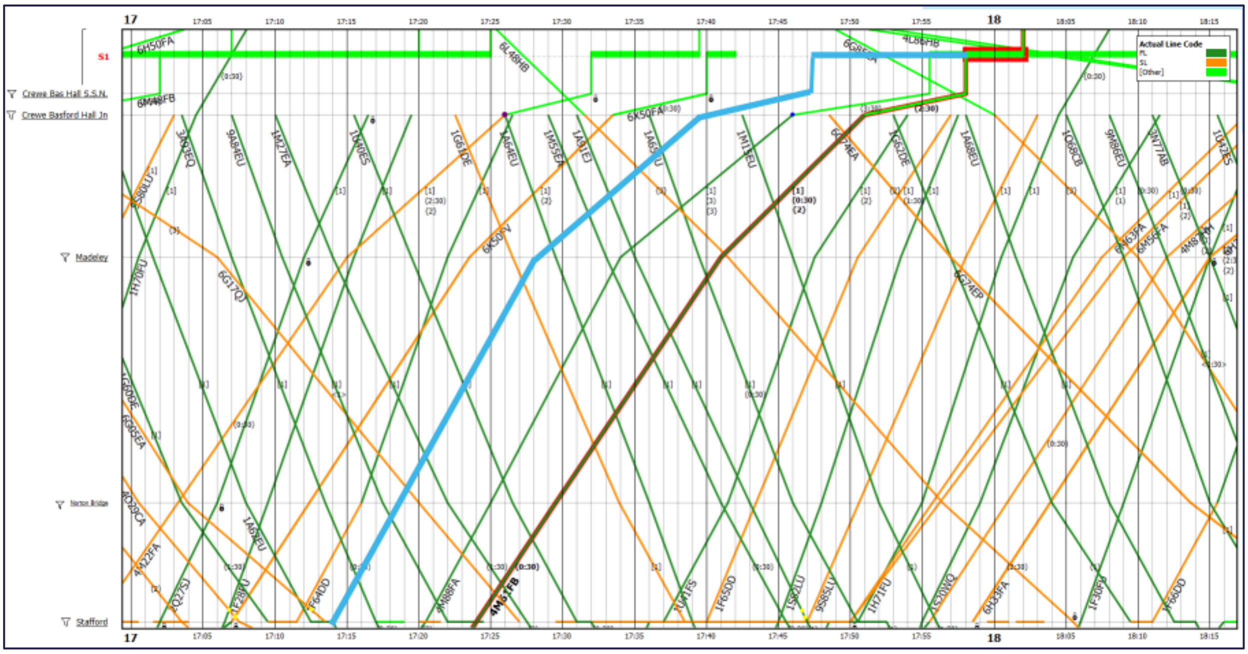
Due to existing passenger services, a faster timing on the SWML is not possible, as shown in Figure 28 below.

Figure 28 Conflicting earlier timing from Southampton



The train could possibly run 10 minutes later to Crewe if the existing period for crew change-over was reduced. Compare the brown line against the blue line in Figure 29 .

Figure 29 Opportunity to run 10 minutes later to Crewe



This potential benefit is not that substantive. The wider point is that, on this complex path, it is not possible to make timing changes without affecting the passenger service. That is of course perfectly acceptable, but it is beyond the scope of this limited timetable study.

6.2.4 Key findings from case study

The key findings from the case study were:

- Using the T1302 methodology, recalculated SRTs for a Class 66 save 5% on existing timings, while Class 70s are 11% faster.
- For the Class 66, 200 tonnes could be added to the train, and it would still stay within current timings.
- The modelled timings using the T1302 methodology align well with existing timings when a clear run is possible, providing further validation to the methodology.
- Current SRTs do not take account of prior pathing, for example, resulting in timings that are too fast through Reading West, leading to unrealistic timetabling
- While an overall reduction in timing is possible, beneficial retiming cannot be undertaken in the current timetable without altering passenger services.
- The key immediate benefit is the opportunity to run heavier trains within the existing timings.

6.3 Case study 2: Great Eastern Main Line (GEML)

6.3.1 Outcome of SRT modelling

Modelling was undertaken for the 4S88 service between Ipswich Storage Sidings and Lea Junction (London). This service currently operates with a Class 66 locomotive, hauling 1,600 tonnes. Recalculated SRTs with T1302 assumptions show a 6.1% reduction on a 78-minute journey time (Table 23). Furthermore, the modelling suggests that a 1,800-tonne train could still operate within the existing SRTs (3.6% faster).

Class 70 traction provides further benefit, with a 1,800-tonne train being 8% faster than existing SRTs (a bigger reduction than a Class 66 at 1,600 tonnes). Single-headed Class 90 locomotives offer a 19.7% reduction in journey time.

Table 23 Summary of modelled SRTs compared to current timings

	Reduction from 78 mins SRTs	Percentage reduction	Relative to Class 66 at 1600 tonnes
Class 66 (1,600 tonnes)	4 mins 57 secs	6.1%	-
Class 66 (1,800 tonnes)	2 mins 46 secs	3.6%	-2.5% (-1 minute)
Class 70 (1,600 tonnes)	7 mins 59 secs	10.2%	4.1% (3 minutes)

Class 70 (1,800 tonnes)	6 mins 16 secs	8%	1.9% (1.5 minute)
Class 90 (1,250 tonnes)	17 mins 20 secs	22.2%	16.1% (12.5 minutes)
Class 90 (1,600 tonnes)	15 mins 22 secs	19.7%	13.6% (10.5 minutes)

6.3.1.1 Comparison of 1,600 tonne timings

The 1,600 tonne T1302 timings (in green above) give a 5-minute time reduction for the Class 66 (6%). A Class 70 gives a further 3 minutes and the paired Class 90s an additional 10.5 minutes, a nearly 20% reduction in total running time. This shows the value of this different traction options.

6.3.1.2 Comparison with different timing weights

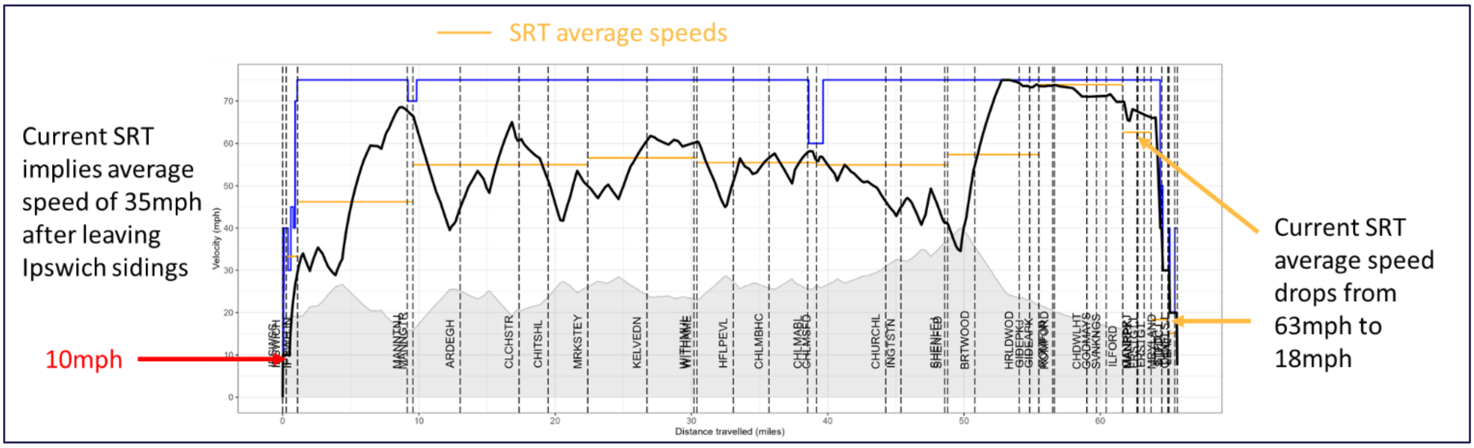
All of the heavier trains (in the salmon colour above) run well within the current SRT reduction. The timings indicate that the 66s could pull up to 2,000 tonnes in the same time allowance (25% increase) and the Class 70s could haul up to 2,400 tonnes, a 50% increase in the same timing allowance.

The lighter train (in blue above) runs at a typical 1,250-tonne weight for an intermodal train. Its time saving with double Class 90 traction is approaching 25%. This demonstrates that if a FOC is prepared to accept a lower average weight on their train for timing purposes and manage within that constraint, they may be able to path trains where they currently are unable to.

6.3.2 Investigation of local timing differences

Figure 30 compares the modelled speeds throughout the journey with the minimum average speed required to meet each section's current SRT. Where the implied average speed is greater than the modelled speed, this suggests that the train cannot meet that section's timing.

Figure 30 Comparison of modelled speeds against SRT-required average speeds for the GEML



While the total running time for this case study is faster than existing timings, there are specific sections where modelled times are slower (or significantly faster) than existing SRTs. These were therefore investigated at a local level, as discussed below.

Between Ipswich and Ipswich Halifax Junction, the modelling suggests significant increases to existing timings are required. This is because the current timings do not account for the train's length to clear the local speed restriction, and the consequential delay in the application of acceleration (10 mph local speed limit).

Between Forest Gate and Stratford, a significant reduction to current timings is possible. It was concluded that current SRTs may be pessimistically pathed for trains from Barking (i.e., from London Gateway/Tilbury/ Dagenham/Purfleet/HS1 at Ribble Lane), whereas most GE trains now run via Gospel Oak–Barking. Since 2018, with the completion of Gospel Oak–Barking electrification, and the ramp up of Elizabeth line operations, freight trains from Barking have been rerouted via South Tottenham (Gospel Oak–Barking line) rather than the North London Line between 06.00 and 23.30.

Table 24 shows the difference between the existing SRTs and modelled SRTs for a range of loads and traction combinations for the timing sections along the route. The cells highlighted in red indicate where the modelled SRTs are higher than the current ones, showing sections where the current timetable cannot be achieved.

Table 24 Sections where modelled SRTs are longer than current SRTs

Section Tiplocs	**Existing SRT**	IRT increase from SRT					
		CL. 66 1600t	CL. 66 1800t	CL. 70 1600t	CL. 70 1800t	CL. 90 1250t	CL. 90 1600t
IPSWSS - IPSWICH	2	0	0	0	0	0	0
IPSWICH - IPSWHJN	1.5	2	2	1.5	2	1.5	2
IPSWHJN - MANNGTR	11	0	1	-0.5	0	-3	-2
MANNGTR - CLCHSTR	8.5	-0.5	-0.5	-0.5	-0.5	-2	-2
CLCHSTR - MRKSTEY	5.5	-0.5	-0.5	-0.5	-0.5	-1.5	-1.5
MRKSTEY - WITHAME	8.5	-0.5	-0.5	-1.5	-1.5	-2	-2
WITHAME - CHLMSFD	9.5	-1	-0.5	-1.5	-1	-2.5	-2
CHLMSFD - SHENFLD	10.5	0	0.5	-0.5	-0.5	-2.5	-2.5
SHENFLD - GIDEAPK	7	-0.5	0	-0.5	-0.5	-1.5	-1.5
GIDEAPK - ILFORD	5	0	0	0	0	0	0
ILFORD - FRSTGTJ	1.5	0	-0.5	-0.5	0	0	0
FRSTGTJ - FRSTGT	0.5	0	0	0	0	0	0
FRSTGT - STFD	4	-2	-2	-2	-2	-2	-2
STFD - CHNELSJ	2	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
CHNELSJ - LEAJ	1	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
	78	-4	-2	-7.5	-5.5	-16.5	-14.5

On closer investigation, all the services were affected by the train length limit in the second section, which was not considered within existing SRTs. The Class 66 1,800-tonne train was still affected in the third section by this delayed acceleration. The Class 66 with 1,800 tonnes also requires an increase to the SRT between Chelmsford and Shenfield. This offsets the reduction found in the previous section.

To avoid arriving early within current timings in the Forest Gate to Stratford section, trains need to slow down significantly to an average of 18 mph down from averaging 63 mph in the previous section. This subsequently causes more issues, because trains are then travelling slower than the relevant line speed and so must accelerate at the following junction, thereby taking longer than planned to clear the junction. This is an example of how early running at key locations can result in an overall delay to the journey.

6.3.3 Timetable impact analysis

Timing comparison shows a single Class 90 can move 1,600 tonnes with the same Class 66 SRT allowance, with a 14-minute time saving. However, timing improvements may not be material due to junction constraints at either end. This was investigated through timetable analysis. It was concluded that there is an opportunity to step up this service, as there are similar paths down the GE and the NLL at 20-minute spacings.

To step up, the train needs:

- twice the train headway
- once to overtake
- once to be clear in front.

This is typically 6–8 minutes.

Because an opportunity to step up the service was found without affecting passenger trains, there may be an opportunity to do a mini 'freight-only' timetable recast for this route and improve other services.

Timetable opportunities were not found for Class 66-hauled services without affecting passenger trains.

6.3.4 Key findings from case study

When modelled using the T1302 methodology, the recalculated SRTs for a Class 66 on this route save 5 minutes (6%), while a single Class 90 gives a 19.7% reduction on present Class 66 timings. Furthermore, a Class 70 can pull 200 tonnes more and still be 8% faster than current Class 66 timings.

Some significant differences were found between modelled and current SRTs at specific locations. These were investigated in more detail, and it was found that:

- Current timings do not allow for complete train passage through 10 mph points at Ipswich.
- The entry speed around Forest Gate has been incorrectly considered.
- Routing has not been updated in London since opening of the Elizabeth line, and a pessimistic view has been taken.

Timetable analysis shows that service could be stepped up when using a Class 90 because of the significant time savings these locomotives can achieve.

6.4 Case study 3: Midland Main Line (MML)

6.4.1 Outcome of SRT modelling

The 6L36 service was modelled between Trent Jn and Radlett Jn, assuming a Class 66 locomotive hauling 2,400 tonnes and limited to 60 mph. The train runs via Corby before rejoining the MML at Kettering. The observed running is typically with 22 wagons, ~2,178 tonnes in practice (i.e., 99 tonnes per wagon, Q = 24.75 tonnes).

Table 25 Summary of modelled SRTs compared to current timings for the MML

	Reduction from 184 mins SRTs	Percentage reduction	Relative to Class 66 @ 2,178 tonnes
Class 66 (2,178 tonnes)	20 mins 29 secs	11.1%	-
Class 66 (2,376 tonnes)	14 mins 53 secs	8.0%	-3.1% (-5.5 minute)
Class 66 (2,574 tonnes)	9 mins 4 secs	4.9%	-6.2% (-11.5 minute)
Class 70 (2,574 tonnes)	18 mins 19 secs	10.0%	-1.1% (2 minutes)
Class 90 (2,376 tonnes)	35 mins 55 secs	19.5%	8.4% (15.5 minute)
2x Class 90 (2,376 tonnes)	52 mins 19 secs	28.4%	17.3% (32 minutes)

For the default Class 66 at 2,376 tonnes, the modelled times using T1302 assumptions show an 8% reduction on a 184-minute journey time (Table 25). Reducing the trailing load to 2,178 tonnes (to reflect real running) will reduce the journey time by a further 7 mins 36 secs (11.1% faster than existing SRTs).

By extension of this timing work, it can be seen that there is an opportunity to increase the trailing load to ~2,800 tonnes for a Class 66 and a Class 70 to 3,200 tonnes within the existing SRTs, a 50% increase.

The use of electric traction provides even greater benefits. A single Class 90 locomotive is over 10% faster than the Class 66 timing, and double-headed Class 90s are 20% better (nearly 30% than the existing SRTs).

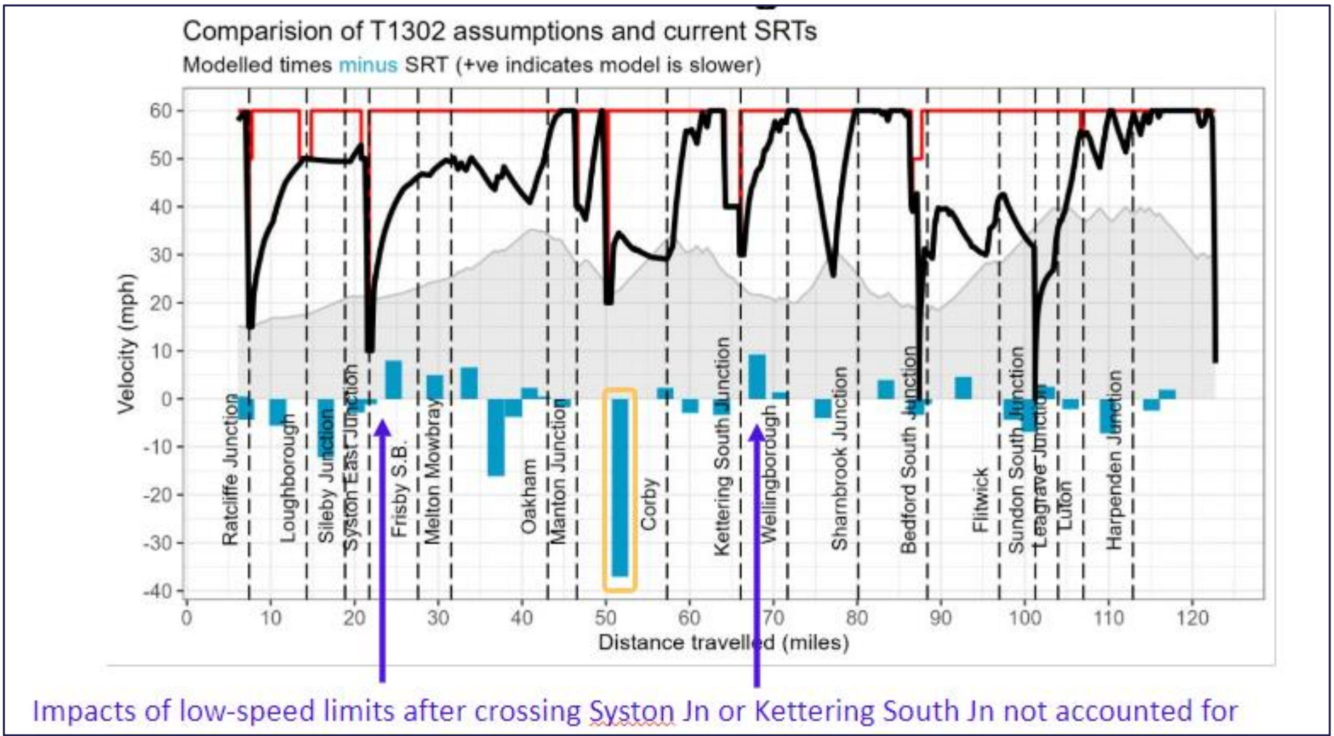
6.4.2 Investigation of local timing differences

Figure 31 below shows several things:

- route geography (shaded in the background)
- line speed (red line)
- modelled performance (black line)

- relative time lost or gained against SRTs (blue bars off the x-axis).

Figure 31 MML train performance



The modelled performance is better than the SRT allowance at the beginning of the run (blue bars below the x-axis), as the locomotive performs better than allowed for going up the gradient from Trent Junction. The first of two relative time losses due to line speed crossings occurs at Syston junction (the other is at Kettering South Junction). In these cases, the timing allowance does not allow sufficient time for the whole train to pass over the local speed restrictions. Acceleration is assumed as soon as the locomotive crosses the point work.

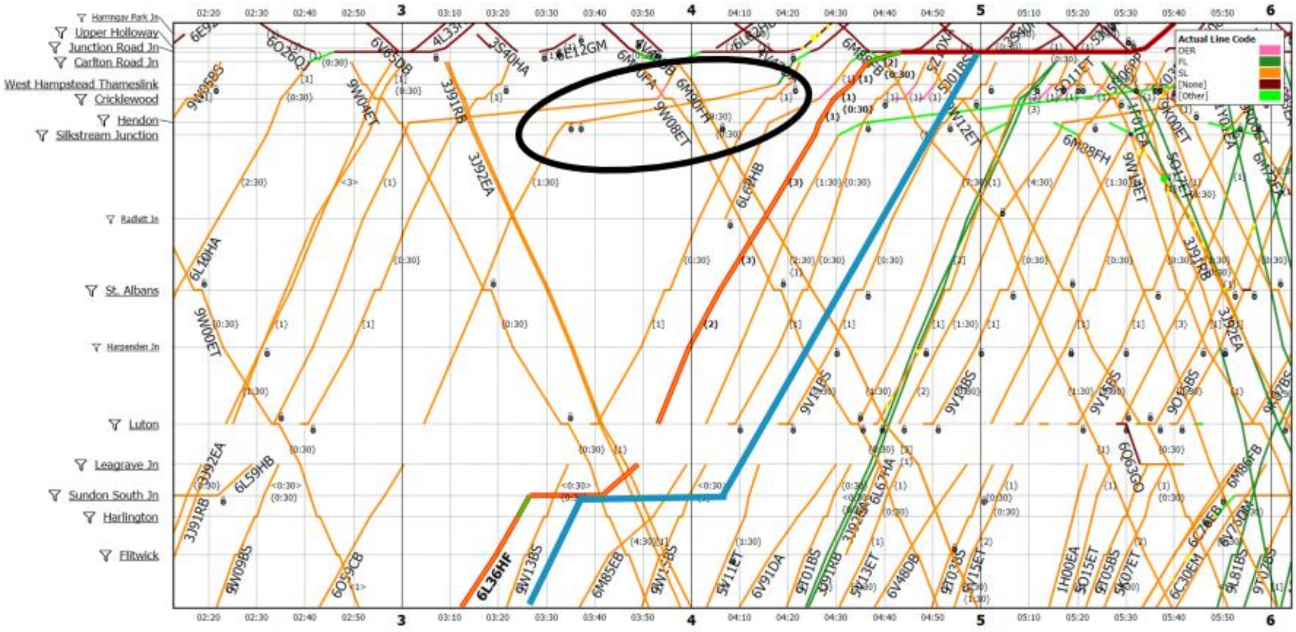
There is a 6-minute improvement going through Corby tunnel, and on investigation, it was apparent that a PSR applied in 2016 for tunnel refurbishment work has not been lifted. NR have flagged this SRT for review.

South of Glendon Jn (Kettering), there is excellent alignment between the proposed 'new' Class 66 2,400-tonne timings and actual running times of existing services, especially on the more challenging uphill sections, where timing calibrations are typically considered.

6.4.3 Timetable impact analysis

Generally, the restrictions due to the presence of passenger trains results in no acceleration or later running being possible, with one exception. The train graph (Figure 32) shows that a 20-minute earlier running is possible in the early morning. The presence of very slow running passenger trains earlier the day (shown by the black oval) preclude any earlier use of this opportunity.

Figure 32 MML train graph showing an early running opportunity



6.4.4 Key findings from the case study

The key findings are:

- The T1302 modelled timings are validated against existing run times.
- The existing SRT allowances can be shortened by 11% for Class 66 running at the same current running tonnage.
- The use of Class 70 or electric traction provides significant opportunity for faster running by up to 28%.
- The opportunity for this faster running is limited by the passenger service. However, these revised timings will allow new services to be easier to path, and should a local recast of the timetable occur, wider benefits could happen then.
- Train weight can be significantly improved within the existing SRT allowances, for example, by 50% if a Class 70 locomotive is used.
- There are inaccuracies within the existing timings. Some of these are to the detriment of freight running (for example, non-removal of the Corby tunnel TSR) and some are to the benefit (no consideration of train length going through junctions).

6.5 Case study 4: West Coast Main Line (WCML)

6.5.1 Outcome of SRT modelling

This case study considered the 4S88 service between Crewe Basford Hall and Coatbridge. This service currently operates with **two** Class 90 locomotives, hauling 1,250 tonnes (although SRTs are older ones that have been calculated for 2x Class 86 locomotives). Recalculated SRTs with T1302 assumptions show a 7.8% reduction on a 233.5-minute journey time. Our modelling suggests a 1,600-tonne train could operate within the existing SRTs (6.5% faster), and extrapolating this modelling suggests 2,400 tonnes could be hauled within the timing allowance.

Table 26 Time savings in modelled SRTS

	Reduction from 233.5mins SRTs	Percentage reduction	Relative to Class 66 @ 2178t
Class 90 (1,250 tonnes)	18 mins 10 secs	7.78%	-
Class 90 (1,600 tonnes)	15 mins 6 secs	6.47%	-1.3% (-5.5 minute)

6.5.2 Investigation of local timing differences

Generally, the modelled timings are very close to the observed timings, with the exception of the impact of entering and exiting sidings. Here the SRTs do not consider the acceleration/slowing of the train and so more time is required. There is a very interesting comparison between the timing differences of different traction; see Figure 33 below.

Figure 33 Performance of different locomotives over Shap

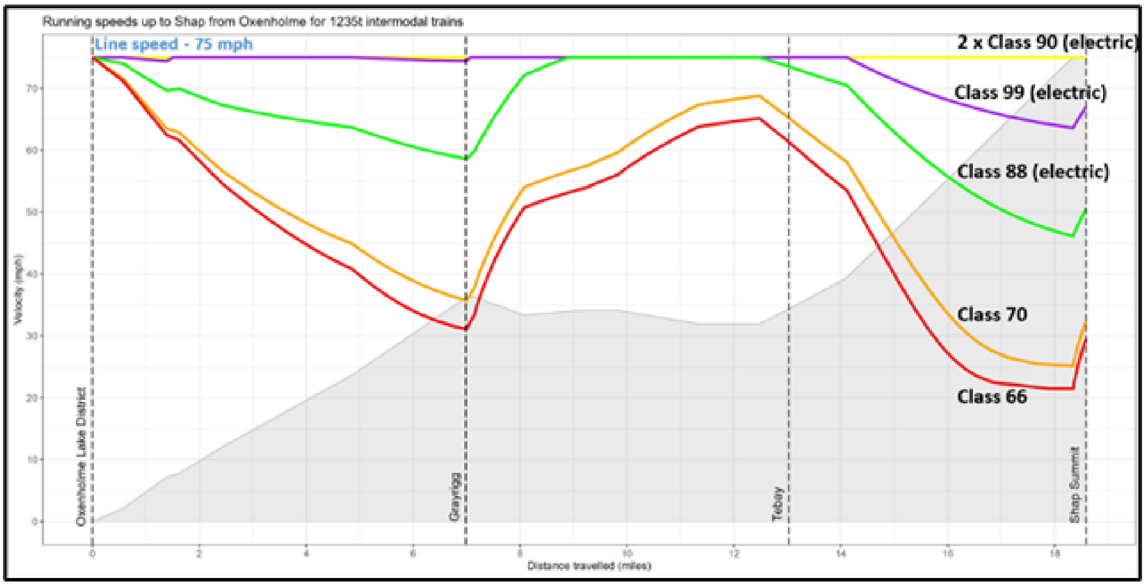


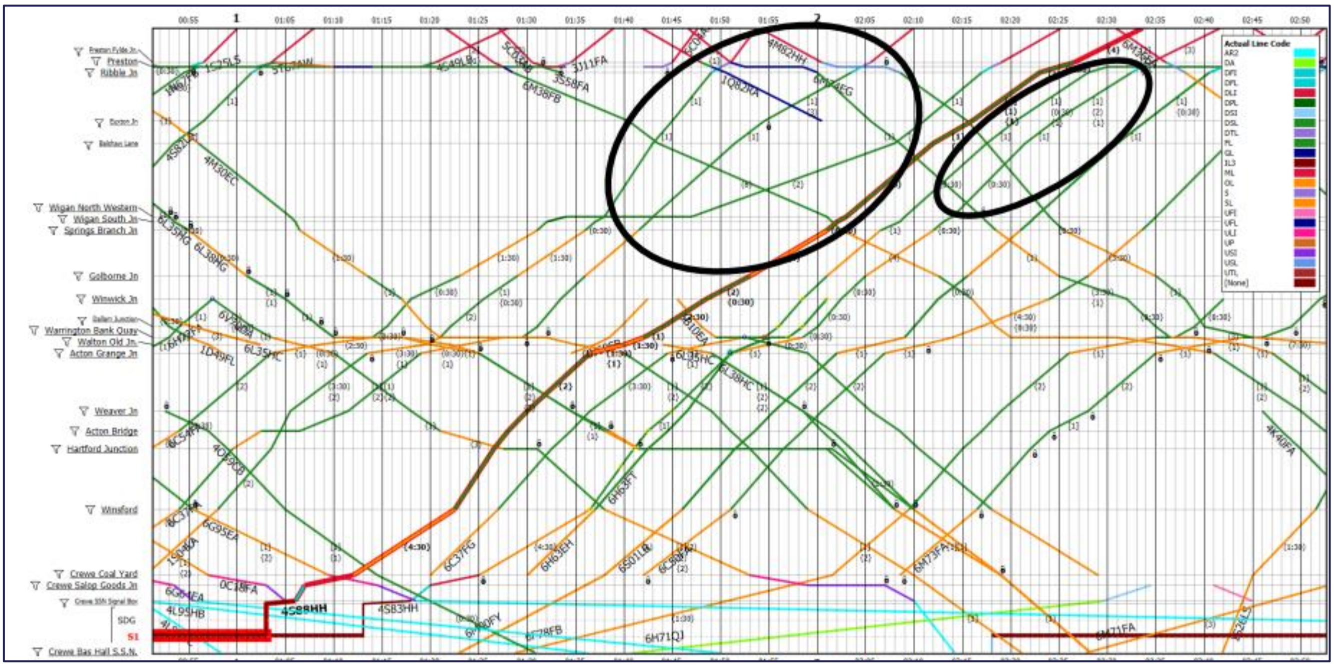
Figure 33 shows the dramatic difference in high-speed tractive effort between electric and diesel locomotives. Both the Class 66 and Class 70 locomotives decelerate significantly over Grayrigg and Shap, whereas the paired Class 90s and the Class 99 barely slow down.

Specifically, significant differences were found in the calculation of timings for the pairs of Class 90 locomotives with different assumptions around the benefit of pairing being used in different places on the WCML. Through our engagement with NE, this situation has been brought to their attention.

6.5.3 Timetable impact analysis

The 4S88 service is constrained by other freight trains as it travels into Scotland (passenger services have ceased for the night). Figure 34 below shows the train graph.

Figure 34 Overnight freight opportunities on the WCML



4S88 is shown in red and is constrained by two other freight trains highlighted by the black ovals. However, the same logic that enables 4S88 to accelerate can be applied to these trains too, giving all freight running at this time the opportunity to accelerate. A mini 'freight-only' timetable recast could therefore enable several overnight trains on the WCML to accelerate.

6.5.4 Key findings from the case study

The key findings from this case study are:

- The T1302 modelled timings are validated against existing run times.
- The existing SRT allowances can be shortened by 8% for Class 66 running at the same current running tonnage.
- Electric traction has significant advantages over this route.

- The opportunity for this faster running is limited by the passenger service. However, an opportunity exists for an overnight freight-only timetable recast, which could enable several trains to accelerate.
- SRT allowances for trains entering or exiting sidings are incorrect.

6.6 Case study 5: West London Line (WLL)

6.6.1 Outcome of SRT modelling

Initially, this case study just considered the WLL from Clapham Junction to Willesden, but it was decided to extend the scope to consider 6D34 service between Hither Green and Willesden South West Sidings. This service assumes a Class 66 locomotive, hauling 2,000 tonnes, limited to 60 mph.

Table 27 Time savings from modelled SRTs

	Reduction from 37.5 mins SRTs	Percentage reduction	Relative to Class 66 @ 2,000 tonnes
Class 66 (2,000 tonnes)	1 mins 50 secs	4.9%	-
Class 66 (2,200 tonnes)	24 secs	1.1%	-3.1% (-1.5 minute)
Class 70 (2,400 tonnes)	1 mins 15 secs	3.3%	-1.6% (0.5 minutes)
Class 70 (2,600 tonnes)	43 secs	0.8%	-4.1% (1 minute)
Class 90 (2,000 tonnes)	2 mins 38 secs	7.0%	3.1% (1 minutes)
2x Class 90 (2,000 tonnes)	4 mins 57 secs	13.2%	8.3% (3 minutes)

The base case study (Table 27) shows that the Class 66 can achieve a 5% reduction across the short 37.5-minute journey time journey time. Use of a pair of Class 90s would more than double this improvement.

There is opportunity to increase the load to ~2,200 tonnes for a Class 66 and around 2,600 tonnes for a Class 70 within the existing SRT allowances.

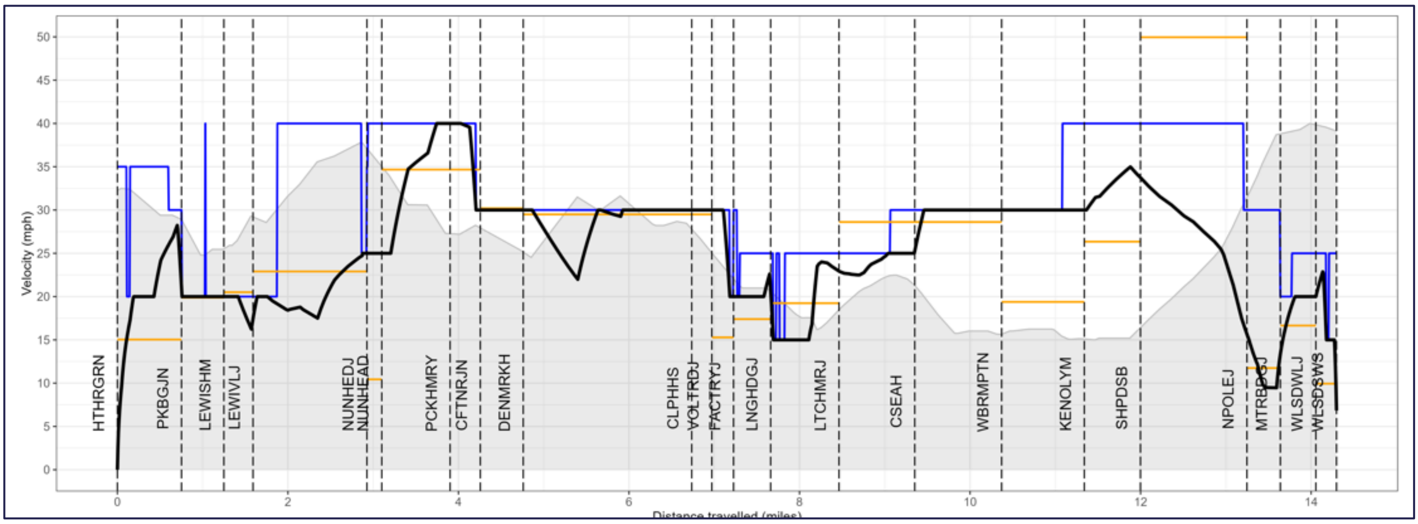
6.6.2 Investigation of local timing differences

Figure 35 below shows several things:

- route geography (shaded in the background)
- line speed (blue line)

- modelled performance
- average speed through the section to meet the SRT requirements.

Figure 35 Modelled speed, line speed, and required minimum average speed, Hither Green to Willesden

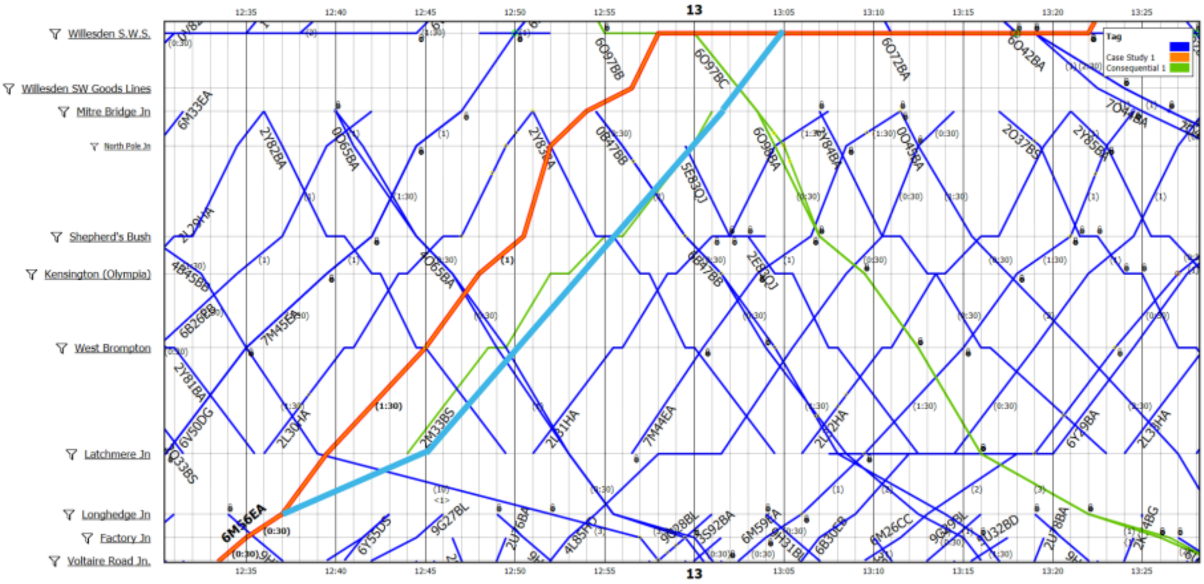


Travelling from Hither Green through Nunhead, Latchmere Junction, and up to West Brompton (Mile 10.5 on the chart), the average speed and modelled speed show an excellent correlation. Through Kensington and Shepherd's Bush, the average speed has been reduced, and our analysis suggests that this is to fit in with the existing passenger timetable, which has stops at several closely spaced stations on this route and therefore a low average speed. Beyond Shepherd's Bush to North Pole Junction, the required average speed to meet the SRT is 50 mph, which is beyond the maximum line speed (40 mph) for a freight train on this section (the '2/3^{rds} rule' applies here), and the train is simultaneously going up a considerable gradient. From Mile 11 to Mile 13, the average speed changes from 20 mph to 50 mph and then back to 10 mph, which is not practically possible.

6.6.3 Timetable impact analysis

The absolute changes in time are relatively small due to the short distance being analysed. However, the analysis identified an opportunity to run 20 minutes earlier if another service is slightly modified (see the train graph in Figure 36 below). This opportunity is possible mainly through a reduction in the time allowances moving through Longhedge Junction, rather than the time savings identified through this research.

Figure 36 WLL train graph



6.6.4 Key findings from the case study

The key findings from this case study are:

- The T1302 modelled timings are validated against existing run times.
- The existing SRT allowances can be shortened by 5% for Class 66 running at the same current running tonnage.
- The trailing load can be increased by 200 tonnes for a Class 66 and 600 tonnes for a Class 70 within the same timing allowance.
- The SRTs seem in places to be influenced by the passenger timings and in other places to require running at above the allowable speed limit. These are quite short sections, and some 'averaging' may have occurred historically to fit observed performance around the passenger trains into the timetable.

6.7 Summary of case study findings

The principal findings of the research are:

- Timings can be improved in all circumstances.
- Heavier trains can be run within the existing timings in all circumstances.
- Electric timings can be significantly improved, and there has been an inconsistent historic approach across different routes.
- Every analysed route has some incorrect infrastructure and/or routing assumptions, for example, existing timings are not updated as infrastructure or routing changes (such as the removal of PSRs).
- Beneficial retiming is generally not possible due to constraining passenger traffic, but sometimes 'stepping up' in front of the preceding passenger train is possible.

- In certain locations and times, a mini freight timing recast should be of value. For example, on the WCML in the early morning, the line is freight only. Therefore, there is potential for improving 'all' freight timings rather than just one, as that will probably conflict with the timings of an 'unimproved' service.

7 Understanding the benefits of an improved SRT calculation methodology

7.1 Introduction

There are four primary benefits that flow from the work undertaken for this project:

- enabling existing train weights to travel faster
- enabling heavier trains to travel within the existing timings
- supporting market growth
- enabling more accurate pathing to be established.

There are also some subsidiary benefits and opportunities:

- Electric traction has significant advantages over diesel traction when rolling tractive effort is the governing factor.
- Empty wagons have a significant aerodynamic drag at speed, so performance and timings could be improved if they were covered.
- Existing timing issues have been identified.

7.2 Primary benefits

7.2.1 Enabling existing trains to run faster, or heavier trains within the same timings

This brings three benefits itself:

- It reduces the unit cost of the journey.
- It decreases the journey time, improving the resilience of the path to external delay, reducing consequential delay to other services, and also reducing unit costs.
- It improves asset utilisation.

7.2.1.1 Reducing the unit cost of the journey

Enabling long trains within the same path brings considerable cost savings. The 'fixed cost' of the train (provision of locomotive, labour, and corporate overhead) remains unchanged, with the variable costs of wagon provision, track access cost, and fuel increasing (although fuel will increase less than proportionally). Assuming a roughly 50/50 split of fixed and variable cost a 10% increase in payload would result in no increase in fixed cost and a 10% increase in variable cost, leading to a total increase in haulage cost of 5%. As revenue is directly related to payload, extending the train leads to a 10% increase in revenue and a 5% increase in cost, or a 5% saving overall. This is significant. With the average cost of train haulage being around £6,000 for a return flow, the saving is £300/train, every day, equalling £78,000 train/year.

Running the same length train in a quicker time saves on variable costs rather than fixed costs. So, if the running time is decreased by 10%, less fuel and labour time is required, leading to an estimated 3% reduction in haulage costs.

7.2.1.2 Improving resilience and reducing delay costs

In the future, this research will enable more accurate timings and therefore more trains running on time. A reduction in late running trains will reduce the amount of conflict they have with other trains on the network. This will improve the overall resilience of the network, as the number of conflicting events reduces, and reduce the number of trains attracting delay compensation events.

Our research shows that this delay cost can be significant, with one train picking up £1.5m of attributed cost per year (this does not automatically mean that the FOC will pay £1.5m of penalty, as it operates with an agreed level of delay each period before compensation occurs, and any compensation liable is mitigated by the performance of NR and the other train operators). However, this is clearly still an issue, and enabling trains to run ‘right time’ more often will only reduce the compensation a FOC pays and may move it to a position where it actually receives compensation.

It will also reduce the incidence of early running trains. While it is always welcome if a train arrives early at its destination, early running can create two problems:

- The train is stopped because it is running too early and will, if not slowed down, conflict with another train either in front of it (for example, catch up with a stopping local passenger train) or when it tries to cross another line at a junction. Each time the train is stopped, additional fuel is required to get the train up to line speed, which has been estimated at £60 at each occurrence.
- If the train is stopped at a junction because it is early, when the route is cleared, the train has to start from a stop. Therefore, the speed of the train through the junction is much less than it would have been if the train had not stopped and was able to proceed the junction in continuous running. Therefore, when stopped at a junction, a train often goes from being early (hence the stop) to late (due to increased running time from the junction).

7.2.1.3 Improving asset utilisation

<u>Out and back in a day</u>

Asset utilisation can be improved by increasing the number of trains that can go ‘out and back’ in day (long-distance trains). Taking the example of an intermodal train, which ideally takes 4 hours to unload and reload, journey times of over 8 hours prevent the train from ‘going out and back’ in a day, as two 8-hour journeys and two 4-hour loading cycles equals 24 hours.

Pathing from Felixstowe to Manchester usually takes 9 hours, so, unless the terminal time can be reduced to 3 hours, this prevents the same set of wagons returning on the same day. Usually, a second set of wagons has to be introduced so that they can be preloaded and the locomotive turned round very quickly at one terminal. This is known as ‘slip working’, where the locomotive ‘slips’ from one set of wagons to the next to reduce terminal time.

Slip working is more expensive, as it requires two sets of wagons to enable a standardised return daily working from point A to point B, increasing haulages costs by around 15%. By speeding the train up using the improved timings demonstrated within this report, Felixstowe–Manchester becomes more achievable on an out-and-back basis. This acceleration of the train expands the 'out-and-back' geographical horizon so that, for example, Tees Port becomes in range of Felixstowe.

This benefit extends to all 'long-distance' trains (> 270 miles each way). For example, the movement of lime from Hardendale Quarry (Shap) to Port Talbot (Margam) takes 9 hours to do the 270-mile journey. Taking into consideration network closures, shunting, loading, and unloading, this cannot be accommodated in 1 day, so the rotation is booked to take 2 days. Reducing the journey time to 8 hours (average journey time increases from 30 mph to 34 mph) gives an extra 2 hours in the daily timetable, enabling this train to potentially run out and back in the day.

If other work can be found for the wagons within the week so they remain fully utilised, this could reduce haulage costs by 40%, saving around £3/tonne, or £300,000 if 100,000 tonnes of material is moved each year.

<u>Two rotations a day from the same set of wagons</u>

Kellingley colliery used to be 3 miles from Eggborough power station and 9 miles from Drax power station. A locomotive and set of wagons could rotate between these locations over six times a day, making the cost of rail haulage very low.

Running from Mountsorrel quarry (just north of Loughborough) to Radlett aggregate terminal takes 4 hours. The train runs with quick discharge hoppers that move through a bottom discharge unit at walking pace, so a terminal time of only 2 hours is required for discharge, and slightly longer for loading. Therefore, a return journey on this flow is on the cusp of being achieved within 12 hours, notionally enabling two rotations a day with the train, subject to pathing.

These examples demonstrate the opportunity for multiple return workings where timings and demand are aligned.

The Mountsorrel–Radlett example cannot be achieved with confidence, as any slight perturbation in the operation of the train, terminal equipment, or the wider rail network would prevent a 2-hour rotation. However, our timings show that this journey time could potentially be reduced to 3.5 hours, putting 2 hours back into the available time of the four journeys, so making the timings much more achievable and resilient. If other work can be found for the wagons within the week, so they remain fully utilised, this would decrease the cost rail haulage by around 35%, as the locomotive and wagon assets are having their utilisation doubled, saving possibly £1 per tonne, and £250,000 year if 240,000 tonnes of material is moved.

Generally, to achieve this benefit, the following is needed:

- The distance between origin and destination needs to be no more than 120 miles.
- Loading and unloading needs to be less than 2 hours, for example, silo loading and bottom discharge unit unloading.
- Sufficient volume needs to be available to keep the wagons fully utilised.

This could be achieved from the larger Midlands quarries (for example), where sufficient volume exists, and haulage distances are shorter into the South East.

7.2.2 Supporting market growth

The above measures lead to a reduction in the unit rate of rail haulage. They also lead to a reduction in the average emissions of rail freight through a combination of faster running and improved train weight. Both factors improve rail's competitive modal challenge to road transport and should therefore lead to market growth.

7.2.3 The operational benefits of more accurate timing

The report highlights one headcode that attracts over £1.5m of delay attribution costs per year. This headcode is clearly running out of path regularly and conflicting with a number of high value services. The information developed within this report enables the detailed timings and the logic behind those timings to be reviewed to minimise this delay. Just a 10% improvement would bring a considerable financial benefit, as well ensuring that the train ran to time more frequently.

More accurate pathing has a benefit both to the FOCs (as detailed above) and also to NR. The Freight Delivery Metric (FDM) is a key benchmark for NR, measuring the percentage of trains arriving at their destination with 15 minutes or less of time delay attributable to either NR or another operator. Having more accurate timings will reduce conflicts and also enable more resilient services through an increase in recovery time, all of which should lead to improvements in the FDM.

7.3 Subsidiary benefits

7.3.1 Increased use of electric traction

This report has clearly articulated the significant improvements in timing and trailing load that can be achieved using electric traction. This information could be used to support the case for increasing electrification for freight, particularly in shorter routes such as around the Willesden South West sidings, access to London Gateway Port/Immingham, or down the Felixstowe branch line.

The report demonstrates that electric traction can improve end-to-end timings and through this offer additional significant environmental benefits.

The report also highlights the inconsistencies taken in evaluating the available power available, not only from the locomotive itself but also when used in pairs. This research has highlighted these issues and defined an appropriate way of evaluating this in the future.

7.3.2 Aerodynamic loading on empty wagons at speed

When empty wagons—particularly box, hopper, and car wagons—travel at speed, they have a significant aerodynamic drag. It can be considered as the locomotive pulling a number of air brakes behind it; vortices develop in the wagons which require additional power to overcome. Differences in the C coefficient (K_{WMR5}) and the wagon for different types of wagon can be seen in Table 28. These differences will impact the amount of aerodynamic loading.

Table 28 Differences in values of the C coefficient (K_{WMR5}), which includes aerodynamic loading, and wagon frontal area (A_W) for different wagon types

Wagon type	K_{WMR5} 'C' coefficient [N/tonne]	A_W wagon frontal area [m^2]	Notes
Intermodal wagon - 60' platform (FEA) loaded with 9'6''	22.241	9.443	Platform height 980 mm
Intermodal wagon - 60' platform (FEA) loaded with 8'6''	22.241	8.699	Platform height 980 mm
Intermodal wagon - 60' platform (FEA) empty	22.241	2.391	Platform height 980 mm
Aggregate box wagon (loaded)	18.683	8.361	
Aggregate box wagon (empty)	53.379	8.361	
Aggregate hopper wagon (loaded)	22.51	8.361	
Aggregate hopper wagon (empty)	58.05	8.361	
Cement tank wagon (loaded)	13.56	7.89	Loaded and empty wagon values are identical
Cement tank wagon (empty)	13.56	7.89	Loaded and empty wagon values are identical
Petroleum tank wagon (loaded)	24.465	7.89	Loaded and empty wagon values are identical
Petroleum tank wagon (empty)	24.465	7.89	Loaded and empty wagon values are identical
Covered steel coil wagon (loaded)	16.0	9.13	Loaded and empty wagon values are identical
Covered steel coil wagon (empty)	16.0	9.13	Loaded and empty wagon values are identical

For box wagons, the C coefficient value increases from 18.7 to 53.4 (a threefold increase). For aggregate hoppers, it increases from 22.5 to 58.0 (a 2.6-times increase). This is so significant that an empty box wagon travelling at 40 mph requires the same amount of power as a loaded wagon moving at the same speed, i.e., the aerodynamic load is equivalent to the payload load. This is demonstrated in the chart Figure 25 earlier in the report, which shows that the loaded and unloaded lines intersect at 40 mph, demonstrating load equivalence.

This develops two opportunities:

- covering wagons to reduce aerodynamic drag
- differential wagon specific SRTs for empty wagons.

7.3.2.1 Wagon-specific SRTs

As wagons have different aerodynamic profiles, their load profile at speed varies considerably. Therefore, an empty intermodal train will run faster through the network than an empty box wagon, so the SRT for a 400-tonne (empty) intermodal train will be significantly reduced compared with the required SRT for a 400-tonne (empty) box wagon train.

This creates an opportunity to develop wagon-specific SRTs, which will enable low aerodynamic vehicles to travel faster when unloaded.

7.4 Identification of existing timing issues

On every route the report has analysed, historic issues with the timing logic have been identified. This has brought some immediate benefit to the industry, for example, NR are removing the 6-minute restriction in Corby tunnel linked to the 2016 possession work.

7.5 Implementation opportunity: Mini freight-only timetable recast

When undertaking the case studies, significant opportunities for improvement were not possible due to conflicts with the existing timetabled trains.

The full beneficial effect of improving the freight timings may not therefore be fully realised until a major timetable recast is undertaken. However, this research has now updated the core underlying information so that revised SRTs can be used when this opportunity becomes available in the future.

In the interim, significant improvements may occur in areas or times when there is only significant freight activity. Overnight/early morning on the WCML is such an opportunity, as that at this time, freight trains are often only constrained by the presence of other freight trains, rather than passenger trains. By undertaking a mini-freight timetabling recast, the timings of multiple freight trains could be improved.

7.6 Financial quantification of the benefits

The financial quantification of the benefits identified is difficult to undertake, as the value per intervention is difficult to quantify, and the number of interventions per benefit type is also difficult to quantify. Table 29 summarises what these benefits could be.

Table 29 Quantification of benefits

Item	Benefit	Effect	Train benefit	Market benefit
1	Enabling existing train weights to travel faster	Reduction in train variable costs, improved asset utilisation	Faster – 3% saving of haulage cost, say £200/train (£6K/train price) Asset utilisation = £250K/train (6.2.1)	5% of 1,000 trains accelerated = £3m pa (300 days) 8 services intensified = £2m pa benefit
2	Enabling heavier trains to travel within the existing timings	Reduction in the unit cost of haulage	£78K/train/year (6.2.1.1)	5% of 1,000 trains/day = £3.9m pa
3	Supporting market growth	Increase turnover and margin		5% growth of an £800m market with a 5% margin = £2m pa of value
4	Enabling more accurate pathing to be established	Reduction in TDA and fuel costs	Save £100 on TDA, = £50 saving on actual cost, plus £50 reduction in fuel = £100/train	Applied to 5% of 1,000 trains for 300 days = £1.5m pa
5	Electric traction has significant advantages over diesel traction when RTE is the governing factor	As items 1 and 2		2% of 1,000 trains accelerated = £1.2m pa (300 days)
6	Improving empty wagons timings	As item 1		2% of 1,000 trains accelerated = £1.2m pa (300 days)
7	Identification of existing timing issues	As item 1		2% of 1,000 trains accelerated = £1.2m pa (300 days)
			Total benefit	**£16m pa**

8 Key learnings and recommendations

8.1 Learnings

This report has provided the engineering background to enable longer, heavier, faster, and more accurately timed freight trains by building on the T1302 knowledge base and demonstrating its value in five different case studies.

The principal findings of the research are:

Operational

1. Overall timings can be improved in all circumstances. Generally, times can be reduced by at least 5% for a Class 66 locomotive and 15% for a Class 70 locomotive. Within this overall headline saving, there are situations where local timings are worse, for instance, when they do not currently allow for the whole train length to pass through a speed restriction before accelerating.
2. Heavier trains can be run within the existing timings in virtually all circumstances over longer sections of route, generally at least 10% more for a Class 66.
3. Electric timings can be significantly improved. Our work demonstrates that electric traction has significant advantages in power availability at line speed, but existing timings do not recognise this.
4. Historically, there has been an inconsistent approach across different routes to determining the appropriate available tractive effort of electric locomotives. Many of the current timings are based on the use of Class 86 locomotives, which started working in 1966, and this is when the timings were produced. In particular, the approach to using double-headed Class 90 vehicles is not consistent across the WCML.
5. Every case study has identified some incorrect infrastructure and/or routing assumptions, for example, existing timings that were not updated following infrastructure or routing changes (for example, the removal of PSRs).
6. Beneficial retiming is generally not possible due to constraining passenger traffic, but sometimes ‘stepping up’ in front of the preceding passenger train is possible.
7. In certain locations and times, a mini freight timing recast should be of value. For example, on the WCML in the early morning, the line is freight only. Therefore, there is potential for improving ‘all’ freight timings, rather than just one in isolation, which could conflict with the timings of an ‘unimproved’ service.
8. There is significant opportunity for reducing the delay minutes for each train by using the ‘right information’. This enables the train to be always within its pathing allowance and prevents early running, which can result in repeated braking and delays at junctions.

Technical

9. The ‘A’, ‘B’, and ‘C’ parameters required to determine the wagon resistances have been updated and have been calculated for a number of different wagon types, as shown in Table 30 below.

Table 30 Wagon parameters for different wagon types

Wagon type	A_W wagon frontal area [m²]	K_{WMR3} 'B' coefficient [N/tonne]	K_{WMR5} 'C' coefficient [N/tonne]
Intermodal wagon - 60' platform (FEA) loaded with 9'6''	9.443	0.147	22.241
Intermodal wagon - 60' platform (FEA) loaded with 8'6''	8.699*	0.147*	22.241*
Intermodal wagon - 60' platform (FEA) empty	2.391	0.147	22.241
Aggregate box wagon (loaded)	8.361	0.085	18.683
Aggregate box wagon (empty)	8.361	0.085	53.379
Aggregate hopper wagon (loaded)	8.361	0.128	22.51
Aggregate hopper wagon (empty)	8.361	0.128	58.05
Cement tank wagon (loaded)	7.89	0.106	13.56
Cement tank wagon (empty)	7.89	0.106	13.56
Petroleum tank wagon (loaded)	7.89	0.128	24.465
Petroleum tank wagon (empty)	7.89	0.128	24.465
Covered steel coil wagon (loaded)	9.13	0.078	16.0
Covered steel coil wagon (empty)	9.13	0.078	16.0

* When developing intermodal timings for a flow yet to commence, 9'6'' timings should be used unless there is certainty that only 8'6'' containers will be used (as on some current waste flows).

10. Two load cases should be considered:

- starting tractive (STE): low internal resistances (low speed), high acceleration
- rolling tractive effort (RTE): high internal resistances (high speed), no acceleration (at line speed).

The old '1-hour continuous tractive effort' rating is no longer relevant and can be discounted due to an increased understanding of train loads and improvements in locomotive capability.

11. The forces applied to a train can be simplified as:

Total train resistance = sum of locomotive and wagon loads (gravity + acceleration + mechanical + curving)

Gravity

$$R_G = g \times \frac{1{,}000}{X} \quad [N/tonne]$$

Acceleration

$$R_{AS} = 1{,}000 \times a_s \quad [N/tonne]$$

where:

a_s = train acceleration at starting (m/s²), suggested value = 0.025 m/s.

Vehicle	Load case	Mechanical	Curving
6 axle locomotive	Starting	$(R_{LMS})[N] = 65.6423 \times \text{locomotive mass [tonnes]}$	$R_{LC(3-axle\ steerable)} = \frac{111{,}500}{(track\ radius\ [m])^2} - \frac{400}{track\ radius\ [m]} + 0.3 \quad [N/tonne]$
	Rolling	$R_{LMR\ 6axle\ leading} = K_{LMR4} \times V^2 + K_{LMR5} \times V + K_{LMR6}$ [N /tonne]	$R_{LCR(3\ axle\ steerable)} = \frac{K_{LCR2}}{(track\ radius\ [m])^2} - \frac{K_{LCR3}}{track\ radius\ [m]} + K_{WCR4} \quad [N/tonne]$
4 axle wagon	Starting	$R_{WMS} = 1.4 \times \left(4.0 + \frac{100}{Q}\right) [N/tonne]$	$R_{WCS} = \frac{1.833 \times K_{WCS1}}{R} \quad [N/tonne]$
	Rolling	$R_{WMR} = 4.0 + \frac{100}{Q} + K_{WMR3} \times V + \frac{K_{WMR5} \times A_w \times V^2}{1024.081 \times M_w} \quad [N/tonne]$	$R_{WCR} = \frac{K_{WCR1}}{R}$

Gravity and accelerative forces have the same derivation in all circumstances.

Rolling mechanical forces have the 'Davis equation' format of a quadratic equation with A, B, and C coefficients, where B and C relate to velocity respectively linearly or with a squared relationship:

$$Mechanical\ Resistance = A + B \times v + C \times v^2, \text{ where v = the train's speed}$$

For starting mechanical forces, the velocity is zero (starting from a stop) and so the forces are simplified.

Curving forces do not have a direct relationship to speed, only to the curvature of the bend the train is going through.

12. Historically, five different approaches have been taken to define locomotive starting and rolling resistances. The approach detailed above consolidates these into one approach, and following figures should be taken for A, B, and C coefficients for modern locomotive types.

13. The locomotive resistance figures are generally in line with previous guidance, except for the Class 66 locomotive, where the 'first principles' approach detailed here leads to a lower available tractive effort. In reality, this is offset through new reductions in the wagon loading coefficients. Starting resistances should be considered for all locomotive classes at 15 lb/Ton (65.6423 N/tonne) or OEM recommended figures if available.

14. Wagon-specific coefficients have been prepared for the commonly used wagons on the routes analysed by the case studies. This enables:

- more accurate timings to be developed
- the possibility for wagon-specific SRTs to be developed to reflect the varying levels of internal resistance between the different types of vehicle.

Detailed technical recommendations based on section 4

Locomotive TE

The recommendations are to:

15. TE assumptions need to be clearly outlined and applied consistently across the network.
16. The existing conservative 95% TE assumption is not needed for newer locomotive types.
    - OEMs are already including a conservative assumption on TE in the TE datasets that they supply.
17. TE impacts of new wheel sets are a conservative assumption and should be retained as the default.
18. The quality of locomotive TE data sets can be improved, as better data that is now available for use will improve the quality and accuracy of SRT calculations.
    - For the vast majority of locomotive types, TE curve data is now at 1 mph increments in the T1302 report and its associated spreadsheet and with additional TE data sets added as part of the T1301 project
    - For the residual locomotive types where it has not been possible to obtain and address TE data quality issues as part of this project, they should be prioritised for future data improvement, e.g.:
        - Class 57
        - Class 67
        - Class 73 (DC operation)
        - Class 90 (further improvement beyond what has been achieved in this project)
        - Class 92 (DC operation).
19. Double-heading is not treated consistently and does not reflect current working practices. Treatment of double-heading should be modified to match current working practices.

Locomotive starting resistance

The recommendations are to:

20. Apply locomotive starting resistance in all cases—use 15 lb/Ton (65.6423 N/tonne).
21. Potentially use OEM data where available. This will likely be lower than the above value for newer locomotive types, which could potentially be in the 35–50N/tonne range. This will require some engagement with OEM, who may not want to provide data

Locomotive rolling resistance

The recommendations are to:

22. Use the T1302 approach that produces smooth curves as the default approach, and use documented OEM or testing data where available (T1302 recommendation).
23. Either: Accept OEM data without evidence if the resistance values are up to 15% less than the relevant T1302 resistance values calculated for that locomotive.
24. Or: Accept with evidence lower OEM locomotive rolling resistance value if the values are more than 15% lower than the T1302 resistance values calculated for that locomotive.
25. Use a lower resistance for the second locomotive when double-heading. However, there is unlikely to be OEM data for non-leading locomotives, which effectively means using the T1302 approach for double-heading.

26. A mechanism is needed not to use unrealistically low data supplied by OEMs (to avoid repeating the Class 66 issue discussed earlier in this section).
27. Use realistic resistances for Class 66.

Wagon resistances

The recommendations are to:

28. Ideally match total trailing weight to existing SRT trailing weights
29. It is important to accurately capture the length of modelled services so that both the resistance and the time take to pass speed restrictions is realistic.
30. For intermodal wagons: Retain existing 75% loaded 25% empty wagon approach, with T1302 equations, but using slightly lower axle loads.
31. For intermodal wagons: Retain a balance between high Q and high number of wagons so that train lengths are accurately modelled.
32. Specific routing needs to be consistently and comprehensively taken into account.

Calculation of additional locomotive and trailing load combinations for SRTs on relevant routes

The recommendations are to:

33. Calculating Class 70 SRTs at 1,600 and 1,800 tonnes is worthwhile on routes where they are frequently used.
34. Calculating accurate double-headed Class 90 SRTs at 1,600 tonnes is worthwhile on routes where they are frequently used.

<u>Benefits</u>

35. There are four primary benefits that flow from the work we have described:
    - enabling trains to travel faster at existing weights
    - enabling heavier trains to travel within the existing timings
    - supporting market growth
    - enabling more accurate pathing to be established.

There are also some subsidiary benefits and opportunities that we have established:

- Electric traction has significant advantages over diesel traction when RTE is the governing factor.
- Empty wagons have a significant aerodynamic drag at speed, so performance and timings could be improved if they were covered.
- Existing timing issues have been identified that are straightforward to correct, leading to improved timekeeping.

36. The financial benefit of these opportunities is valued at £16m pa. This is a very conservative and subjective judgement based on only 5% of trains achieving any primary benefits and 2% of trains achieving any secondary benefits.

8.2 Next steps

8.2.1 Implementation

The project team has worked very closely with the NR capacity planning team to ensure that the revised methodology and engineering background can be incorporated into 'business-as-usual' timing calculation. This will require modification of the core assumptions within the NR RailSys model.

In addition to the case studies, the team has also worked through examples with some other NR routes (Southern and Wales) and the NR freight team to raise their knowledge about this opportunity.

It is recommended that the new T1301/2 methodology should be used to update existing SRTs, produce new SRTs for Class 68, 70, 88, 93, and 99 locomotives, and to undertake substantive revision of the existing timings for Class 90 and 92 locomotives.

8.2.2 Further areas of study

The partially complete corridor assessments of the main lines should be completed:

- WCML south of Crewe
- GWML between Pilning and Didcot and between Reading and Paddington
- MML from Trent Junction to Sheffield and from Radlett to St Pancras
- ECML in its totality.

Some other key freight routes should be considered, for example, North London Line, Doncaster–Immingham

This report has not considered the effects of freight train braking, and further opportunities for improvement could arise there. This subject is currently being addressed by RSSB research project T1348.

9 Acknowledgements

With thanks to the following technical contributors:

- Jack Pocock (Rail Aspects Limited)
- Jack Neil (Rail Aspects Limited)
- Karol Tyszka (D2 Global Limited)
- Jessica Tandy (D2 Global Limited)
- Kieran Lee (Aether Limited)
- Lewis Blannin (Aether Limited)
- Kate Attard (Aether Limited).

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