RAIL SAFETY AND STANDARDS BOARD

Report

T1302: Guidance on limits of freight train trailing length as governed by tractive effort

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Executive summary

This report is intended for experienced railway engineers and operational staff with an interest in improving the efficiency of freight trains through increasing a train's trailing load when it is restricted by locomotive tractive effort.

To reduce unit costs wherever possible freight trains try to run with their maximum 'trailing load', that is, the total weight of all wagons and their payload behind the locomotive. These maximum trailing loads, known as the 'Trailing Load Limit' (TLL), are defined in Network Rail's Freight Train Loads Book (FTLB). The FTLB is a series of Excel spreadsheets which define by locomotive class the maximum TLL on a section of track.

By increasing the permitted TLL, a given tonnage could be delivered with fewer trains and:

- Reduce unit delivery cost
- Reduce emissions
- Encourage of freight modal shift
- Release network capacity.

MT19 back calculation

Presently, TLLs are defined within the FTLB based on a historic British Rail document known as MT19, 'The manual of maximum train loads on gradients for various types of locomotives'. It is estimated that MT19 came into use in 1967 and was last revised in 1989.

The last comprehensive update to the FTLB was the addition of the Class 66 locomotive in the late 1990s. Since then, the science and methodology behind TLL calculations defined in MT19 has been lost. For some critical locations and for some newer locomotive types the historic TLLs from MT19 have been challenged through the Network Rail Service Plan Review (SPR) process where heavier loads have been trialled and approved for inclusion in the FTLB – a time-consuming process.

The first deliverable of this report redefines the lost MT19 calculation process behind the FTLB values.

The report defines four categories of forces which must be overcome (note: within this document when we refer to a 'train' we mean the locomotive and wagons in the consist):

- Gravity – the tractive effort required to take the train up a gradient
- Curving – the tractive effort required to move the train laterally through a curve in the track
- Acceleration – the tractive effort required to increase the speed of the train
- Total mechanical resistances – the tractive effort required to overcome the aerodynamic and internal frictional resistances within the train.

Through documented research, review of international comparators, and the use of engineering principles an empirical model was developed to describe these forces, based on the Davis Equation[1]. It was successfully used to back-calculate the values in MT19, and through that provides understanding of some anomalies in that document.

Having this empirical tool now enables us to produce TLL values for newer locomotive types and update the various coefficients used within the model to reflect the 30 odd years of development since MT19 was introduced.

Load cases and available power

The model also enables us to characterise two widely referred to load-cases which are presently poorly defined:

- Starting Tractive Effort (STE). When starting the mechanical resistances are low, but the acceleration force is high.
- Rolling Tractive Effort (RTE). When at speed (rolling) the mechanical resistances are high, but the acceleration force is zero (just maintaining line speed).

The STE is based on the maximum available locomotive tractive effort, capped by the vehicle's weight multiplied by the coefficient of friction between the wheel and the rail head (to avoid wheel slip). Within the MT19 calculation, a limiting coefficient of friction (μ) of between 0.22 and 0.33 is adopted depending on the characteristics of the locomotive class or sub-class and assumed track condition. The continuing validity of the maximum value of 0.33 had not been reassessed for over three decades.

This μ value was reviewed against international comparators and research papers and it was recognised that it could be changed, based on the type of traction motor, the number of locomotive axles, and the effectiveness of the locomotive's traction control system.

The report suggests for certain locomotive types the coefficient of friction is raised from 0.33 to up to 0.38, leading to a 9% increase in Tractive Effort (TE) for a Class 60 and a 15% increase for a Class 70. The new formula also allows new, higher, figures of available TE to be calculated from the modern Class 68, 88, 93 and 99 locomotives.

The available tractive effort for a number of locomotive classes varies with speed, however electric locomotives lose much less of their power at higher speeds compared to diesel locomotives. Generally, they have three times as much power at speeds of over 20 mph which means their RTE is higher and their ability to maintain maximum line speed is much higher.

[1] The 'Davis Equation' is an historic algebraic formula which expresses locomotive loading in relation to a number of constants and a linear and squared relationship with velocity.

Modelling

Using this data, we developed an Excel model which calculates the maximum trailing load at a location based on:

- horizontal and vertical alignment
- locomotive type and wagon types (up to three within the consist)
- coupler type
- single or double headed consist
- Rail head adhesion condition (low friction option available).

This model enables precise values to be calculated at key locations. Improvements are possible not only from the better understanding of forces but also from the more precise definition of geography – at some locations adverse gradient and/or curvature does not affect the whole train length.

This Excel model was then used as a basis to develop a model within the statistical package 'R' which can consider an extended geography. An intermediate optimisation tool was developed to reduce calculation time and together they were used to establish TLL and through running times in four case study locations.

Consideration of timing

There are three 'legs' on the 'stool' supporting the attainment of maximum trailing load. These are:

- Sufficient locomotive power
- Sufficient coupler strength
- The ability to travel through the network within the available time allowance[2]

Network Rail divide their network into timing points (known as 'TIPLOCs') and the track between them is known as a timing 'section'. 'Sectional Running Times' (SRTs) are defined for each locomotive class in a number of different load conditions, and they represent the time allowance Network Rail recognises as required for that loaded train to travel through the section. Usually there are four SRTs for each consist depending on whether the train is through running (pass – pass), running though 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.

The SRT is compared against the available time within the timetable to see if the train can pass through without affecting different services and the aggregation of the SRTs through the journey defines the train's overall schedule.

[2] The available power from the electrification system is a fourth constraint, but outside the scope of this project.,

Newly available route geography from Network Rail and the current SRTs, and the running time of various consists, was applied to a train performance model based on the Davis Equation that replicates earlier timetabling models (called ‘SRTcalc’) to compare the modelled and actual SRT allowances in four key freight locations: Shap (a section of the West Coast Main Line), West London Line, Midland Mainline, and the Southampton line between Eastleigh and Basingstoke.

The project has compared the performance of trains running up Shap and shown that electric locomotives have significantly higher speeds up Shap summit and its predecessor climb up to Greyrigg. Diesel locomotives slow down to around 30 mph on Greyrigg and they do not recover to line speed on the following flat section. The performance of the electrically powered locomotives, particularly the six axle Class 99 and eight axle paired Class 90s, is significantly different. They do not slow down going up Greyrigg and only slightly slowed down (if at all) up Shap. When a ‘junction to junction’ timing is taken on this section of the West Coast Main Line Class 66 takes almost twice as long up the gradients as a Class 90.

However, the Class 66 locomotive going up Shap still performs over 10% better than its stated SRT timing, implying that the load could be increased by this amount and still run within the timetabled time allowance. In this, and other case studies, we find opportunities for running longer trains within the same timing allowance and a secondary opportunity for running longer trains when there is greater timing allowance off-peak or overnight.

When we model the performance of a Class 66 locomotive against its stated SRT timings on the West London Line heading north from Latchmere Junction (near Clapham Junction) to Mitre Bridge Junction (near Willesden High Level station) we find in the first three timed sections the modelled timings are significantly less than the stated SRTs. In these locations the stations are less than 2 km apart and the track is either descending or flat. The SRT allowance of 4 minutes is clearly not required from a performance perspective, but we think that the timings may have been set based on operational constraints; the timing is similar to the frequently stopping passenger trains on this line. However, this SRT timing always applies, even when passenger trains are not running overnight or have an extended off-peak headway.

This appears to be an area of opportunity and what is a core freight route being the most easterly rail freight crossing of the River Thames. Flows include Channel Tunnel trains, jet fuel to Heathrow from the Isle of Grain, and aggregate trains to Purley and Stewarts Lane, and from Angerstein Wharf.

At the end of the line there is a short severe gradient of 1:60 up to Mitre Bridge. Our modelling shows the importance of maintaining momentum into this area. When the locomotive is stopped at the bottom of the hill it can struggle to reach the top in poor rail head conditions but when approaching at line speed it has no problem in climbing the gradient.

Cost benefit analysis

Significant savings of over £2,000 per return journey can be achieved through increasing the train's maximum TLL. Even if only 20% of the daily trains are able to do this, the saving to the industry will be over £52m. Some of this value will result in additional modal shift from road to rail.

Increases in TLL will enable fewer trains to move the same tonnage of material: a 20% increase in TLL equates to 20% fewer trains for the same volume. This will improve congestion on the network by reducing the absolute number of freight trains.

Further benefit will come through the release of network capacity; if the same number of goods are carried longer trains result in fewer trains. This has benefits in both the availability of pathing (more timetable 'whitespace') and the resilience of the network (fewer freight trains 'getting in the way'). However, these benefits are hard to quantify and have therefore been left out of the cost benefit analysis.

Additional research requirements

The report identifies six areas where we feel additional research would be of value. These are around improving understanding of locomotive tractive effort data, railhead adhesion, and the internal resistance characteristics of locomotives and wagons.

Conclusions

The key conclusions from this report are as follows:

1. Train length extension through the adoption of the recommendations within this report will significantly reduce the unit cost of running freight trains. Based on 20% of the daily freight services being extended the industry will benefit through a cost saving of over £50m pa.
2. It has been possible to 'back-calculate' the historic FTLB values derived from MT19 using four components: gravity, curving, acceleration, and internal resistances
3. Through the analysis in the report we have updated some of the force coefficients within the above model as they have not been reviewed for roughly 30 years. More work needs to be done in this area and detailed recommendations are included in Section 11. Some of these recommendations were initially identified over 40 years ago by British Rail.
4. Two load cases have been defined:
    - STE: maximum acceleration, minimum internal resistances
    - RTE: no acceleration (hold line speed), maximum internal resistances

    Previously a 'continuous' load case has been considered, often expressed as a maximum load based on a 'continuous loading' and this significantly reduced calculation complexity. Now, due to the ability to accurately and easily model performance based on actual geography and locomotive performance, we do not consider this load case is now relevant as it is superseded by the more accurate definition of

RTE now possible. Secondly, the thermal degradation of modern locomotive traction equipment performance is much lower so this state (or even close to it) is very unlikely to be relevant for new locomotive types on the GB network.

5. By placing this model into Excel and allowing specific route geography to be input it is possible to more accurately restate TLLs. This is particularly of value where the steepest gradient is less than the whole train length.
6. Within MT19, maximum locomotive tractive effort is capped by a locomotive (sub-)class specific rail head friction co-efficient (μ) of up to 0.33, and in certain situations for older locomotive types is reduced to below 0.25. For more modern locomotive classes this previous maximum figure is overly conservative and can be increased, up to 0.38.
7. Electric locomotives have significantly more power at higher line speed than diesel locomotives. Consequently, their usual failure mode is Starting Tractive Effort, as only a smaller proportion of their much higher maximum power can be delivered at low speeds where adhesion is the limiting factor. However, these consists may not be able to start if they are stopped, so if this benefit is to be realised a ‘let it run’ policy is required, which at times will be operationally difficult.
8. From the four case studies undertaken within the study, historic SRTs for various locomotives and consists appear conservative, with generally at least a 10% improvement in trailing weight possible. For the modern electric locomotive (Classes 88, 93 and 99) SRTs should be established which take account of their significantly improved RTE which will lead to the ability to either run longer trains, or run existing length trains at reduced SRT allowances.
9. In places SRT allowances appear to reflect operational constraints of working around the passenger timetable in mixed use applications, with the freight trains given a longer than required SRT to avoid conflict. However, when the passenger trains are not running these SRT allowances are unchanged, unnecessarily slowing the freight trains and increasing their fuel usage. This should be amended and where this is an issue ‘peak’, 'off-peak', and ‘no passenger service’ SRTs developed and used.
10. As custodians of both the Loads Book and the Timetable management process Network Rail are key to the implementation of the opportunities identified within this report. Immediately positive change can be made through the development of new SRTs, adoption of revised (and variable within the year) coefficients of friction values, and increased train length enabled through the Service Plan review process. In the medium term for these changes to be efficient changes to some of the systems used by Network Rail will require updating, which will lead to a requirement for capital spending and staff training.

Implementation

The ownership of the FTLB and the timetabling process around SRTs is Network Rail’s, so the first stage of the implementation of the conclusions of this report is to ensure their buy-in. This process has already commenced as Network Rail have representatives on the Steering Group and many one-to-one conversations have been had with appropriate people within the organisation.

It is hoped that the wider stakeholder group involved in the development of this project will support Network Rail in the implementation of the conclusions.

Network Rail are currently considering moving to a digitised FTLB where all of the information in the current Excel spreadsheets is accessed through a digital application. Route geography is available within this application so the calculation models defined by this project could be incorporated into the digital FTLB.

Our work indicates that some of the SRTs in current usage need to be reviewed, initially using the modelling output and then by running longer trains using the existing Service Plan Review process.

Value

We conclude that the adoption of the conclusions within this report will deliver a direct benefit of over £50m pa representing a reduction in train haulage costs through the running of longer trains. Additional unquantified benefits will occur through an increase in network capacity (fewer trains for the same volume) and network reliability/resilience (fewer trains = fewer conflicts with passenger services).

1 Introduction

The maximum load that can be hauled by a locomotive over a given route is called the Trailing Load Limit (TLL) for that section of track. By increasing the permitted TLL a given tonnage can be delivered with fewer trains thereby:

- Reducing unit delivery cost
- Reducing emissions
- Encouraging freight modal shift
- Releasing network capacity.

Presently, TLLs are defined within the Freight Trailing Loads Books (FTLB) based on MT19 (shown below in Figure 1). It is estimated that MT19 came into use in 1967 and was last revised in 1989. The last comprehensive update to the FTLB was the addition of the Class 66 locomotives in the late 1990s and since then the science and methodology behind TLL calculations in the UK has been lost.

Figure 1 MT19 cover

For some critical locations, the historic TLLs from MT19 have been challenged through the NR Service Plan Review (SPR) process, where heavier loads have been trialled and approved for inclusion in the FTLB on a one-off basis – a time-consuming process.

Since the last update of the FTLB, several new locomotive classes with improved power and traction capabilities have been introduced to the GB rail network. These include the use of AC traction motors (instead of DC traction motors), improved wheel slip control, and alternative traction modes. Without the TLL calculation methodology, newer locomotives have to undergo trial runs to establish that increased trailing loads do not interfere with efficient network operations (sectional running times and so on). Failing this, operators must use potentially conservative TLL values based on other locomotive types which do not reflect the locomotives' true capabilities.

This project will review the logic used in MT19 and other sources to derive a thorough understanding of the science/methodology of TLL calculation leading to a proposed new method. This will enable new locomotives to have appropriate TLLs as well as enabling increases to existing locomotive TLLs where appropriate. This work will enable a better understanding of the derivation of FTLB TLLs and aligns with Network Rail's current intiative to digitise the FTLB.

In short, this project aims to re-characterise the relationship between freight locomotive tractive effort and TLL, replacing lost knowledge with new guidance that can be shared and further developed by the rail industry.

Having completed this analysis, the report goes on to consider further opportunities for increasing TLLs though a consideration of the running time of the train. On the British mixed-use railway, freight trains have to pick their way through the fixed passenger service, where timetabling space between these trains exists. Having gained a better understanding of the engineering constraints behind train running, the report evaluates the opportunity for either improving TLL within existing timings or modifying the timings to enable longer trains.

The remainder of this introduction provides a definition of TLL (Section 1.1), introduces some of the basic factors governing TLLs (Section 1.2), summarises the background of MT19 (Section 1.3), explains the remaining structure/layout of this report (Section 1.4), and provides some of the constants and conversions (Section 1.5).

1.1 Definition of trailing load limit (TLL)

The load a freight train pulls is its 'trailing load', which can be simplistically thought of as the number of wagons behind the locomotive multiplied by the gross laden weight of each wagon. The achievable trailing load of a freight train over any route section is limited by the smaller of:

a) the tractive effort of the locomotive

b) the strength of the couplers fitted to the locomotive and the wagons.

Network Rail's FTLB records the TLL for different locomotive types for each section of track between junctions. The FTLB TLL values account for factors such as track geometry (for example, gradient, curvature, and so on) along each section of track. The FTLB is held within a series of route-specific Excel spreadsheets, for example, see Figure 2.

Figure 2 Typical FTLB book entry

INDEX Ref	ROUTE : Kent Route / Sussex Route			RA	Lngth LIMIT	LOCOMOTIVE TYPE MAXIMUM LOAD excluding locomotive weight																		Coupling Strength		
	From	To	AEA Ref		SLU's	20	31/1	33	37/0	37/4	37/7	47/0	56	57	58	59	60	66	66/6	67	FL PH	73/1	66H	23t	34.5t	56t
SN/01	Victoria	Battersea Pier Jn	1001	8	36	775	665	820	1055	1125	1245	1145	1230	1305	1165	2145	2140	2085	2205	675		710	2085	1135	1700	2765
	* To Route Page 21 Ref SN/92 Battersea Pier Jn- Stewarts Lane																									
	* to Route Page 22 Ref SN/110 Battersea Pier Jn- Battersea Park Jn																									
SN/02	Battersea Pier Jn	Factory Junction	1002-03	8	36	1085	950	1145	1480	1570	1735	1605	1720	1820	1635	3110	3105	3030	3195	1000		995	3030	1545	2315	3760
	* To Route Page 21 Ref SN/95 Voltaire Rd Jn- Crofton Jn																									
SN/03	Factory Junction	Brixton Jn.	1004-05	8	121	1085	950	1145	1480	1570	1735	1605	1720	1820	1635	3110	3105	3030	3195	1000		995	3030	1545	2315	3760
	* To Route (Page 23) Ref SN/133 Brixton Jn - Canterbury Road Jn																									
SN/04	Brixton Jn -	Herne Hill	1006	8	62	1295	1145	1370	1770	1880	2075	1920	2060	2170	1960	3830	3825	3730	3935	1245		1190	3730	1825	2740	4450
	* To Route Page 23 Ref SN/141 Herne Hil Tulse Hill																									

The FTLB lists TLLs for various locomotive type and coupling strengths. On the first line of the Figure 2 example, the maximum trailing load by locomotive type varies from 3,445 tonnes for a Class 20 locomotive to 15,605 tonnes for a Class 60. This variation reflects the variation in the hauling capability of each locomotive, known as its 'tractive effort' (TE). This is defined as the longitudinal force which can be applied by the locomotive at the rail head. This is a function of several parameters, including the size of the engine, traction gearing, traction system, locomotive mass, and adhesion.

The final three columns in Figure 2 define the maximum TLL as governed by coupler strength. There are historically three different coupler strengths in use, varying from 23.5 tonnes to 56 tonnes. It is the lesser of these which decides the TLL, for example, in Figure 2, while a Class 60 could haul 15,605 tonnes based on TE, its 56 tonne couplers would break at only 9,995 tonnes.

There are other constraints on the TLL which are not addressed in the FTLB:

- Physical constraints on the length of the train, which could be:
  - Terminal loading/unloading constraints
  - Any loops into which the train is planned to dwell
  - The physical distance between signals, which is generally taken to mean that the maximum length of a train on the GB network is 750 m unless special working measures are put in place.
- The ability of the train to pass through each section of the track within the allotted time in its timetabled path. This allotted time is known as the SRT, and it prevents very heavy trains crawling up steep hills and delaying trains behind them.
- The available time to go through a junction (the Junction Occupation Time).

1.2 Trailing load limit components

Throughout our analysis we have used the principle that for a train not slowing down, the available power from the locomotive has to be greater than or equal to the resistance forces within the train, as shown in Figure 3.

Figure 3 Key forces acting on a train

Tractive Forces (F_{LT})	≥	Total Loco Resistance Force (R_{LT})	+	Total Wagon Resistance Force (R_{WT})

These forces are considered as follows.

1.2.1 Tractive forces

This is the 'tractive effort' of the locomotive, capped by the friction of the wheel on the rail, after which wheel slip occurs. The tractive effort (TE) depends on:

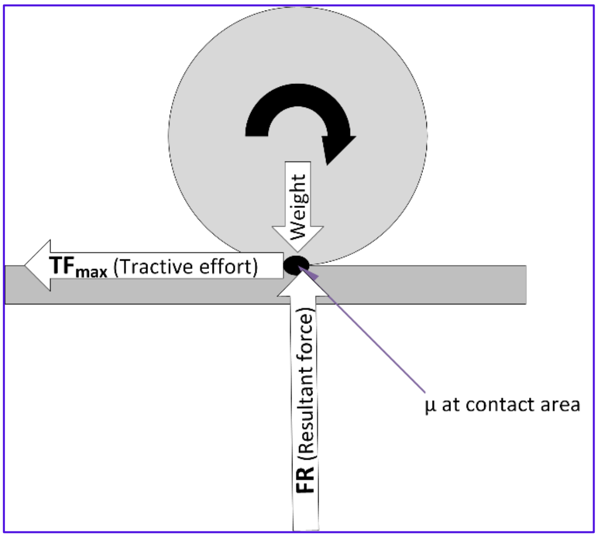
- Input torque to the driving wheels: this is a function of torque generated at the traction motor output shaft and the gearing between the traction motor shaft and axle. The maximum torque available from the traction motor at standstill is restricted in accordance with the traction motor, propulsion system, and transmission limits, and reduces as speed increases in accordance with the traction motor and propulsion system power rating.
- Wheel diameter: the tractive effort at the rail head is a function of the input torque (axle torque) to the driving wheels and the driving wheel diameter.

The tractive effort which can be successfully exerted by a locomotive is limited by the coefficient of friction (μ) between the driving wheels and rail. The maximum force at the wheel-rail interface before spin/slip (while applying power) or slide (while braking) is limited by:

$$TF_{max} = \mu \times FR$$

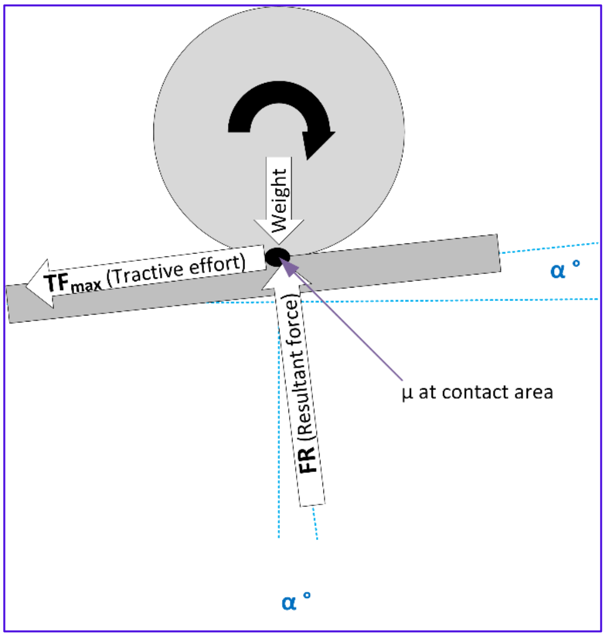
where TF_{max} is the maximum force (tractive effort), μ is the coefficient of friction and FR is the resultant force – the component perpendicular to the railhead of the vehicle's weight acting on the driving axle.

Figure 4 Explanation of adhesion equation terms



This constraint is often referred to as rail ‘adhesion’, that is, the ‘stickiness’ of the wheel-rail interface. Lower ‘stickiness’ (lower µ) is often experienced in autumn through leaf mulch on the rail which leads to wheels spinning on acceleration and sliding on braking. The maximum adhesion occurs on level track where all the weight per wheel/wheelset is perpendicular to the railhead. The maximum adhesion decreases as the track gradient increases (for both uphill and downhill, with the effects downhill being more than compensated for by other changes in train resistances).

Figure 5 Explanation of adhesion equation terms (on inclined track)



$$TF_{max} = \mu \times RF$$

$$TF_{max}\,[kN] = \mu \times locomotive\ adhesion\ mass\,[tonnes] \times g \times \cos\alpha$$

Up to a certain speed, the tractive effort is almost constant as it is adhesion limited (a function of coefficient of friction and driving wheel loadings). As speed increases further, the power delivered by the traction motors per unit distance falls, and hence so does the tractive effort.

- In Newtonian mechanics power = force (aka 'tractive effort') * speed, that is, $P = TF \times v$
- Which can be rearranged to give tractive effort: $TF = \frac{P}{v}$, so for constant power when not limited by the adhesion, tractive effort decreases as speed increases.

Further details about the factors behind rail adhesion are given in the appendix (Section 14).

1.2.1.1 Tractive effort cases

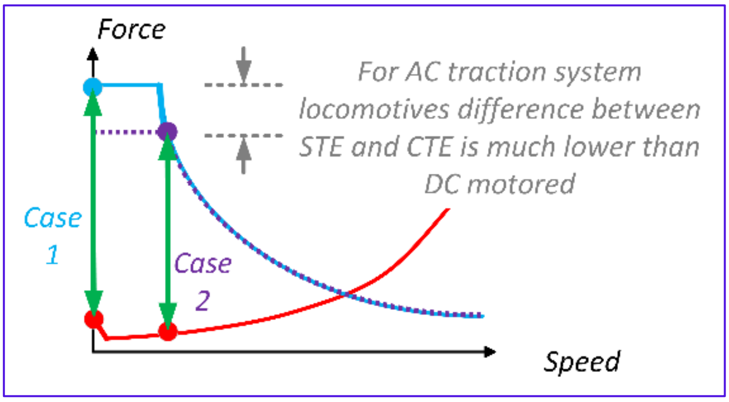
Throughout this document two distinct cases of tractive effort are considered:

- Case 1 - STE – starting from a stand without thermal degradation of power available from motors.
- Case 2 – RTE – varies with speed and thermal degradation of the traction motors and electrical equipment. Two specific cases of RTE are:
    - Case 2a – ContinuousTE – maximum thermal degradation of power delivered due to continuous running, at full power and at a specified speed.
    - Case 2b - 1-hour TE – thermal degradation of power delivered due to running for one hour, at full power and at a specified speed.

A diagrammatic explanation of the TE cases is shown in Figure 6 below. The difference between Cases 1 and 2 is far smaller for new locomotives than old ones because of improvements in traction electrical equipment. Key points to note are:

- Older BR locomotives (Class 58 and earlier) are typically Case 2 limited, whereas more modern DC traction motor locomotives (for example, Class 59, 60 and 66) are a mixture of Case 1 and Case 2 limited.
- TE at lower train speed is limited by the locomotive's adhesion, and at higher speeds by the torque available at the wheels (governed by engine power, electrical power, control systems, and so on).
- At low speeds, newer locomotives with entirely AC traction equipment will almost always be Case 1 limited using the MT19 methodology.
- Delivery of very high TE requires ideal adhesion conditions (that is, high μ) and conservative assumptions for μ may result in the TE for TLL calculation purposes being lower than either starting or continuous TE.

Figure 6 Explanation of tractive effort curve and the two limiting cases typically examined



1.2.1.2 Traction motor control

Good traction motor control is required to optimise adhesion by controlling the wheel-rail slip rate and make best use of the available adhesion (μ). This is largely a function of accurate control of traction motor torque at a given train speed (or traction motor rotational speed given chosen fixed gearing and wheel diameters) – greater inaccuracy results in the target tractive effort having to be reduced to prevent wheel spin occurring.

Different types of traction electrical systems enable different levels of torque at different motor speeds, as well as the accuracy of control of that torque, and this often leads to large difference in deliverable torque at low motor speeds, and thus low train speeds. With older locomotive types this leads to a compromise to improve deliverable torque at low speed by decreasing the gearing ratio (defined as the number of teeth on the output gear divided by the number of teeth on the input gear) and reducing driving wheel diameter, such that the motor spins faster at lower train speeds.

The downside of this compromise is that it reduces maximum train speeds (to avoid centrifugal forces damaging the motor) and results in a slight reduction in tractive effort at higher train speeds. Newer traction technologies, such as three-phase AC drives and the associated squirrel cage traction motors, or microprocessor control separately excited DC traction motor control, enable better low speed torque delivery and control than is possible with older equipment, thus enabling better performance and efficiency across the entire speed range.

$$TF = \eta_G \times \frac{\tau_M}{(K_G \times WØ)}$$

where:

τ_M = Traction motor torque [Nm]

η_G = Gearing efficiency, typically 0.97 - 0.98

K_G = Gearing ratio, typically in the range 2 to 5.5.

$WØ$ = Locomotive wheel diameter [m].

Further details about the importance of traction motor control are provided in the appendix (Section 14).

1.2.2 Resistance forces

We have defined four types of resistance force:

- Gradient – the force needed to raise the train up a hill.
- Curvature – the force needed to change the direction of travel around a curve, as a function of the curve radius.
- Total mechanical resistance – 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. This force is speed dependent.
- Acceleration – the force required to overcome inertia and accelerate the train.

A quadratic function can be used to model the variation of the mechanical resistance with speed, an approach which has been used for well over a century in multiple countries. This model has a generic structure of:

$$Mechancial\ Resistance(v) = A + B \times v + C \times v^2$$

This equation (known as the Davis equation) recognises that the total mechanical resistance force has a certain constant value and elements which increase both with speed and the squared value of speed. The total train mechanical resistance 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:

- Bearing resistance
- Rolling resistance
- Track resistance

B coefficient:

- Flange friction
- Flange impacts
- Velocity-dependent rolling resistance between wheel and rail
- Wave action of the rail

C coefficient:

- 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

Climbing uphill or descending downhill leads to changes in the potential energy of the train, often referred to as body forces (in the Newtonian mechanics sense). The rate at which the potential energy change occurs is a function of the track gradient. Travelling uphill requires an input of energy, equivalent to applying an increased resistance when on the level. Travelling downhill releases energy, equivalent to applying a decreased resistance when on the level. The body force experienced by a vehicle due to change in elevation is:

$$Force = -m \times g \times \sin(\alpha)$$

Where α is the angle of slope; positive for uphill and negative for downhill. For small angles $\sin(\alpha)$ can be adequately approximated by using the decimal gradient (sine small angle approximation), for example:

$$Force = -m \times g \times gradient$$

Train dynamics follow Newton's second law which in its simplest general form can be stated as:

$$Force = mass \times acceleration$$

$$Force = mass \times \frac{dv}{dt}$$

The rail application is somewhat more complex as some elements of the force also have mass (weight) dependencies (often at vehicle rather than train level, for example, adhesion) and there are many sub-components of the overall force; hence it is often rearranged into a form for ease of use so that the left-hand side is at the train level and the right-hand side is the sum of many components at the vehicle and axle level:

$$mass \times \frac{dv}{dt} = \sum Force$$

When broken out into the four category groups of force (each of which acts at the vehicle or axle level) this equation becomes:

$$m \times \frac{dv}{dt} = Tractive\ Effort\ (v) - Mechancial\ Resistance\ (v) - Curvature\ Resistance - Brake\ Force - m \times g \times gradient$$

If the value 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. The speed at which $m \times \frac{dv}{dt} = 0$ is known as the balancing speed as the TE and resistance forces balance, resulting in no nett force. Often a small positive acceleration rate is used as the threshold instead of $\frac{dv}{dt} = 0$, to define a difference between 'acceleration' and 'no change in speed' as the train would take a very long time to reach the 'no change in speed' state as the acceleration rate approaches 0. The three behaviour states for values of $m \times \frac{dv}{dt}$ are shown in Table 1 below:

Table 1 Train behaviour for the three critical value ranges of $m \times \frac{dv}{dt}$

$m \times \frac{dv}{dt}$ value	Train behaviour
> 0	accelerates
0	no change in speed
< 0	decelerates

In practice small positive values of $m \times \frac{dv}{dt}$ are assumed for the no speed change case (for example, to allow for rotational inertia in wheelsets). For calculating the maximum trailing load of through-braked freight trains the brake force is not relevant so the equation can be simplified to:

$$\boldsymbol{m \times \frac{dv}{dt} = Tractive\ Effort\ (v) - Mechancial\ Resistances\ (v) - Curvature\ Resistance - m \times g \times gradient}$$

1.3 Background and history of MT19

MT19 lists the trailing load limits for various locomotive and wagon combinations, for specific track curve radii and gradient conditions for starting, 1-hour, and continuous running situations. MT19 only covers diesel locomotives and the diesel mode of electro-diesel locomotives. A separate different method has been used in the FTLB for 25 kV AC electric locomotives that includes their ability to keep to timetabled paths for maximum 60 mph services (Class 6 paths) and 75 mph services (Class 4 paths).

MT19 initially covered the locomotives listed below:

- Class 08
- Class 09
- Class 20
- Class 26
- Class 31
- Class 33
- Class 37/0
- Class 47
- Class 50
- Class 73/0 (operating on diesel)
- Class 73/1 (operating on diesel)

The locomotive types listed below were added to MT19 over time (that is, as new locomotives were introduced, or older locomotives received traction upgrades):

- Class 37/4 (post modifications)
- Class 37/7 (post modifications)
- Class 50 (new starting and continuous data post modifications, but previous original 1-hour rating TE data retained though no longer applicable)
- Class 56
- Class 58
- Class 60

The input data for Class 60 used for the MT19 calculations was based on preliminary design and specification data (before the first locomotive was completed) rather than real world testing. The Class 60 values in MT19 do not match data gathered in 1991 from real world testing post-locomotive construction.

For the Class 50 tables only the inputs for the starting and continuous cases appear to have been updated when the locomotives were modified as part of a major overhaul in the early 1980s, with the original 1-hour rating input data being inconsistent with the other two sets of input data.

Class 56 and Class 58 continuous rated speeds in MT19 are the same at 17.4 mph, yet other British Rail and current data sources have the Class 56 continuous speed as slightly lower at 16.8 mph. The wagon mechanical resistances for Class 56 and 58 in MT19 are different which strongly suggests that two different speeds were used for calculating the wagon mechanical resistances, but this does not align with the stated inputs at the top of the MT19 tables. This also suggests that resistance values may have been pre-calculated and input rather than being calculated as part of the tabulated trailing load calculations.

This understanding is based on the printed tables of the last known set of calculation runs. For most locomotive classes the calculations were run in September 1986; for the Class 60 this was done in June 1989, with the tables printed in September 1989. MT19 is known to have had at least two updates in methodology/input assumptions from its initial state in 1967 to the last known calculations in the mid/late 1980s. The first known update was in or after 1978 and incorporated a revision to the curvature methodology based on research carried out in 1977-78.

The second update of MT19 was in or after 1984 and implemented some minor changes recommended in two British Rail reports (Headech, 1982 and British Rail, 1983). The majority of the recommendations in those reports were seemingly not actioned, probably because they would have needed more extensive further research before implementation. The first report (Headech, 1982) was to examine the requirements and data gaps involved in unifying calculation methodologies and data sets for calculation of trailing load and timetabling performance for both passenger and freight. The second report (British Rail, 1983) was focused on smaller, more actionable interim improvements to MT19, some of which appear to have been subsequently made.

1.4 Structure of this report

An initial review of MT19 is made in Section 2 where the listed TLLs are replicated. The methodology for determining TLLs in MT19 is reviewed in Sections 3, while methodologies used elsewhere are reviewed in Section 4. Within both of these sections the structure is first all vehicles factors (gradient and acceleration resistance), followed by locomotive factors (adhesion, tractive effort, starting resistance, and rolling resistance), and then followed by wagon factors (starting resistance and rolling resistance).

Within each subsection key learnings to develop the new methodology are flagged in a 'shaded' box.

The proposed new methodology to determine TLLs is given in Section 5 and the calculation tool is explained in Section 6. Comparisons with the current values in the FTLB are discussed in Section 6.5. Opportunities to gain improvements in running time are discussed in Section 8.

The calculation tool is used to perform a cost-benefit analysis that is described in Section 9 and an implementation plan is presented in Section 10. Areas for future development are described in Section 81, and final conclusions are given in Section 12. Section 13 contains references and Section 14 is an appendix with a detailed discussion of factors affecting adhesion.

1.5 Constants and conversions

In preparing this report we have used these values:

1 Ton (imperial)	= 1.12 ton (short, US)
1 Ton (imperial)	= 1.0160469 tonnes (metric)
1 kg	= 2.20462 lb
g	= 9.80665 m/s^2
1 chain	= 22 yards = 20.11685 m

2 Initial assessment of MT19 methodology

MT19 lists the TLLs for:

- Wagon types:
  - 'mixed' – plain and roller bearings, bogie, and 2-axle wagons
  - 'bogie' – roller bearings
- Track condition:
  - mainline routes (better quality)
  - secondary (worse quality).

These are presented in MT19 in four tables (MT19 Tables 1, 2, 3, and 4) as summarised in Table 2 below.

Table 2 Summary of the four tables of TLLs listed in MT19

Wagon types	MT19 table number	
	Mainline routes (MS)	Secondary line routes (SS)
Mixed	1	3
Bogie vehicles	2	4

Within each of the four MT19 tables are 'sub-tables' listing the TLLs for various locomotives and track geometry. For example, MT19 Table 2:60, shown in Figure 7 below, lists TLLs for bogie wagons on mainline routes, hauled by a Class 60 locomotive with various track curvatures and gradients.

Figure 7 Example of MT19 sub-table 2:60

MAXIMUM GROSS TRAILING LOADS ON RISING GR/ 'ENTS - TONNES MXLD0148 CALCULATED 2? 5/89 PRINTED 23/06/89 TABLE 2: 60
LOCO CLASS 60 Prop d B.R. diesel electric Class 60 loco => ›visional loads <= LOD1060G
TRAILING LOAD BOGIE VEHICLES TRFR08

LOAD REF	SPEED - MILE/H	ADHESION	RTE USED LB	LIMITED BY	LOCO RATING	LOCO WEIGHT - TONNES	LOCO RES LB/TON
L1	0.00	0.330	92000	TRACTION	STARTING LIMIT	127.71 IN WORKING ORDER	20.00
L2	11.60	0.316	75600	TRACTION	CONTINUOUS	127.71 FOR ADHESION 2	4.88

RISING GRADIENT 1 IN	MAXIMUM LOAD FOR TYPE OF TRACK					
	Very Sharply Curved		Sharply Curved		Relatively Straight	
	L1	L2	L1	L2	L1	L2
RES LB/TON	19.00	9.56	9.00	7.19	6.00	4.83
36	1020	950	1165	980	1215	1015
38	1070	1000	1225	1035	1285	1075
40	1115	1050	1290	1090	1350	1135
42	1160	1100	1350	1145	1415	1190
44	1205	1150	1410	1200	1485	1250
46	1250	1200	1465	1250	1550	1305
48	1295	1250	1525	1305	1610	1365

CLASS 60 LOCOMOTIVE

Provisional loads subject to revision for:-

Main Line Track

To ensure that the methodology within MT19 is understood, the parameters given at the top of each of the sub-tables were used to replicate the TLLs listed. Data from MT19 Table 2 and Table 4 were investigated in detail as these are for bogie roller bearing wagons, that is, the most applicable to the current and future wagon fleets.

The previous work for RSSB's T1256 research project was expanded and from this it was established that the formula used in MT19 was:

$$F_{LT} = m_L \times R_{LT} + m_W \times R_{WT}$$

where:

F_{LT} = The total tractive force of the locomotive at a given speed, kg
m_L = Mass of locomotive, tonnes
R_{LT} = Locomotive total specific resistance, kg/tonne
m_W = Total mass of the wagons (or trailing load), tonnes
R_{WT} = Wagon total specific resistance, kg/tonne.

At the trailing load limit (TLL) the mass of the wagons is defined as:

$$TLL = m_W = \frac{(F_{LT} - m_L \times R_{LT})}{R_{WT}}$$

We have been able to use this formula to replicate the MT19 data, apart from some minor rounding errors (for example, 15,780 tonnes versus 15,785 tonnes); see Figure 8.

Our conclusion on the MT19 data is therefore as follows:

- The resistance data presented in MT19 is a single figure and does not differentiate the component parts (for example, R_{WC}, R_{WA}, and R_{WM}).
- The wagon resistances sometimes vary with locomotive type (that is, the Class 60 uses lower starting resistances on all curves and the Class 73/1 uses higher, for example, see Figure 9). This is counterintuitive as any wagon type could be hauled by any locomotive type. Therefore, the wagon resistance was expected to be consistent, regardless of the locomotive type.
- When comparing mainline tables (for example, MT19 Table 2) with secondary line tables (for example, MT19 Table 4), the wagon resistances are consistent for each locomotive type (for example, Class 47 very sharply curved is 25 lb/Ton for both MT19 Table 2 and MT19 Table 4).
- Many locomotives have no wagon resistance data for the 1-hour condition; see Figure 10.
- The wagon continuous resistance is the most inconsistent between locomotive types; see Figure 11.

Figure 8 Examples of replication of MT19 TLLs

MAXIMUM GROSS TRAILING LOADS ON RISING GR/ 'ENTS - TONNES MXLD0148 CALCULATED 2? 5/89 PRINTED 23/06/89 TABLE 2: 60
LOCO CLASS 60 Prop d B.R. diesel electric Class 60 loco => ›visional loads <= LOD1060G
TRAILING LOAD BOGIE VEHICLES TRFR08

LOAD REF	SPEED - MILE/H	ADHESION	RTE USED LB	LIMITED BY	LOCO RATING
L1	0.00	0.330	92000	TRACTION	STARTING LIMIT
L2	11.60	0.316	75600	TRACTION	CONTINUOUS

LOCO WEIGHT - TONNES	LOCO RES LB/TON
127.71 IN WORKING ORDER	20.00
127.71 FOR ADHESION 2	4.88

MAXIMUM LOAD FOR TYPE OF TRACK

RISING GRADIENT 1 IN	Very Sharply Curved L1	Very Sharply Curved L2	Sharply Curved L1	Sharply Curved L2	Relatively Straight L1	Relatively Straight L2
RES LB/TON	19.00	9.56	9.00	7.19	6.00	4.83
36	1020	950	1165	980	1215	1015
38	1070	1000	1225	1035	1285	1075
40	1115	1050	1290	1090	1350	1135
42	1160	1100	1350	1145	1415	1190
44	1205	1150	1410	1200	1485	1250
46	1250	1200	1465	1250	1550	1305
48	1295	1250	1525	1305	1610	1365
50	1335	1295	1585	1355	1675	1420
52	1375	1340	1640	1405	1740	1475
54	1415	1390	1695	1455	1800	1530
56	1455	1435	1750	1505	1865	1585
58	1490	1480	1805	1555	1925	1640
60	1530	1525	1860	1605	1985	1695
62	1565	1565	1910	1650	2050	1745
65	1615	1630	1990	1725	2135	1825
68	1670	1690	2065	1795	2225	1905
71	1720	1755	2140	1860	2315	1985
75	1780	1835	2240	1950	2430	2085
79	1845	1915	2335	2040	2540	2185
83	1900	1990	2430	2125	2650	2285
88	1970	2080	2545	2235	2785	2410
94	2050	2190	2675	2355	2945	2550
100	2125	2295	2805	2475	3100	2690
108	2220	2425	2965	2630	3300	2875
115	2300	2540	3105	2760	3470	3030
125	2400	2690	3290	2940	3705	3250
137	2510	2860	3505	3145	3975	3500
150	2620	3030	3720	3355	4250	3760
167	2750	3240	3980	3615	4595	4080
188	2890	3475	4275	3905	4990	4460
200	2960	3600	4430	4065	5200	4665
214	3040	3735	4600	4235	5440	4895
250	3210	4050	4995	4645	6000	5440
300	3400	4420	5465	5130	6680	6120
375	3610	4855	6020	5730	7530	6985
500	3845	5385	6700	6480	8620	8125
750	4115	6040	7555	7445	10075	9700
1000	4265	6430	8065	8045	11000	10740
1500	4425	6875	8645	8750	12110	12025
LEVEL	4785	7970	10100	10590	15155	15785

****
* CLASS 60 LOCOMOTIVE *
* Provisional loads subject to revision for:- *
* Main Line Track *
****

fx =(D$28-$C$19*(D$26+C31))/(D$24+C31)

B	C	D	E	F	G	H	I
MT19 table	2:60						
Loco class	60						
Loco weight W.loco =	127.71 t						
	Curve	very sharply		sharply		relatively straight	
	Condition	L1	L2	L1	L2	L1	L2
		Starting	Continuous	Starting	Continuous	Starting	Continuous
	R.wagons	19.00 lb/T	9.56 lb/T	9.00 lb/T	7.19 lb/T	6.00 lb/T	4.83 lb/T
		8.479 kg/t	4.266 kg/t	4.016 kg/t	3.208 kg/t	2.677 kg/t	2.155 kg/t
	R.loco	20.00 lb/T	4.88 lb/T	20.00 lb/T	4.88 lb/T	20.00 lb/T	4.88 lb/T
		8.925 kg/t	2.178 kg/t	8.92 lb/T	2.18 lb/T	8.92 lb/T	2.18 lb/T
	Loco RTE	92,000 lbs	75,600 lbs	92,000 lbs	75,600 lbs	92,000 lbs	75,600 lbs
		41,731 kg	34,292 kg	41,731 kg	34,292 kg	41,731 lbs	34,292 lbs
G 1:X	G X/1000						
36	27.8	1,022	951	1,165	983	1,216	1,018
50	20.0	1,336	1,296	1,584	1,356	1,677	1,420
71	14.1	1,719	1,756	2,143	1,863	2,314	1,984
137	7.3	2,514	2,860	3,505	3,148	3,975	3,499
1500	0.7	4,429	6,878	8,650	8,755	12,113	12,023
Level	0.0	4,787	7,973	10,107	10,601	15,160	15,781
G 1:X	G X/1000						
36	27.7777778	1020	950	1165	980	1215	1015
50	20.0	1,335	1,295	1,580	1,355	1,675	1,415
71	14.1	1,715	1,755	2,140	1,860	2,310	1,980
137	7.3	2,510	2,860	3,500	3,145	3,975	3,495
1500	0.7	4,425	6,875	8,645	8,755	12,110	12,020
Level	0.0	4,785	7,970	10,105	10,600	15,160	15,780

Figure 9 Wagon starting resistances

Figure 10	Wagon 1-hour resistances

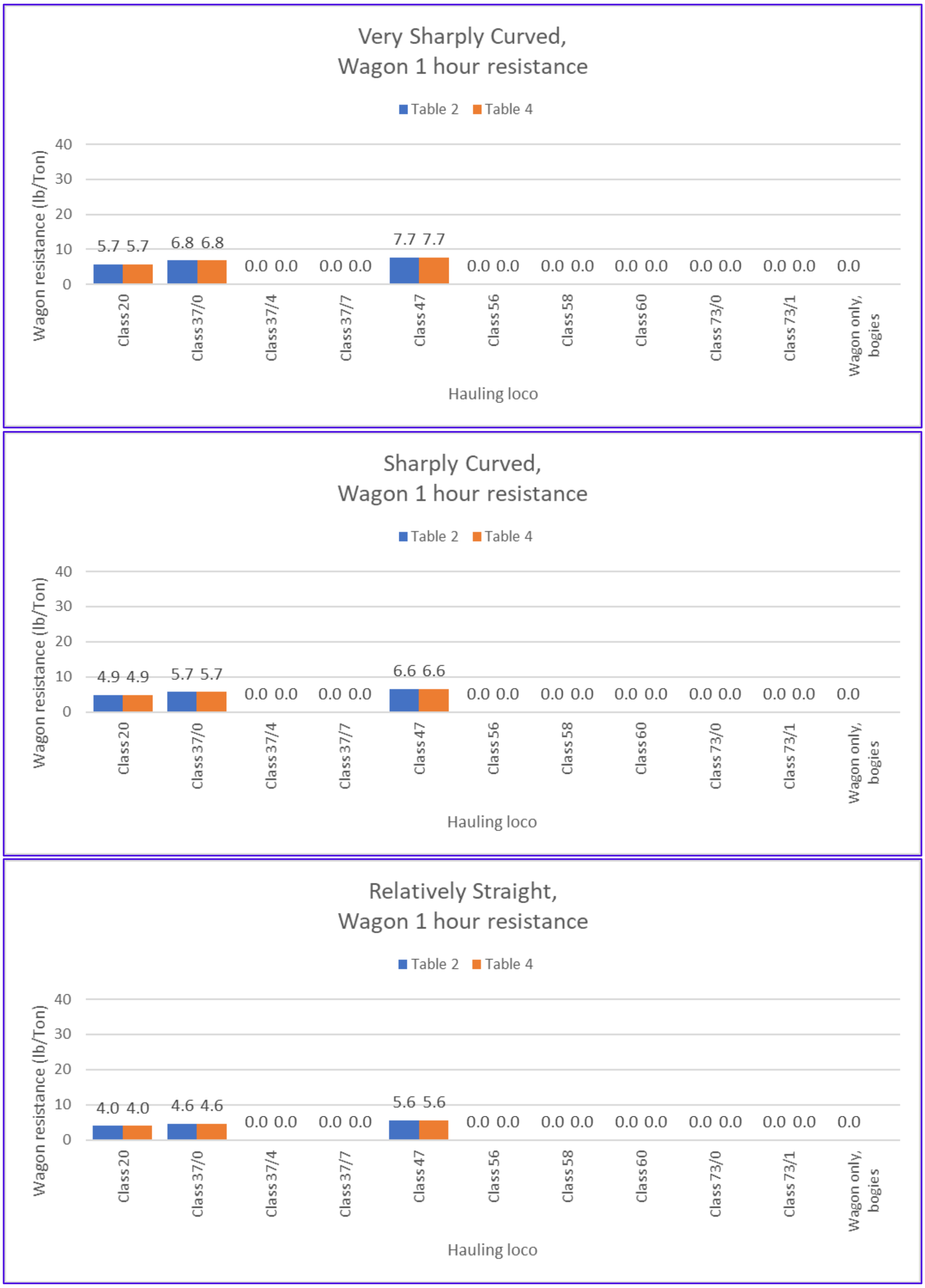


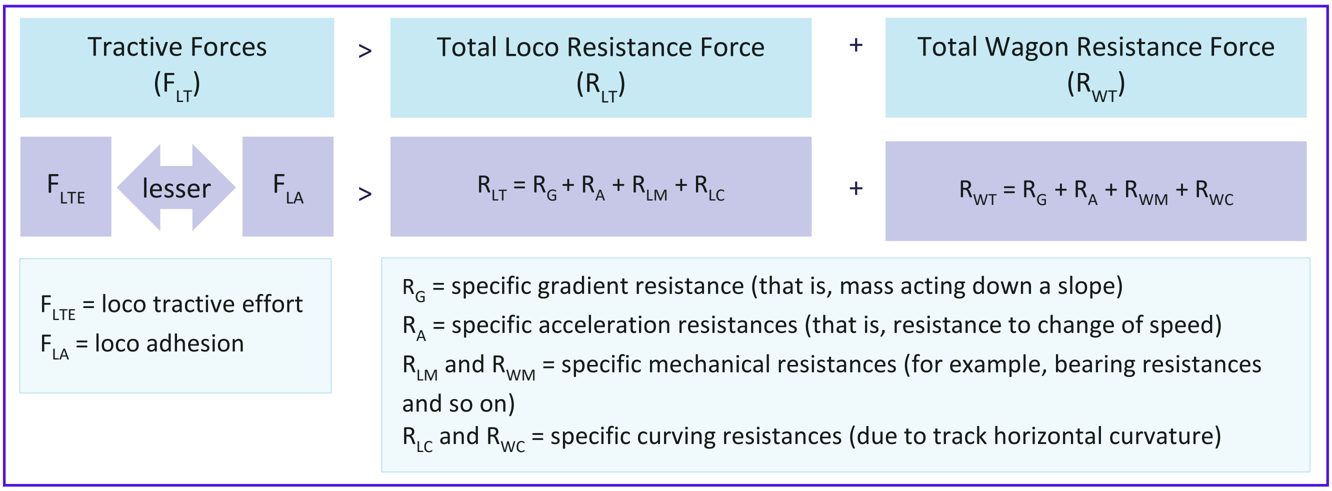
Figure 11 Wagon continuous resistances

3 Detailed assessment of MT19 methodology

Having established how MT19 calculated the TLLs (Section 2 above), it was further analysed to determine how the input parameters may have been developed and used. The principal characteristics are presented in a 'visualisation' in Figure 12 (which is an expansion of Figure 3) and each of the terms will be discussed in this section.

Throughout this section, there will be a mixture of imperial and metric units. The proposed new method (formulae) will be presented in metric units (see Section 5).

Figure 12 Principal characteristics governing TLL



The fundamental factors affecting TLLs are:

- All vehicles: resistances only
- Locomotive: TE, adhesion, environmental conditions, resistances
- Wagons: resistances only.

3.1 All vehicles factors

The common factors influencing all vehicles in a train are gravity and acceleration resistance as detailed below.

3.1.1 Vehicle gradient resistance, RG

Gradient resistance is the downhill force acting on vehicles on a gradient. It is well understood, and it applies consistently to all vehicles, whether starting or rolling.

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

where:

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

X = track gradient (for example, for 1:50, X = 50).

It is assumed that this was used for all vehicles throughout MT19 for gradient resistance.

3.1.2 Vehicle acceleration resistance, RA

The acceleration resistance is the force required to accelerate the vehicles. It is well understood, and it applies consistently to all vehicles, whether starting or rolling.

However, it was noted that in MT19 the acceleration resistance was not applied to locomotives. It is assumed that this was to save processing time and was justifiable at the time, particularly as it has low impact on the calculated TLL.

It was found that the acceleration resistance was simply based on Newton's second law whereby, force = *m*.*a*, where *m* = mass (kg) and *a* = acceleration (m/s^2). However, a value for minimum acceleration, *a*, was required. British Transport Commission (1954), British Rail (1983), Corus (2009) and Rangelov (2012) were reviewed, and it was decided to apply the value of 2.5 cm/s^2 as described in British Rail (1983) as shown by the orange box in Figure 13. British Rail (1983) is a discussion of MT19 and therefore the values contained within are assumed to be the most appropriate for understanding MT19.

Figure 13 Acceleration, excerpt from British Rail (1983)

It is understood that 1.7 daN/t (3.8 lbf/ton) is commonly used by SNCF for general applications with freight trains in conjunction . with a minimum acceleration of 2.5 to 3 cm/s^2 (0.06-0.07 mile/h/s), and that on grades they do not, in every case, modify the basic figure

The SNCF method has been evaluated in comparison with the standard B.R. method(5). Very similar results were obtained from both methods.

Consequently:

a = 2.5 / 100 = 0.025 m/s^2 = 0.245 g

Therefore, based on $F = m \times a$, the vehicle acceleration resistance is:

R_{AS} = 1 kg x 0.025 m/s^2 = 0.025 N/kg = 25 N/tonne (= 5.71 lb/Ton).

The minimum acceleration of 2.5 cm/s² is also used by some current passenger rolling stock manufacturers as their minimum acceleration rate assumption when defining the maximum design speed for multiple units on level track.

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

where:

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

It is assumed 2.5 cm/s² is used throughout MT19 for starting acceleration resistance of wagons only.

It is assumed that, in the rolling condition, the speed is constant and there is no acceleration resistance (that is, the train is not accelerating), therefore the vehicle acceleration resistance is set to zero for rolling resistance.

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

where:

a_R = train acceleration at rolling (m/s²), suggested value = 0 m/s² so:

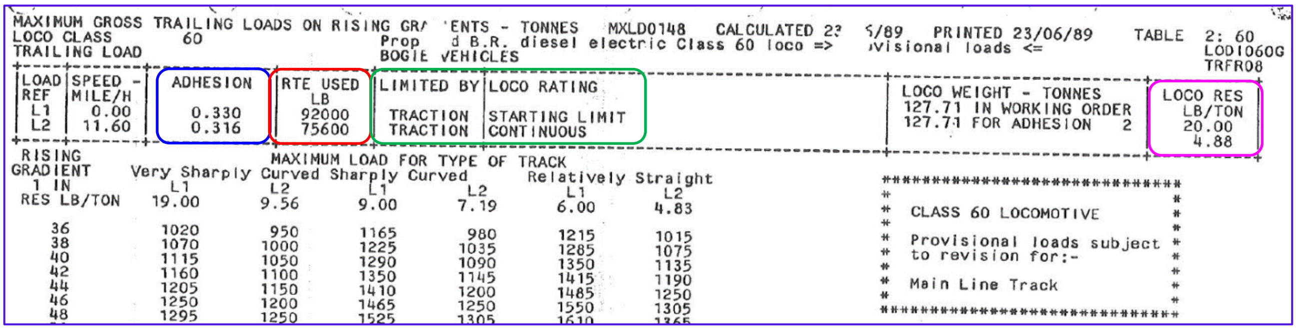
$$R_{AR} = 0 \ [{}^{N}/_{tonne}]$$

It is assumed 0 cm/s² is used throughout MT19 for rolling acceleration resistance.

3.2 Locomotive factors

In MT19 various locomotive factors are provided in each table header, for example, see the highlighted parts of Figure 14: adhesion (blue), tractive effort (red), and specific resistance (pink) for the starting and continuous cases (green).

Figure 14 Example of MT19 locomotive factors



MAXIMUM GROSS TRAILING LOADS ON RISING GR/ 'ENTS - TONNES MXLD0148 CALCULATED 2? 5/89 PRINTED 23/06/89 TABLE 2: 60
LOCO CLASS 60 Prop d B.R. diesel electric Class 60 loco => ›visional loads <= LODI060G
TRAILING LOAD BOGIE VEHICLES TRFR08

LOAD REF	SPEED - MILE/H	ADHESION	RTE USED LB	LIMITED BY	LOCO RATING	LOCO WEIGHT - TONNES	LOCO RES LB/TON
L1	0.00	0.330	92000	TRACTION	STARTING LIMIT	127.71 IN WORKING ORDER	20.00
L2	11.60	0.316	75600	TRACTION	CONTINUOUS	127.71 FOR ADHESION 2	4.88

RISING GRADIENT 1 IN	Very Sharply Curved L1	Very Sharply Curved L2	Sharply Curved L1	Sharply Curved L2	Relatively Straight L1	Relatively Straight L2
RES LB/TON	19.00	9.56	9.00	7.19	6.00	4.83
36	1020	950	1165	980	1215	1015
38	1070	1000	1225	1035	1285	1075
40	1115	1050	1290	1090	1350	1135
42	1160	1100	1350	1145	1415	1190
44	1205	1150	1410	1200	1485	1250
46	1250	1200	1465	1250	1550	1305
48	1295	1250	1525	1305	1610	1365

CLASS 60 LOCOMOTIVE

Provisional loads subject to revision for:-

Main Line Track

3.2.1 Locomotive adhesion

When assessing adhesion, the proportion of total locomotive weight on each individual axle is required. In the simplest cases the weight under static conditions is evenly distributed across all axles. However, for some locomotive types, the weight is not evenly distributed between the axles. In MT19 this is handled by defining a lower 'Loco weight – for adhesion calculations' which assumes the lowest loading on an axle applies to all the driven locomotive axles and uses this value for calculations. This can be seen in Table 3, that is, for Class 20 and Class 37/0. It was found that this weight was used in conjunction with the coefficient of friction to determine the locomotive adhesion force.

Table 3 Locomotive weight used for adhesion in MT19

Locomotive class	Loco weight – in working order (tonnes)	Loco weight – for adhesion calculations (tonnes)	% Adhesion weight of Total weight
Class 20	73.87	73.10	99.0
Class 37/0	106.69	102.21	95.8
Class 37/4	106.00	106.00	100.0
Class 37/7	117.01	117.01	100.0
Class 47	118.88	118.88	100.0
Class 56	125.38	125.38	100.0
Class 58	129.01	129.01	100.0
Class 60	127.71	127.71	100.0
Class 73/0	76.31	76.31	100.0
Class 73/1	76.81	76.81	100.0

Adhesion levels decrease as speed increases. We have determined that in MT19 a relatively simplistic approach to handling this is taken whereby a single value is used for starting adhesion and a single lower value (typically lower by 0.01) is used for rolling adhesion. This was a reasonable approach for the older locomotive types extant when MT19 was first developed (when the achievable adhesion values were lower than for recent locomotive types).

For the Class 60, the TE is limited in both the starting and continuous cases by the chosen adhesion levels, therefore the MT19 approach is too simplistic and leads to significantly lower TLLs than can be obtained in practice. Furthermore, when the Class 60 was included in MT19 there was a lack of evidence of its deliverable adhesion which dictated a conservative choice of adhesion values.

For most older locomotive classes where reliable TE curves are available (for example, Class 37, 47, 56 and 58) the values of μ appear to have been back-calculated from the TE and locomotive adhesion weight (that is, μ = TF/FR, where TF = tractive force and FR = resultant force due to locomotive weight) rather than explicitly experimentally determined. Or alternatively an assumption was made that limits coefficient of friction to a value lower than the maximum back-calculated value. The mainline and secondary route cases in MT19 where assumptions for μ_{max} are made rather than back-calculated from μ = TF/FR (in practice the calculated μ value is rounded up to the nearest 2 decimal places, for example, 0.237 is rounded to 0.24).

MT19 considers mainline and secondary routes which we have taken to mean mainline passenger lines and freight-only secondary routes, respectively. For secondary routes for virtually all locomotive variants covered in MT19 Tables 3 and 4, the maximum value of μ is 0.02 lower than for the equivalent locomotive variant for mainline routes covered in MT19 Tables 1 and 2 where back-calculation from μ = TF/FR is used. The single exception to the 0.02 offset is for Class 37/7 in MT19 Table 1 where the value is already 0.02 lower than MT19 Table 2 so further reduction is not applied in MT19 Table 3. This could either be an unintentional error or a later assumption for the use of this locomotive class on steel/iron ore traffic (often double headed). The exception is highlighted in bold in Table 4 below.

Note that for Class 60 on mainline routes (MT19 Tables 1 and 2) the value has been set to μ = 0.33 as a conservative assumption. This assumption aligns with assumptions used in continental Europe at the time (France, Germany, and Benelux) for locomotives with similar new traction equipment with improved TE delivery and control. The MT19 assumption for maximum adhesion for Class 60 on secondary routes in MT19 Tables 3 and 4 is 0.03 lower than in MT19 Tables 1 and 2 (also highlighted in bold in Table 4 below) in a similar way to the reduction for secondary routes used for other locomotive types in MT19.

Table 4 Maximum starting adhesion (μ) values used in MT19 Tables 1 to 4

Locomotive class	MT19 Table 1 μ values	MT19 Table 2 μ values	MT19 Table 3 μ values	MT19 Table 4 μ values	0.02 difference between MT19 Tables 1&2 and Tables 3&4 values?
Class 20	0.24	0.24	0.22	0.22	Yes
Class 37/0	0.24	0.24	0.22	0.22	Yes
Class 37/4	0.24	0.24	0.22	0.22	Yes
Class 37/7	**0.22**	0.24	0.22	0.22	Yes for Table 2
Class 47	0.22	0.22	0.20	0.20	Yes
Class 56	0.24	0.24	0.22	0.22	Yes
Class 58	0.24	No data in MT19	0.22	0.22	Yes
Class 60	0.33	0.33	**0.30**	**0.30**	**No, 0.03**

Class 73/0	0.22	0.22	0.20	0.20	n/a
Class 73/1	0.24	0.24	0.22	0.22	n/a

In summary, a value of 0.24 for maximum adhesion (at starting) has been taken for mainline routes and 0.22 for secondary routes; these values apply to ex-British Rail locomotives with older DC traction equipment.

The adhesion values for the Class 60 (0.33 for mainline routes and 0.30 for secondary routes) are out of step for several reasons:

- Upgraded DC traction equipment (two generations on from previous locomotives)
- The authors of the MT19 methodology adjusted the adhesion values to enable some of the greater TE potential of the locomotive to be realised
- The values in MT19 were conservative assumptions made before a Class 60 had been manufactured.

Where the maximum TE is limited by adhesion the following is used in MT19 to calculate the maximum TE:

$$TF_{max} = \mu \times RF$$

$$TF_{max}\ [kN] = \mu \times locomotive\ adhesion\ mass\ [tonnes] \times g \times \cos\alpha$$

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

It is assumed μ = 0.24 for mainline and μ = 0.22 for secondary routes has been used throughout MT19. Except for the Class 60, where μ = 0.33 for mainline and 0.30 for secondary routes was used.

3.2.2 Locomotive starting tractive effort

It is thought that TE data used in MT19 was in most cases derived from real-world testing and measurement, except for Class 60 where preliminary design data (with lower values than those later derived from real world testing and measurement) was used. The locomotive TE values used in MT19 are given in Table 5 below. The TLLs in MT19 Table 1 and 2 are mostly unaffected by the maximum adhesion limits in MT19 (Table 4 in Section 3.2.1 above) except for the Class 60 values which are capped. The TLLs in MT19 Table 3 and 4 are mostly reduced because a lower maximum adhesion assumption is used for secondary routes (only Classes 58 and 73/1 are not affected).

Table 5 Locomotive starting tractive effort values used in MT19

Locomotive class	Locomotive Starting TE (kN)	
	MT19 Tables 1 & 2	MT19 Tables 3 & 4
Class 20	172	158
Class 37/0	236	220
Class 37/4	250	229
Class 37/7	275	252
Class 47	256	233
Class 56	274	270
Class 58	274	274
Class 60	409	376
Class 73/0	165	150
Class 73/1	160	160

The locomotive starting tractive effort values given in Table 5 above are used in MT19.

3.2.3 Locomotive rolling tractive effort

In MT19 the locomotive RTE for the 1-hour and continuous cases are given at the top of the table for each locomotive and these are reproduced in Table 6 below. Data for the 1-hour case is only available for some older locomotive types because data collection for the 1-hour rating in MT19 was discontinued in the early 1970s (between Class 50 and Class 56 construction). Also, the continuous rating is consistent between MT19 tables except for the Class 56 and 58 (highlighted in bold).

Table 6 Locomotive rolling tractive effort values used in MT19

Locomotive class	Locomotive rolling TE (kN)			
	1-hour		Continuous	
	MT19 Table 1 & 2	MT19 Table 3 & 4	MT19 Table 1 & 2	MT19 Table 3 & 4
Class 20	124	124	111	111
Class 37/0	157	157	147	147
Class 37/4	-	-	185	185
Class 37/7	-	-	185	185
Class 47	149	149	137	137
Class 56	-	-	**240**	**206**
Class 58	-	-	**240**	**212**
Class 60	-	-	336	336
Class 73/0	-	-	73	73
Class 73/1	-	-	60	60

The locomotive rolling tractive effort values given in Table 6 above are used in MT19.

3.2.4 Locomotive starting resistance (mechanical and curving)

In MT19 a simple, single uniform value of 20 lb/Ton (87.5230 N/tonne) is used for all locomotive types for total locomotive starting resistance (R_{LTS}) (see Table 7). This is assumed to include both mechanical and curving resistance and is clearly independent of each locomotive's characteristics (for example, number of axles, vehicle length, and so on).

Table 7 R_{LTS} values used in MT19

Locomotive class	Locomotive Starting Resistance R_{LMS} (lb/Ton)
Class 20	20
Class 37/0	20
Class 37/4	20
Class 37/7	20
Class 47	20
Class 56	20
Class 58	20
Class 60	20
Class 73/0	20
Class 73/1	20

A simple, single uniform value of 20 lb/Ton (87.5230 N/tonne) is used for all locomotive types in MT19 for total locomotive starting resistance, including mechanical and curving resistances.

3.2.5 Locomotive rolling resistance

The continuous locomotive resistance values (lb/Ton) used in MT19 are shown in Table 8 below.

Table 8 Locomotive 'continuous' resistance used in MT19

Locomotive class	Locomotive Rolling Resistance R_{LMR} (lb/Ton)
Class 20	4.80
Class 37/0	4.87
Class 37/4	4.69
Class 37/7	4.69
Class 47	5.36
Class 56	4.95
Class 58	4.95
Class 60	4.88
Class 73/0	4.75
Class 73/1	4.83

It was observed that the locomotive rolling resistance is simplified compared to wagon resistance (that is, compared to Sections 3.3 and 3.4) but is not simplified to the same extent as locomotive starting resistance (that is, compared to Section 3.2.4). The origins of the data in Table 8 are investigated in more detail below.

3.2.5.1 Curving rolling resistance

In MT19, unlike wagon curving rolling resistance (for example, see Section 3.3.2.2), locomotive curving rolling resistance is not an explicit function of track curvature. The overall impact of locomotive curvature resistance on the TLL is small and therefore this was a reasonable simplification at the time. However, the introduction of steerable axle bogies on more modern locomotive designs (for example, Class 66) will reduce locomotive curving rolling resistance but this cannot be reflected by the existing MT19 methodology.

3.2.5.2 Mechanical rolling resistance

For the overall investigation of MT19, we initially investigated the 'continuous' resistance of ten locomotive types, with either four or six axles, that are still in use on the network. However, it soon became clear that all available rolling resistance data would be needed. Therefore, the investigation was enlarged to include all locomotive types and 1-hour data sets for the oldest locomotive types. The 1-hour rating was discontinued in the early 1970s for newer locomotives in MT19 (that is, between the construction of Classes 50 and 56) so there are usually only two limiting test cases for newer locomotive (that is, Class 56, 58 and 60) or significantly modified locomotives (for example, Class 37/4 and 37/7).

The initial assessment concluded that:

- The locomotive resistance versus speed relationships were different for 4-axle and 6-axle locomotives and they should be assessed separately.
- The Class 50 1-hour rating data in MT19 had not been revised after the locomotives were re-engineered and refurbished between 1979 and 1984, so the 1-hour dataset and assumption as a whole was not consistent and did not align with the Class 50 starting and continuous data sets (which both align with the post refurbished locomotive state) so was not used for further analysis in this project.
- The Class 60 datasets were created three years after the last iteration of all the other locomotive data and often has different underlying assumptions compared to other locomotives. From initial analysis it appeared that the Class 60 locomotive running resistance data had been created using the approach for a 4-axle locomotive rather than as 6-axle, so the Class 60 was handled separately for further investigation in this project.

In MT19 there appear to be three factors impacting R_{LMR}:

- Total number of axles (not just driven axles)
- Locomotive speed
- Average axle load.

We chose to examine the relationship between these variables and R_{LMR} in two iterations. The first iteration considered the largest impacts on R_{LMR} that is, the number axles and speed. The second iteration considered the lesser impact of the average axle load.

Iteration 1, Analysis of number of axles and speed

Figure 15 shows two distinct sets of specific resistance-speed relationships correlating to 4-axle and 6-axle locomotives, including the anomalous Class 60 data point.

For the 4-axle resistances, the following best-fit line equation was derived:

$$\textit{4-axle locomotive specific rolling resistance (lb/Ton)} = 4.5 + 0.002375 \times v^2$$

This is plotted as a blue line in Figure 15 where all the data points are reasonably close to this best-fit curve but not perfectly on the curve.

Similarly for 6-axle locomotives (excluding Class 60 shown as the orange triangle in Figure 15) a best-fit line equation was derived:

$$\textit{6-axle locomotive specific rolling resistance (lb/Ton)} = 4.5 + 0.001583 \times v^2$$

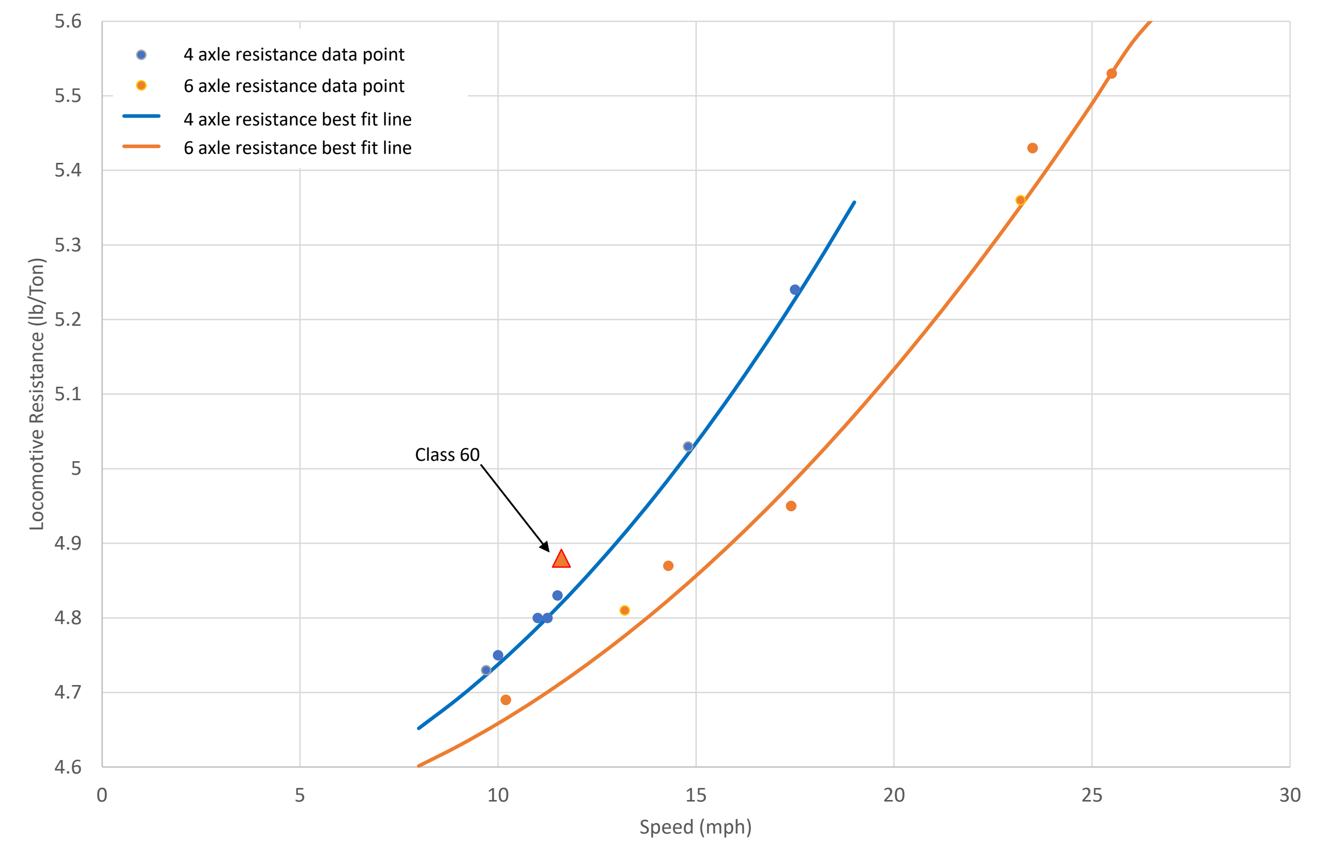
This is plotted as an orange line in Figure 15 where all the data points are reasonably close to this best-fit curve (but not as close as the 4-axle case).

The differences between the curve and data points in the respective 4-axle and 6-axle curves and data points (due to variations in axle loads) are analysed in Iteration 2 below.

The best-fit line equations can be combined into the following format:

$$\textit{Locomotive specific rolling resistance (lb/Ton)} = 4.5 + \frac{0.0095}{Number\ of\ axles\ (n)} \times v^2$$

Figure 15 Locomotive rolling resistance at continuous and 1-hour speeds



Iteration 2, Analysis of axle load

Locomotives with higher axle loads tend to have lower specific resistances and those with lower axle loads tend to have higher specific resistances than predicted by Iteration 1. Taking this into account, and attempting to minimise the difference in results, the following additional factor is needed for both 4-axle and 6-axle locomotives:

$$+ (19.8 - Axle\ load\ (Q)[in\ tonnes]) \times 0.0175$$

After which the final combined formula for both 4-axle and 6-axle locomotives is:

Specific locomotive rolling resistance [lb per ton]:

$$\mathrm{R}_{LMR} = 4.5 + \frac{0.0095}{Number\ of\ axles\ (n)} \times v^2 + (19.8 - Axle\ load\ (Q)[in\ tonnes]) \times 0.0175$$

Locomotive rolling resistance [lb]:

$$\mathrm{R}_{LMR} = \text{locomotive mass [Tons]} \times (\frac{0.0095}{Number\ of\ axles\ (n)} \times v^2 + 4.5 + (19.8 - Axle\ load\ (Q)[in\ tonnes]) \times 0.0175)$$

This formula replicates the MT19 specific resistance values (Table 8) to within 0.1% as shown in Table 9, except for the anomalous Class 60. However, if this formula is applied to the Class 60 with number of axles (n) = 4 (rather than the correct 6), then the MT19 Class 60 specific resistance is also replicated to within 0.1%. Hence, we believe the Class 60 continuous rolling resistance value in MT19 has been erroneously calculated.

Table 9 Locomotive combined 'continuous' resistance comparisons

Locomotive class	Locomotive Rolling Resistance R_{LMR} (lb/Ton)		
	MT19 'continuous'	Calculated	Difference
Class 20	4.80	4.79	-0.01
Class 37/0	4.87	4.88	+0.01
Class 37/4	4.69	4.68	-0.01
Class 37/7	4.69	4.68	-0.01
Class 47	5.36	5.36	0.00
Class 56	4.95	4.95	0.00
Class 58	4.95	4.95	0.00
Class 60	4.88	*4.88**	0.00
Class 73/0	4.75	4.76	+0.01
Class 73/1	4.83	4.83	0.00

* Note: The Class 60 value is believed to be erroneously based on 4 axles, the calculated 4-axle value is shown.

It is assumed that this formula (Iteration 2) for locomotive rolling resistance was used in MT19.

3.3 Wagon factors for 4-axle bogied wagons

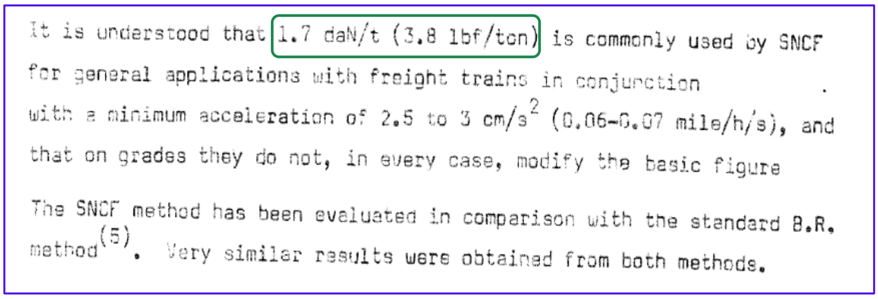
After some experimentation it was concluded that the wagon resistances used in MT19 Tables 2 and 4 were sourced from the DBTRFR08 data set (stated as 'TRFR08' in the top right corner of each table). This data set is discussed in Section 5.5.2 of Headech (1982) where it was noted that its form could not be reproduced (that is, some source data *'cannot now be traced'*). Therefore the source of the MT19 4-axle (bogie) wagon resistances will be deduced in the following sections.

3.3.1 Starting resistance for 4-axles

3.3.1.1 Mechanical starting resistance for 4-axles

The wagon mechanical resistance at starting is denoted as R_{WMS} in this document. Mechanical resistance differs between wagon types, but, for simplicity, we assume a mechanical starting resistance value of 1.7 daN/tonne, or 17 N/tonne, or 3.88 lb/Ton was used for all wagon types in MT19. This value is derived from British Rail (1983), as shown in green in Figure 16.

Figure 16 Mechanical resistance, excerpt from British Rail (1983)



It is understood that 1.7 daN/t (3.8 lbf/ton) is commonly used by SNCF for general applications with freight trains in conjunction with a minimum acceleration of 2.5 to 3 cm/s^2 (0.06-0.07 mile/h/s), and that on grades they do not, in every case, modify the basic figure

The SNCF method has been evaluated in comparison with the standard B.R. method(5). Very similar results were obtained from both methods.

It is assumed that 1.7 daN/tonne was used for wagon starting resistance in MT19.

3.3.1.2 Curving starting resistance for 4-axles

Curving resistance depends on many factors (for example, axle-base, rail profile, wheel profile, check rails, friction modifiers, track gauge, bogie type, suspension characteristics, track stiffness, and so on).

MT19 considers wagon resistances for 'very sharply curved', 'sharply curved' and 'straight' track, which, according to Figure 17, are track curve radii of 10, 15, and 30 chains (201 m, 302 m, and 603 m), respectively.

We believe the formula shown in Figure 18, as defined in Headech (1982) and British Rail (1983), was used in MT19, that is, curving starting resistance is 7,390 N.m/tonne (753.6 kg.m/tonne, 1,689 lb.m/Ton).

However, it was noted that MT19 has a significant and disproportionate increase in curving resistance at 10 chains (201.2 m). It is hypothesised that MT19 increases the wagon resistance for tight curves, possibly due to other influences (for example, check rails which are typically installed on curves of 200 m and below). After some 'trial and error' it was found that an additional 1,412 lb.m/Ton (630 kg.m/tonne, 6,178 N.m/tonne) was needed to give a match at 10 chains. This is equivalent to an extra $^5/_6$th (that is, an additional 83.3% or a multiplier of 1.833). It is not known how this might have been applied in MT19 at curves below 10 chains, therefore, it was decided to include the additional 1,412 lb.m/Ton for all curves below 10 chains. This gave the deduced curving resistance shown in Figure 19 (see Figure 20 for the total resistance). The deduced resistance was a good match to the MT19 total wagon resistance values at 10, 15 and 30 chains; see Section 3.3.1.3 and Figure 21.

It is assumed that the following was used for wagon starting resistance in MT19:

When R >= 201 m, R_{WCS} = 7,390 / R (N/tonne)

When R < 201 m, R_{WCS} = 1.833 x 7,390 / R (N/tonne)

Figure 17 Curve radii, MT19 versus British Rail (1983)

Table 2 For Bogie Vehicles

Track Curvature	Specific Resistance
Straight (More than 25 chns)	12 lb/ton
Sharply Curved (About 15 – 25 chns)	15 lb/ton
Very Sharply Curved (Less than 15 chns)	25 lb/ton

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Timing work for B.R. has not so far taken account of curve resistance in this way, as it is thought to have little effect in B.R. conditions, and the above facility has only been used on overseas project work.

Although curve resistance has not been applied in production of computer timings, for B.R. values used for running at slow speeds in the preparation of N tables are obtained from the formula :-

$$Rc = \frac{T}{1065R}$$

where :-

Rc = curve resistance (lbf/ton)
T = rail tractive effort (lbf)
R = radius of curvature (chains)

for very sharply curved track R = 10
for sharply curved track R = 15
for relatively straight track R = 30

Figure 18 Curving resistance R_{WCS} from Headech (1982) and British Rail (1983)

$$R_c = \frac{7390}{r} \text{ Newtons/tonne}$$

where R_c = curve resistance (N/tonne)

r = curve radius (metres)

3.2 Curve Resistance

Various formulae for curve resistance have been identified[6] and found to produce similar results. From these it has been proposed to adopt for B.R. as a general formula :-

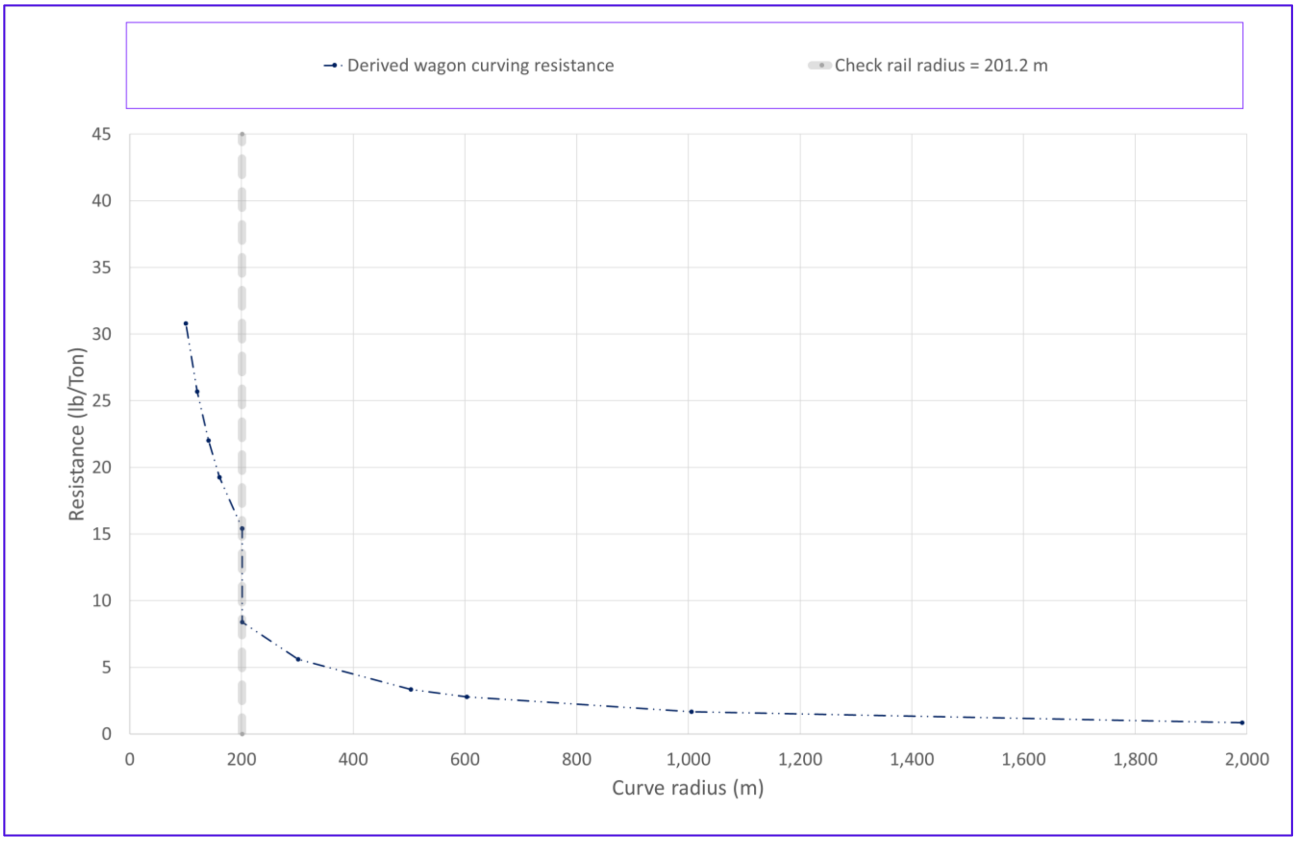
$$Rc = \frac{739}{r}$$

where :-

Rc = curve resistance (daN/t)

r = curve radius (m)

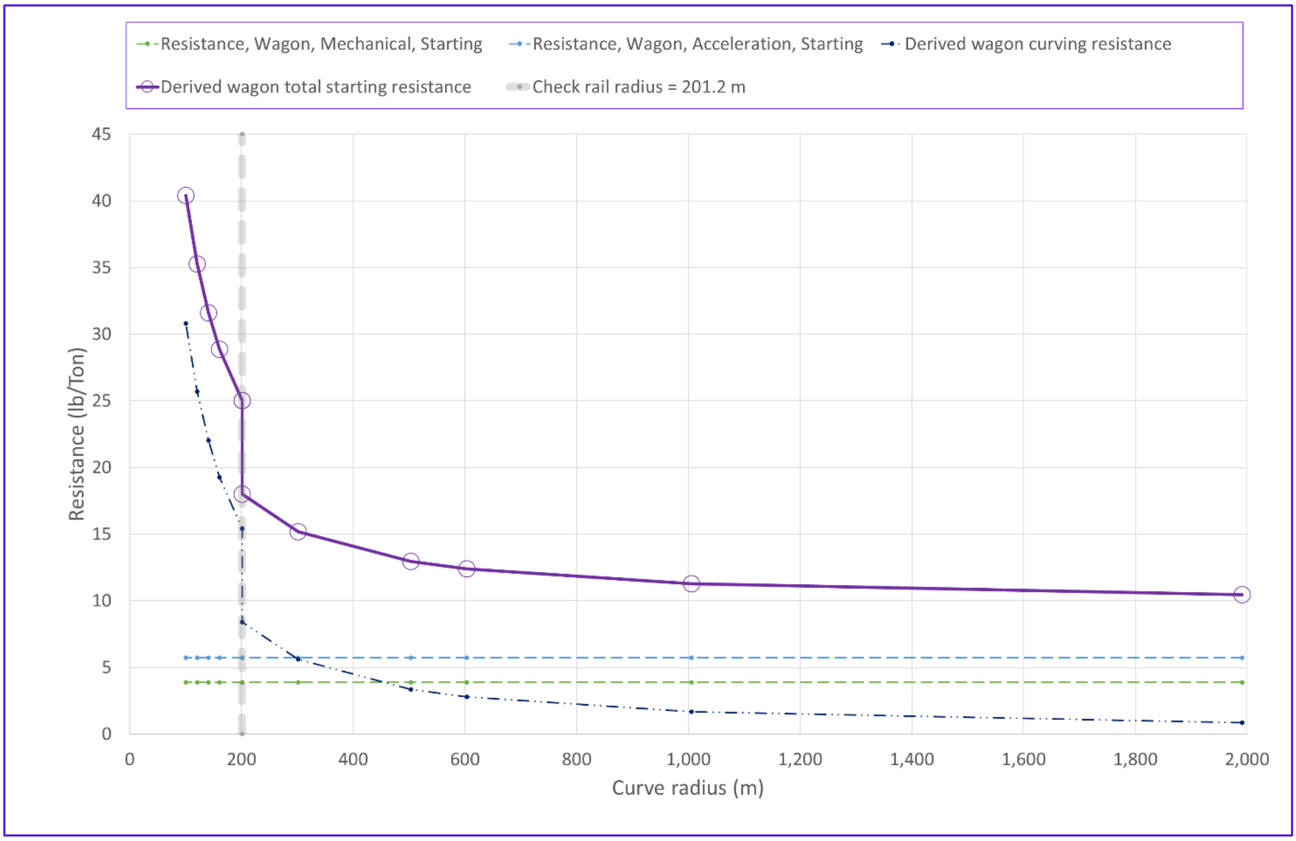
Figure 19 Deduced MT19 wagon curving resistance, R_{WCS} versus curve radius



3.3.1.3 Combined starting resistance for 4-axles

When the acceleration, mechanical, and curving starting resistances are combined (added) they give the wagon resistance shown in Figure 20 (purple line).

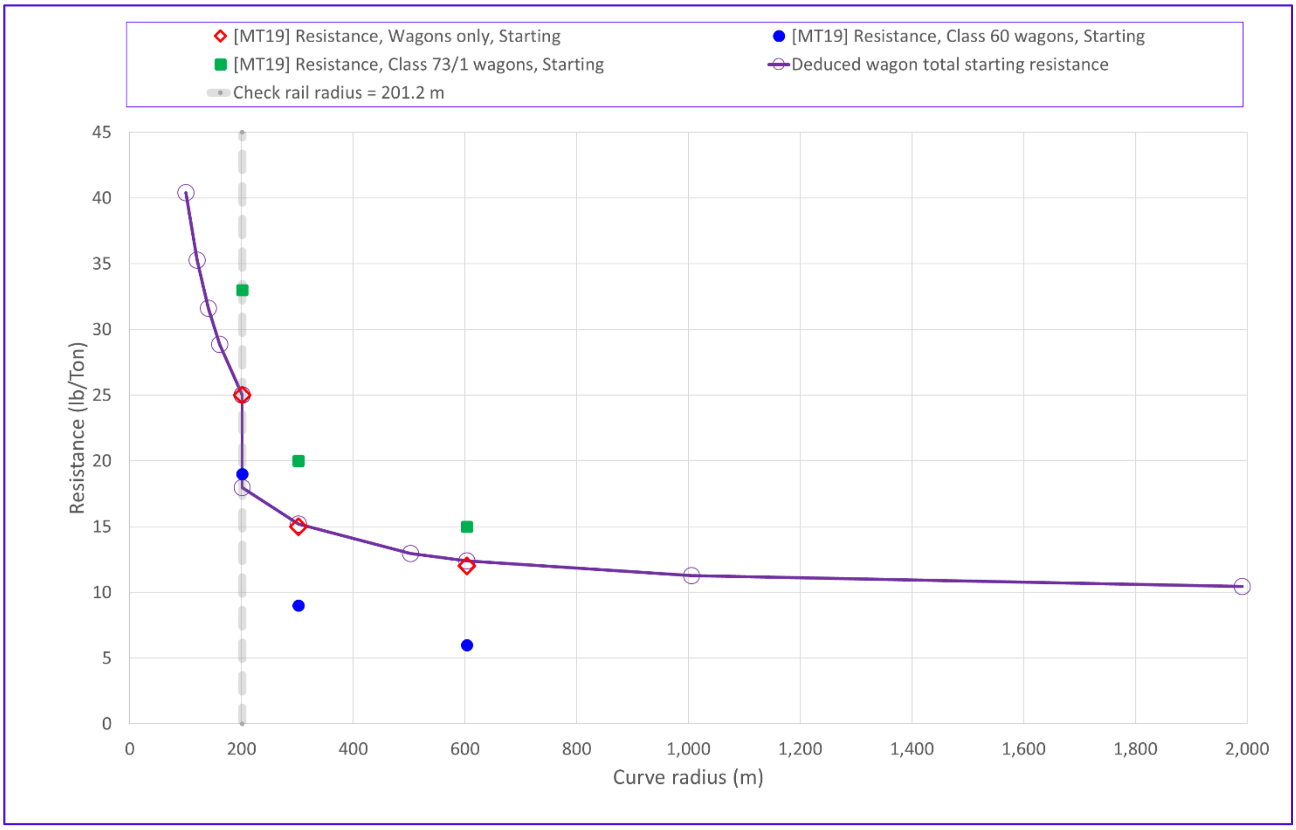
Figure 20 Deduced MT19 wagon starting resistance versus curve radius



This is compared with the MT19 Table 2 and Table 4 values as shown in Figure 21. The deduced resistance is a reasonable match to the predominant values of 25, 15, and 12 lb/Ton used in MT19 (the red diamond data points in Figure 21, from Figure 9) and it sits between the higher and lower values used for the Class 73/1 and Class 60.

It is assumed that this approach, the combination of mechanical, curving, and starting resistance, is a suitable interpretation of that used for the MT19 trailing load limits for starting on curves.

Figure 21 Wagon starting resistances comparisons



3.3.2 Rolling resistance, 4-axles

3.3.2.1 Mechanical rolling resistance for 4-axles

To understand the MT19 methodology, two formulae for wagon rolling resistance, R_{WMR}, at various speeds, were considered:

From Section 8 in Headech (1982) for 'bogie freight stock':

$$R_{WMR} = 7.9 + \frac{79}{Q} + 0.067 \times v + \frac{0.036}{Q} \times v^2 \; [\frac{N}{tonne}]$$

where:

Q = axle load, tonnes

v = Speed, kph.

From Section 7 in Corus (2009) for 'rolling resistance for a standard freight wagon':

$$R_{WMR} = 1.5 \times m_W + 18.125 \times n \times m_W \times V + c \times A_W \times V^2 \; [lb]$$

where:

A_W = Average cross-sectional area (90 sq. ft. for wagons)

b = Coefficient of moving friction (0.015 lb/ton/mph)

c = Coefficient of air resistance and turbulence (0.0005 lb/ton/mph^2/ft^2)

m_W = Gross wagon mass in short (US) tons

n = Number of axles on the wagon

Q = axle load, tonnes

V = Speed, mph

v = Speed, kph.

The formulae were used to produce Table 10 and Figure 22, based on a 100 Ton, 4-axle wagon. As can be seen from Figure 22, the specific resistances vary between the two methods.

It was also noted that the specific resistances from the two methods diverge even more for lower axle loads, especially at higher speeds; see Figure 23 which shows the specific resistances for various GLW 4-axle wagons. However, up to about 25 mph (the maximum continuous speed used in MT19) the differences are relatively small.

The two methods are compared in Section 3.3.2.3, Combined rolling resistance for 4-axles, where the determination of the approach that was used in MT19 is made.

Table 10 Calculated resistance mechanical rolling, R_{WMR}

Speed (mph)	R_{WMR} (lb/Ton)	
	Corus (2009) calculated GLW = 100 Ton	Headech (1982) calculated 25.4 tonne axle load
3	2.46	2.60
5	2.50	2.66
10	2.62	2.85
15	2.76	3.07
20	2.92	3.34
25	3.11	3.66
40	3.80	4.84
60	5.03	7.01
80	6.63	9.85
100	8.59	13.36

Figure 22 Chart of calculated resistance mechanical rolling, R_{WMR}

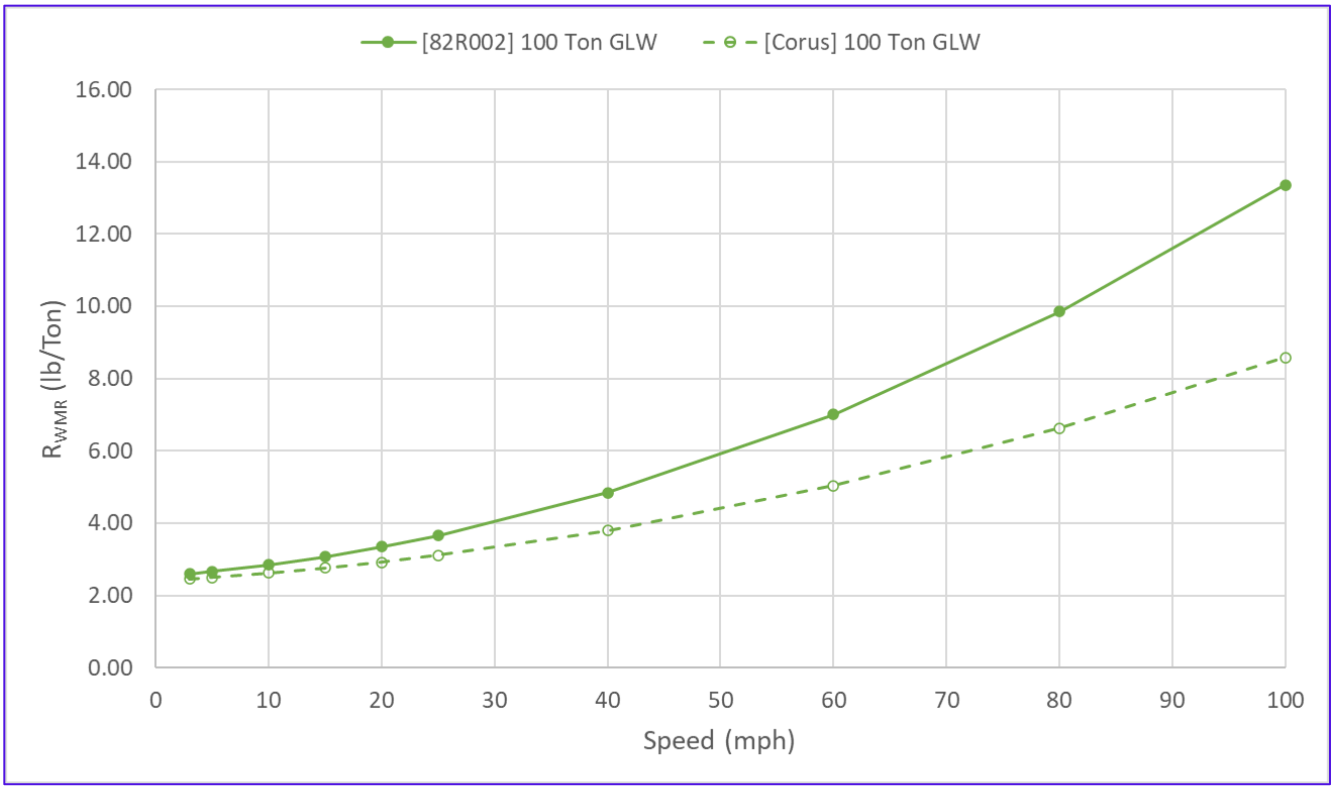
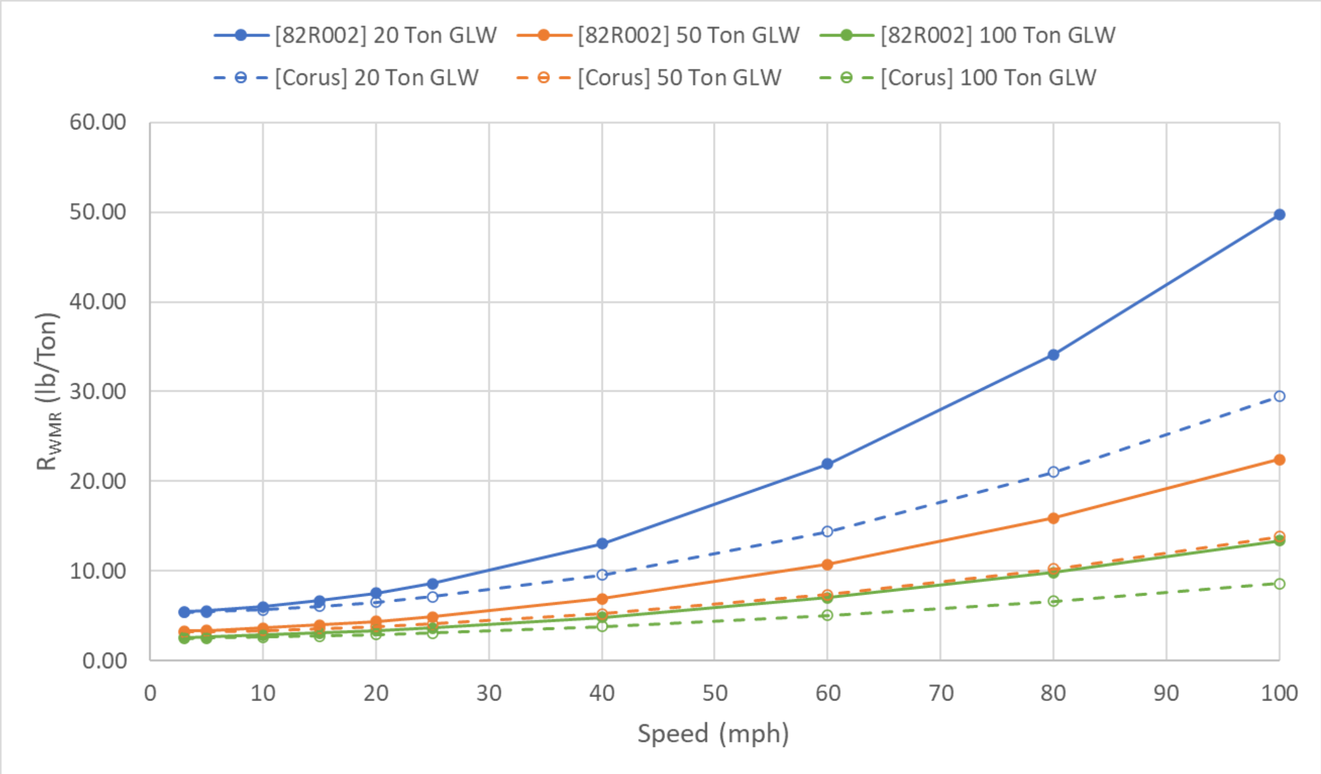


Figure 23 Resistance mechanical rolling, RWMR for various GLWs



3.3.2.2 Curving rolling resistance for 4-axles

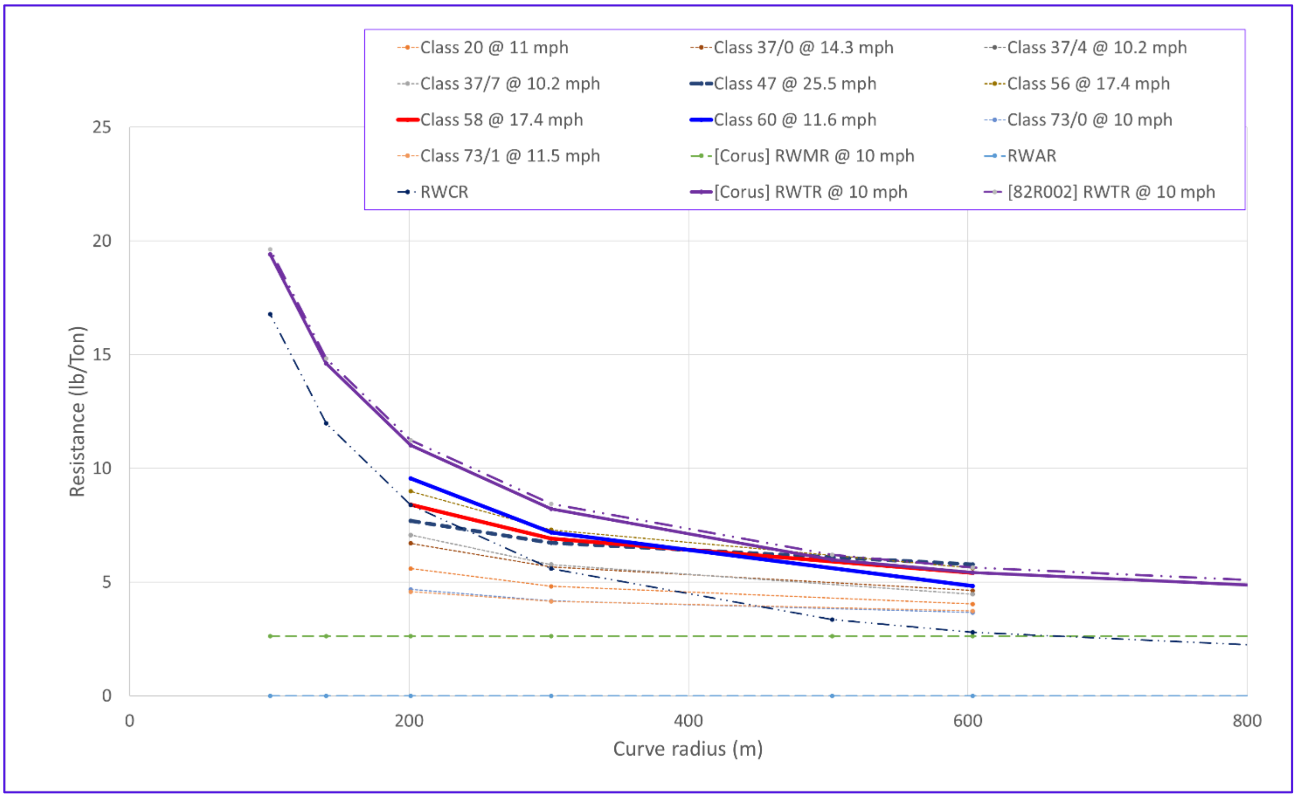
To understand the MT19 methodology, Headech (1982) and British Rail (1983) were reviewed. These reports did not distinguish between starting and rolling curving resistance. Therefore, the value for starting curving resistance from Section 3.3.1.2 was assumed to have been used in MT19.

> It is assumed that 7,390 N/tonne was used in MT19 for curving rolling resistance, but with no ‘step change’ below R201 m.

3.3.2.3 Combined rolling resistance for 4-axles

The combined rolling resistance is dependent on speed, therefore, to enable a comparison with the MT19 tables, a speed of 25 mph was selected from the ‘high’ values in Table 11. When the rolling acceleration, rolling mechanical (at 25 mph), and curving resistances are combined (added) they give the resistance shown in Figure 24 (solid purple line is the Corus (2009) method and the chain dot purple line is the Headech (1982) method, both for a GLW 100 Ton, 4-axle wagon; for details refer to Section 3.3.2). The MT19 Table 2 and Table 4 values for wagon resistances associated with various locomotives are included in Figure 24 for comparison.

Figure 24 Wagon total running resistance versus curve radius

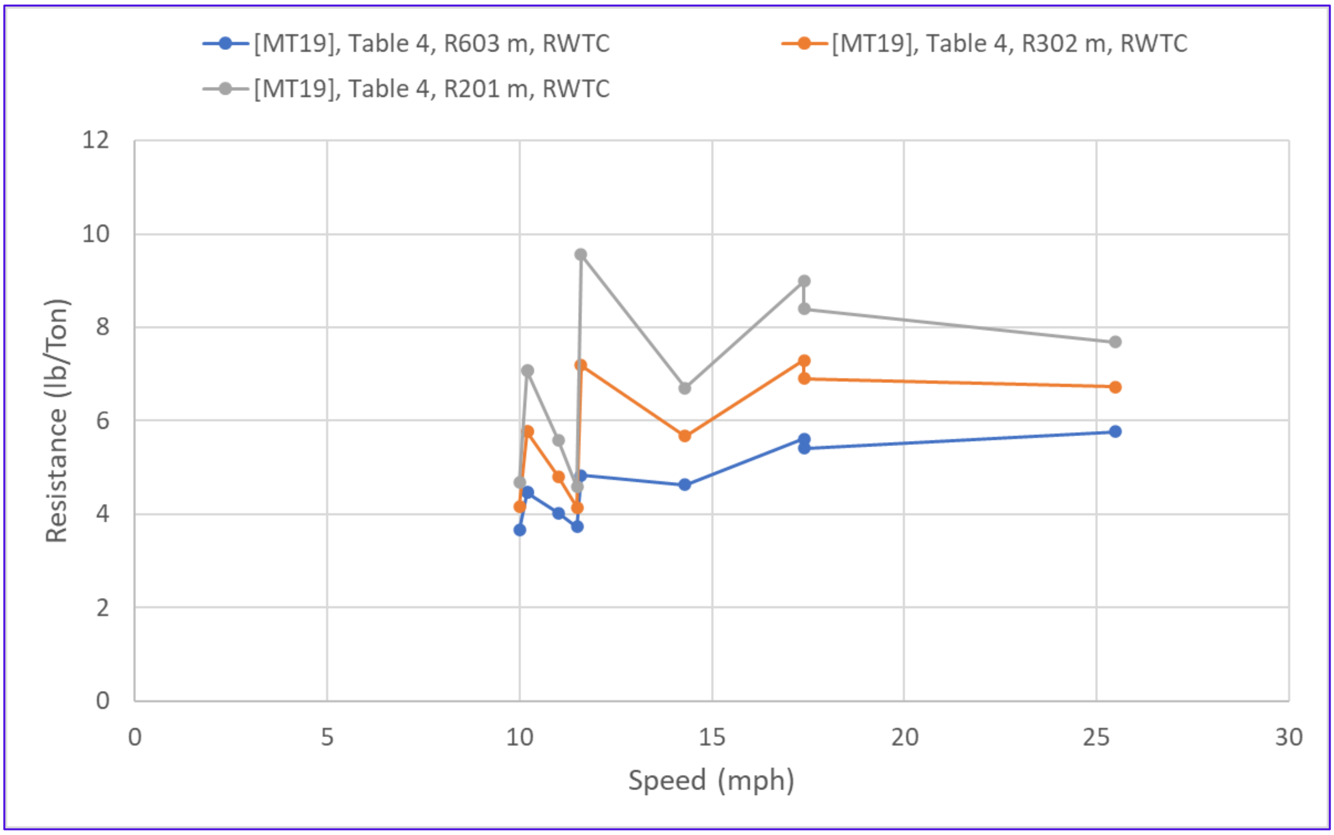


It was noted that a 'one size fits all' method could never match MT19 due to the large variation in wagon rolling resistance used in MT19 (as shown by the variation in wagon resistances for the different locomotives in Figure 24). It was postulated that this was due to the various 'continuous speeds' for each locomotive type (see Table 11), however, when these are plotted, there is no discernible correlation between speed and resistance; see Figure 25.

Table 11 Rolling speeds used in MT19

Locomotive class	Speed used in MT19 Table 4 (mph)
Class 73/0	10.0
Class 37/4	10.2
Class 37/7	10.2
Class 20	11.0
Class 73/1	11.5
Class 60	11.6
Class 37/0	14.3
Class 56	17.4
Class 58	17.4
Class 47	25.5

Figure 25 MT19 wagon resistance versus speed based on locomotive continuous rating TE speeds for three different curvatures



As can be seen in Figure 24, the Corus (2009) and Headech (1982) methods produce conservative (high) wagon resistances which do not reflect the MT19 values; the exact reasons for this are unclear. Therefore, after reviewing other sources (see Section 4) an alternative method was proposed to address wagon rolling resistance; see Section 5.5.2.

The MT19 method for wagon rolling resistance was not replicated and therefore other sources were reviewed (see Section 4).

3.4 Wagon factors for 2-axle non-bogied wagons

3.4.1 Starting resistances for 2-axles (mechanical and curving)

3.4.1.1 Combined starting resistance for 4-axles

It is assumed that this is the same as for 4-axle wagons, that is, the same as Section 3.3.1.3.

3.4.2 Rolling resistance for 2-axle wagons

3.4.2.1 Mechanical rolling resistance for 2-axle wagons

After some experimentation, it was concluded that the MT19 Tables 1 and 3 resistances used for 2-axle wagons come from the DBTRFR07 data set (stated as 'TRFR07' in the top right corner of each table). This is well defined in Headech (1982) Section 5.5.1 (unlike the DBTRFR08 data set used for 4-axle bogie wagons; see Section 3.3). The Headech (1982) formula is repeated below.

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

where:

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

V = speed (mile/h)

Q = axle load (Ton).

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. This equation was also incorporated in timetabling calculations.

When the above is converted to metric/mph and factors (for example, K_{WMR1}) are added for computation purposes, it becomes:

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

where:

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

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

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

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

where:

K_{WMR11} = 4.38 (this metric value replaces the imperial value of 1)

K_{WMR12} = 57.8 (this metric value replaces the imperial value of 13.0)

K_{WMR13} = 0.19 (this metric value replaces the imperial value of 0.07)

K_{WMR15} = 0.025772 (this metric value replaces the imperial value of 0.015)

Q = axle load (tonnes)

V = speed (mph)

Using the above, R_{WMR} can be written:

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

It is assumed that the formula above was used for the mechanical rolling resistance in MT19.

3.4.2.2 Curving rolling resistance for 2-axle wagons

It is assumed that this is the same as for 4-axle wagons, that is, the same as Section 3.3.2.2.

3.5 Key MT19 observations

Observations at the whole-train level are that:

- The MT19 calculation methodology uses different calculations and assumptions than those used for timetabling planning. While MT19 does an effective calculation of predicting low-speed TLLs based on the limitations of coupler strength and tractive effort (fulfilling its initial remit), MT19 is notably not appropriate for predicting TLLs at higher speeds.
- Only locomotives operating on diesel are included in MT19. TLLs for electric-hauled services have been calculated for the FTLB using a methodology that includes timetable assumptions and higher-speed running which is different from the MT19 methodology.
- MT19 only considers two discrete rolling cases (that is, only the continuous and 1-hour rolling cases). These are at two fixed, relatively low speeds and are linked to the locomotive performance in thermally degraded conditions. Real performance is usually better than thermally degraded cases, but these cases exist to assess worst-case performance and TLLs.
- While the MT19 methodology could be used to understand limitations in more rolling cases at different speeds, sufficient data on locomotive tractive effort and adhesion versus speed is not available in MT19.

MT19 has limited applicability to modern diesel locomotives, electric locomotives, and 4-axle wagons. Its assumptions do not align with timetabling calculations.

3.5.1 MT19 locomotive adhesion, tractive effort, and resistance observations

As locomotive resistance is a small component of the overall train resistance when calculating the TLL, some conservative simplifications have often been made in MT19:

- The locomotive starting resistance values are independent of locomotive characteristics and are very high (for example, over four times the rolling resistance: compare Table 7 in Section 3.2.4 versus Table 8 in Section 3.2.5).

- There is no explicit locomotive curvature resistance. This may have been compensated for by the use of locomotive starting and rolling resistances that are higher than that seen in other data sets from the UK and abroad. Continuing with this approach does not work for newer locomotive types that have steerable bogies.
- The methodology only assesses the use of a single locomotive so lower resistance values for a second locomotive are not provided.
- Class 60 TE values are provisional values from before completion of the first locomotive and do not align with measured values from two years later. Furthermore, Class 60 resistance values do not align with the relationships for other locomotives. This appears to be determined based on the incorrect use of four axles. Consequently, the Class 60 is a complex choice for case studies to attempt to understand MT19 methodology, FTLB TLL values and real world running.

Some of these simplifications may have been made to make computation in the late 1960s easier and less memory intensive, and/or some may have been due to lack of available data or confidence levels in that data at the time.

Handling of locomotive resistance needs to be improved from that used in MT19. Accurate Class 60 TE and resistance data should be used.

3.5.2 MT19 wagon observations

The following is a list of observations about the wagon factors used in MT19:

- The wagon type characteristics, assumptions and data sets used in MT19 were developed between 1957 and 1964. The wagon cases in MT19 are not representative of current wagons because in MT19:
    - Axle loadings are too low
    - Roller bearings are not considered for 2-axle wagons
    - No account is taken of variability in wagon aerodynamics and a worst case of mixed wagon types is the default assumption.

  It is therefore not possible to assess impact of these factors on a typical current block train in real world usage. For instance, a genuinely full aggregate train has far higher axle loadings, while an empty aggregate train has higher aerodynamic resistance. Furthermore, modern block trains will have better aerodynamic characteristics compared to older mixed-traffic trains.
- British Rail reviews of train resistance calculations, data sets, and assumptions (Headech, 1982; British Rail, 1983) recommended changes and improvements to both trailing load and timetabling calculations, specifically recommending replacing the 4-axle approach. However, this recommendation was not implemented. Other simpler recommendations with less impact, such as changes to wagon starting and curvature resistance, were implemented in MT19 in the 1980s.

The treatment of wagons in MT19 does not align with current wagon characteristics. Previous reviews of MT19 recommended a complete overhaul of the 4-axle wagon methodology.

4 Review of other sources

4.1 Introduction

Other sources of train resistance and adhesion calculation methodologies are reviewed in this section. These include reviews and reports that cover MT19 (Headech, 1982; British Rail, 1983; Corus, 2009; Rangelov, 2012), as well as historic and current international practice. These findings, along with the findings from the review of MT19 (Section 3), will be used to propose the new method (see Section 5).

Within this section the structure is first all vehicles factors (gradient and acceleration resistance), followed by locomotive factors (adhesion, tractive effort, starting resistance, and rolling resistance), and then followed by wagon factors (starting resistance and rolling resistance). Key international comparators are reviewed to see if any areas of opportunity can be found. This analysis also considers factors such as higher speeds and axle weight limits, which were not considered within MT19.

Recurrent themes will be seen here throughout international work that can inform comparisons with MT19 and provide learnings for a new methodology:

- **Minimal simplification:** An important point to note is that post-MT19 work has likely not been constrained by computing limitations and so treatments are generally more complex than MT19.
- **Realistic wagon loadings:** International work has load cases for wagons that align with real world usage (for example, genuinely full or empty aggregate wagons).
- **Realistic wagon resistances** reflecting modern wagon types.
- **Universal calculation methodology:** A combined set of locomotive and wagon resistances that is suitable for maximum trailing load and timetabling calculations.
- **Use of up-to-date data sets:** For example, adhesion limit values that reflect current technologies.

A wide range of different units (and ways of measuring curvature) are used in international work and often changed over time, so we have made conversions to metric with the exception of mph in this section and following sections.

Calculation of TLLs for diesel locomotives by Railtrack and then later Network Rail for the FTLB utilised MT19 methodology and data, apart from utilising new data for post-MT19 locomotive types or revised data in the following several areas:

- Locomotive starting adhesion assumptions - μ_0:
  - Revised: Class 60
  - New: Class 59, Class 66 (75-mph geared), Class 66 (65-mph geared), Class 67.
- Locomotive starting and continuous tractive effort data:
  - Revised: Class 60

    - New: Class 59, Class 66 (75-mph geared), Class 66 (65-mph geared), Class 67.
- Calculation of a Class 66 ’66-H’ case using locomotive starting and 1-hour rating tractive effort data instead of the usual starting and continuous ratings used for all the other diesel locomotive types in the FTLB.

These changes in data and assumptions are discussed in Sections 4.3.1 and 4.3.2. In other areas listed below there have been no changes from the MT19 methodology, data, or assumptions outlined in Section 3:

- Gradient resistance
- Train acceleration resistance
- Wagon mechanical resistance
- Wagon curvature resistance.

The FTLB diesel locomotive calculations use the same methodology and data as MT19 which are outlined in Section 3. For electric freight locomotives an alternative timing-based (non-MT19) approach is used for the regional FTLB based on maximum train speeds of 60 mph (Class 6 freight train) or 75 mph (Class 4 freight train). This results in lower TLLs in order to keep to required timing paths over very long route sections.

4.2 All vehicles factors

4.2.1 Track gradient resistance

It was found that the methodology for determining resistance due to track gradient was the same in all sources reviewed, that is, simply the downhill force due to gravity.

Continue to use the gradient resistance as defined in Section 3.1.1.

4.2.2 Train acceleration resistance

It was found that the methodology for determining resistance due to train acceleration was the same in all sources reviewed, that is, simply a target minimum acceleration at starting and zero at rolling as defined in Section 3.1.2. MT19 uses 2.5 cm/s^2 as the minimum acceptable train acceleration (see Section 3.1.2). This is also used as the minimum acceptable train acceleration for passenger trains. Internationally this value is also used for freight (for example, in France). Note that for freight trains, acceleration rates are substantially lower than for passenger trains so for freight trains the impact of inertia of rotating masses (that is, wheelsets) is not significant. Therefore the common practice internationally is to account for any rotating inertial impact through the use of acceleration resistance.

We therefore consider 2.5 cm/s^2 to be an appropriate value to continue to use for train acceleration from a stand and 0 cm/s^2 is used for rolling acceleration resistance.

4.3 Locomotive factors

4.3.1 Locomotive adhesion

4.3.1.1 Introduction

Locomotive adhesion is affected by four main characteristics:

- Gradient
- Speed dependency
- Traction equipment characteristics
- Track quality and weather.

The impact of gradient was discussed in Section 1.2.1. The other characteristics are discussed in turn below.

4.3.1.2 Speed dependency

The usable coefficient of friction reduces with speed as degradation of μ occurs due to a less efficient connection between the wheel and rail.

Figure 26 below shows how speed affects μ based on three main approaches used globally.

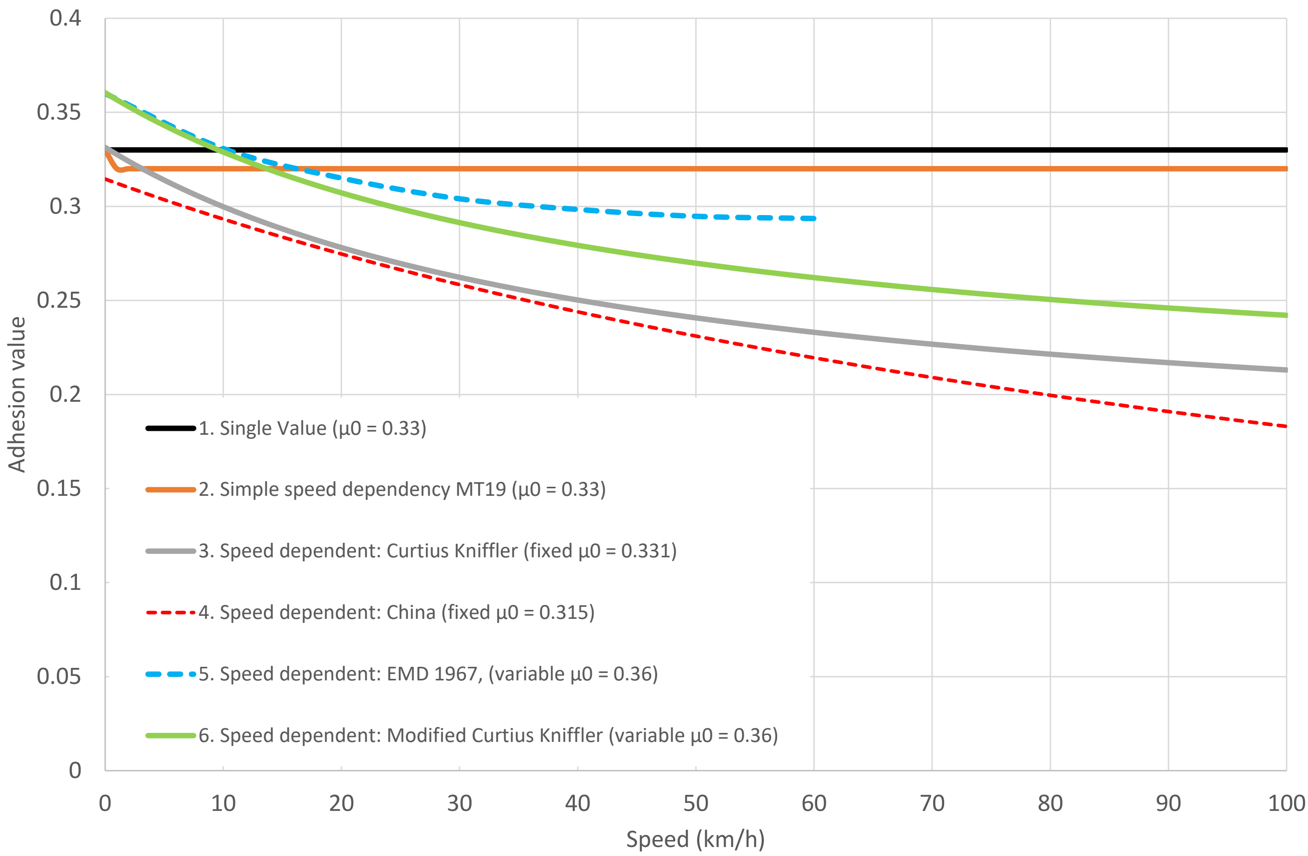
Curve 1 in Figure 26, a single adhesion value, is the simplest approach and is currently used by Swiss Railways (CFF). If a universal value is taken, an overly conservative (lower) value must be adopted.

The second type of approach (Curve 2 in Figure 26), that is, MT19, has one starting adhesion value and one rolling adhesion value all other speeds. In MT19 a single value was adopted for each locomotive class and track condition, with a 0.01 reduction from this value when rolling. Often the tractive effort of some of the oldest locomotive types reduces relatively quickly with speed so this cap is never reached in the 1-hour or continuous cases assessed for the older locomotives in MT19. However, this cap in MT19, which does not have a variable speed dependency, becomes an issue for more modern locomotives because this simplistic approach cannot optimally represent the practical adhesion limits for both starting and rolling cases (which are up to 80% higher than for locomotives listed in MT19).

Setting two values with a fixed offset inherently causes issues as neither cap will be representative of real-world limits. For example, if a higher value of μ_0 is chosen then at higher speeds the cap will be too high. A value of lower μ_0 to ensure validity at higher speeds will severely limit the locomotive's starting TLL. Using the latter compromise for the Class 60 in MT19 is part of the reason why the locomotive's starting performance capability has been understated. A more sophisticated approach than that used in MT19 is needed that would mirror real world speed dependency that is non-linear.

The third type of approach (all other curves shown in Figure 26) is more sophisticated than MT19. It is based on some kind of best-fit curve developed from real-world observations and is widely used internationally. There are several variations in level of sophistication for this approach. However, the two main approaches to equation types used internationally are the Curtius-Kniffler curve which was developed in 1943 (Curtius and Kniffler, 1944) and a simpler curve developed by EMD in 1965 (Marta et al., 1972). These two curves are shown in Figure 26 as Curves 3 and 5. The Curtius-Kniffler approach has often been applied in other countries outside Germany with minor variations, such as France, Spain, India, and Japan, including accounting for weather conditions and timetabling performance margins. All these formulations typically result in a reduction in µ of around 0.12 between 0 and 50 mph (80 km/h).

Figure 26 Selected approaches to speed dependency of adhesion



The Curtius-Kniffler curve will work at all speeds, whereas the simpler EMD curve is only valid up to 30 mph (50 km/h). Furthermore, while the EMD curve is adequate for use with diesel locomotives, it is not suitable for modern electric locomotives which can have very high tractive effort and very high deliverable adhesion above 30 mph.

Since the Curtius-Kniffler curve will work at all speeds we recommend its usage for the new calculation of maximum adhesion. However, the original Curtius-Kniffler curve formulation assumes a fixed starting value of

0.331 for μ (curve 3 above). To account for the differing traction capabilities of different locomotives the Curtius-Kniffler curve needs to be adapted from its original formulation of:

$$\mu_v = \frac{7.5}{(v + 44)} + 0.161 \ [v \ in \ km/h]$$

first by conversion to mph:

$$\mu_v = \frac{4.6612}{(V + 27.346)} + 0.161 \ [V \ in \ mph]$$

then by adjusting the y-axis intercept to reflecting differing higher adhesion performance and limits for modern locomotives from the late 1980s onwards. This can be achieved by replacing the fixed 0.161 value which sets the intercept at 0.331. It is important to note that the shape of the speed dependency curve does not change.

The adapted Curtius-Kniffler equation generates the value of μ_V in the formula below which was presented in from 1.2.1:

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

The μ value is derived using a speed dependent formula adapted from the older Curtius-Kniffler speed-dependent formula that has been adapted to be able to vary the value of μ at 0 mph (defined as μ_0) rather than just the fixed value of 0.331 that is inherent within the Curtius-Kniffler formula. The modified format is shown as Curve 6 in Figure 26 with μ_0 = 0.36

A revised formulation for the speed dependency of μ at a given speed μ_V can therefore be stated as:

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

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).

There is a speed dependency for adhesion. Using an adaptation of Curtius-Kniffler is recommended but with a variable value of μ_0 that depends on particular locomotive characteristics.

4.3.1.3 Traction equipment characteristics

The traction motor type and control characteristics have a significant impact on starting adhesion. The number of axles, number of axles per bogie, whether the bogies are steerable, bogie geometry, traction motor location compared to the wheel set it is driving, and individual axle loadings have a lesser impact on starting adhesion. The reasons for this are discussed at length in the appendix (Section 14). These factors influence the choice of starting adhesion limit (μ_0) values for locomotives internationally. As discussed in the previous section, adhesion will reduce from the selected starting adhesion levels with increasing speed.

Table 12 below shows a comparison of international starting adhesion values for a wide of range of international locomotive types with relevant characteristics and learnings for UK locomotives. The main characteristics in Table 12 are:

- Starting adhesion value
- Is a speed dependency assumption used to adjust the starting adhesion value at other speeds (this will affect the choice of starting adhesion value)?
- Assumed weather conditions, impact on track conditions and probability of adhesion delivery (for example, 99% probability of completing a journey in all weather conditions)
- Traction motor characteristics and whether the traction electronics have individual axle control
- Bogie characteristics
- Manufacturer information.

Where two values are listed in Table 12 for starting adhesion, the first value is used for the equivalent of TLL calculations, while the second value in brackets is the maximum the locomotive can regularly achieve in more optimum conditions. This concept of the starting µ assumption having two values and consequently differing potential TLLs has also been seen in the UK. For instance, in MT19 the Class 60 has a starting adhesion assumption of 0.33 (or 0.34 for FTLB calculations) but the locomotive can achieve between 0.395 and 0.42 in good conditions (which cannot always be guaranteed). A similar situation is seen in the original manufacturer's data and the adhesion assumption in MT19 for the Class 37, but the impact for older locomotives is not as significant (for example, a reduction of 0.01).

Table 12 Comparison of international starting adhesion assumptions grouped by locomotive characteristics and technologies

Place	Intro date	Coefficient of friction			Drive		Bogies			Manufacturer		
		Starting adhesion value	Speed-dependent adhesion assumption?	Conditions	Traction motor type	Individual axle control	Steerable bogies	Number of Axles	Axle Load - Q (tonnes)	OEM	Product type	Electric equipment supplier
North America	1950	**0.18 - 0.20**	Yes, formula	All weather 99%	DC	-	-	4 or 6		EMD and GE	For example EMD: SW1200, GP7, GP9, GP/SD20, GP/SD30; GE: pre-U series	EMD and GE
	1965	**0.2**	**Yes, formula**	All weather 99%	DC	-	-	6		EMD	EMD SD40	EMD
	1972	**0.21**	**Yes, formula**	All weather 99%	DC	-	-	6		EMD	EMD SD40-2	EMD
	1977	**0.21**	**Yes, formula**	All weather 99%	DC	-	-	6		EMD	GE Dash 7	EMD
	1984	**0.28**	**Yes, formula**	All weather 99%	DC	-	-	6	31 - 32	EMD	SD60	EMD
	1982	**0.27**	**Yes, formula**	All weather 99%	DC	-	-	6	31 - 32	GE	GE Dash 8	GE
	1992	**0.325**	**Yes, formula**	All weather 99%	DC	-	**Yes (Active)**	6	31 - 32	EMD	SD70	EMD
	1993	**0.34**	**Yes, formula**	All weather 99%	DC	-	**Yes (Active)**	6	31 - 32	GE	GE Dash 9	GE
	1994	**0.355**	**Yes, formula**	All weather 99%	**AC**	-	**Yes (Active)**	6	31 - 32	EMD	SD70MAC	Siemens & EMD
	1994	**0.38 (0.42)**	**Yes, formula**	All weather 99%	**AC**	**Yes**	-	6	31 - 32	GE	AC4400CW	GE
	2002	**0.38 (0.41)**	**Yes, formula**	All weather 99%	**AC**	**Yes**	**Yes (Active)**	6	31 - 32	EMD	SD70-ACe	Mitsubishi & EMD

Place	Intro date	Coefficient of friction			Drive		Bogies			Manufacturer		
		Starting adhesion value	Speed-dependent adhesion assumption?	Conditions	Traction motor type	Individual axle control	Steerable bogies	Number of Axles	Axle Load - Q (tonnes)	OEM	Product type	Electric equipment supplier
North America	2005	**0.38 (0.42)**	**Yes, formula**	All weather 99%	**AC**	**Yes**	-	6	31 - 32	GE	ES44AC	GE
	2015	**0.38 (0.46)**	**Yes, formula**	All weather 99%	**AC**	**Yes**	-	6	31 - 32	GE	ET44AC	GE
North America - retrofit	2018	**0.38 (0.42)**	**Yes, formula**	All weather 99%	**AC**	**Yes**	**Yes (Active)**	6	31 - 32	GE	Upgraded GE Dash 9 - AC conversion	CAF
	2013	**0.34**	**Yes, formula**	All weather 99%	DC*	**Yes**	-	6	31 - 32	EMD	Upgraded SD-40-2 with new microprocessor controlled separate excitation electrical equipment	NRE
	2010	**0.35**	**Yes, formula**	All weather 99%	DC*	**Yes**	-	6	31 - 32	EMD	Upgraded SD-40-2 with new microprocessor controlled separate excitation electrical equipment	Republic
	2013	**0.35**	**Yes, formula**	All weather 99%	DC*	**Yes**	-	6	31 - 32	EMD	Upgraded SD-40-2 with new microprocessor controlled separate excitation electrical equipment	Wabtec/MPI

		Coefficient of friction			Drive		Bogies			Manufacturer		
Place	**Intro date**	**Starting adhesion value**	**Speed-dependent adhesion assumption?**	**Conditions**	**Traction motor type**	**Individual axle control**	**Steerable bogies**	**Number of Axles**	**Axle Load - Q (tonnes)**	**OEM**	**Product type**	**Electric equipment supplier**
	2012	**0.36**	**Yes, formula**	All weather 99%	DC*	**Yes**	-	6	31 - 32	EMD	Upgraded SD-40-2 with new microprocessor controlled separate excitation electrical equipment	ZTR
Europe	1988	**0.33**	**Yes, formula**	All weather	**AC**		-	4	22	Alsthom	BB26000 ('SyBic'), AC motors, Thyristor chopper control	Alsthom
Europe	1992	**0.33**	**Yes, formula**	All weather	**AC**	**Yes**	-	6	21	Brush / ABB	Class 92 or CC92 in France, 3 phase AC motors, GTO inverters	ABB
	2001	**0.4**	**Yes, formula**	Dry	**AC**	**Yes**	-	6	30	Alstom (Bombardier)	Alstom (Bombardier) Octeon	Bombardier
	2001	**0.36**	**Yes, formula**	Wet, sand as needed	**AC**	**Yes**	-	6	30	Alstom (Bombardier)	Alstom (Bombardier) Octeon	Bombardier
	2001	**0.34**	**Yes, formula**	**Below Zero**	**AC**	**Yes**	-	6	30	Alstom (Bombardier)	Alstom (Bombardier) Octeon	Bombardier
	2001	**0.36 (0.364)**	**Yes, formula**	All weather	**AC**	**Yes**	-	4	22	Alstom (Bombardier)	Alstom (Bombardier) Traxx - current design	Bombardier

Place	Intro date	Coefficient of friction			Drive		Bogies			Manufacturer		
		Starting adhesion value	Speed-dependent adhesion assumption?	Conditions	Traction motor type	Individual axle control	Steerable bogies	Number of Axles	Axle Load - Q (tonnes)	OEM	Product type	Electric equipment supplier
	2001	**0.36 (0.37)**	**Yes, formula**	All weather	**AC**	**Yes**	-	4	22.5	Siemens	Siemens Vectron	Siemens
	2001	**0.36 (0.37)**	**Yes, formula**	All weather	**AC**	**Yes**	-	4	22.5	Alstom	Alstom Prima	ABB
	2018	**0.33**	No, single value	All weather	**AC**	**Yes**	-	4	18 - 21.5	Stadler	Current Stadler production models	ABB
	2018	**0.35**	No, single value	All weather	**AC**	**Yes**	-	6	18 - 21.5	Stadler	Current Stadler production models	ABB
India	1995	**0.38**	Single values for two test cases	'Fair weather with sand' as needed (correlates to at 90% of US basis **without sand**)	**AC**	**Yes**	-	6	22.5	ABB	ABB (WAG 9)	ABB
	1988	**0.38**			**AC**	**Yes**	-	6	22.5	Hitachi	Hitachi (WAG 6)	Hitachi
	1997	**0.41**			**AC**	**-**	**Yes (Active)**	6	22.5	EMD	EMD WDG 4 (SD70MAC clone)	Siemens & EMD
	2010	**0.4**			**AC**	**Yes**	-	8	22.5	Alstom (Alstom)	Alstom Prima 2 (WAG 12)	ABB
	2015	**0.4**	Single values for two test cases	'Fair weather with sand' as needed (correlates to at 90% of US basis **without sand**)	**AC**	**Yes**	-	6	22.1	GE	ES58Aci	GE
	2015	**0.4**			**AC**	**Yes**	-	6	23	GE	ES43Aci	GE

		Coefficient of friction			Drive		Bogies			Manufacturer		
Place	Intro date	Starting adhesion value	Speed-dependent adhesion assumption?	Conditions	Traction motor type	Individual axle control	Steerable bogies	Number of Axles	Axle Load - Q (tonnes)	OEM	Product type	Electric equipment supplier
China	2011	**0.385**	Yes	n/a	**AC**	**Yes**	-	6	25	CRRC (Dalian)	HXD3B based on Alstom (Bombardier) Traxx	Bombardier
Pakistan	2015	**0.35**	Believed to be non-speed dependent	n/a	**AC**	**Yes**	-	6	23	GE	ES43ACi	GE
Australia	1984	**0.31**	**Yes, formula**	No standardised method to describe	DC	-	**-**	6	21.5	EMD / Downer	NSW Class 81 (EMD SD50 based)	EMD
	1994	**0.33**	**Yes, formula**		DC	-	**Yes (passive)**	6	22	EMD / Downer	NSW Class 82 (EMD SD70 based)	EMD
	1994	**0.33**	**Yes, formula**		DC	-	**Yes (passive)**	6	29.5	EMD / Downer	NSW Class 90 (EMD SD70 based)	EMD
	1996	**0.34**	**Yes, formula**		DC	-	**-**	6	22	GE / UGL	Cv40-9i (GE Dash 9 AC based)	GE
	1997	**0.31**	**Yes, formula**		DC	-	**Yes (passive)**	6	22.3	EMD / Downer	GT46C (SD70 based)	EMD
	2007	**0.42**	**Yes, formula**		**AC**	**Yes**	**Yes (passive)**	6	22.3	EMD / Downer	GT46-Ace (SD70 Ace based)	Mitsubishi & EMD

Place	Intro date	Coefficient of friction			Drive		Bogies			Manufacturer		
		Starting adhesion value	Speed-dependent adhesion assumption?	Conditions	Traction motor type	Individual axle control	Steerable bogies	Number of Axles	Axle Load - Q (tonnes)	OEM	Product type	Electric equipment supplier
Australia	2008	**0.405**	**Yes, formula**	No standardised method to describe	**AC**	**Yes**	-	6	22.3	GE / UGL	C44ACi version 1	GE
	2009	**0.415**	**Yes, formula**		**AC**	**Yes**	-	6	23	GE / UGL	C44Aci version 2	GE
	2012	**0.425**	**Yes, formula**		**AC**	**Yes**	-	6	32	EMD / Downer	SD70 Ace	Mitsubishi & EMD

* Microprocessor-controlled Separate Excitation with individual axle control

Table 12 shows that there is a range of different starting adhesion values in different countries.

The acceptable value of μ in the US has increased over time from 0.2 in the 1950s to 0.38 now (or greater for the newest locomotive types in most conditions). A cap of 0.38 was defined by AREMA in 2020 (AREMA, 2022); previously this had been 0.37 but values of 0.41-0.42 are achievable and are below the 0.45-0.47 maximum values for the newest locomotives. These current values are based on AREMA's assumption of a 6-axle locomotive being the default in North America (0.2 was based on a 4-axle locomotive assumption).

European values of μ are capped at 0.36 usually by infrastructure operators in individual countries, a position that has not been changed since the early 2000s. This value is based on an assumption of a 4-axle freight locomotive being the default on the continent (a situation that has only started to change in the last 5 years). The leading wheelset on locomotives performs a significant role in railhead cleaning and as a result can suffer from reduced adhesion levels. On 6-axle locomotives the overall proportion of non-leading axles is lower resulting in a lower impact from reduced adhesion on the leading axle, hence a difference in deliverable starting adhesion levels of 0.02 between modern high tractive effort 4-axle and 6-axle locomotives is in line with expectations.

In India higher values of up to 0.41 for μ are used. However, higher wagon resistances are also used in India (which include an assumption of higher resistance due to impaired track geometry during and after the monsoon season). Given that the monsoon-related assumption increases rolling resistance, Indian Railways allow the starting adhesion value to be higher to achieve sensible results for TLLs overall.

Most countries have starting adhesion limits for TLL calculation purposes that are lower than what locomotives can achieve good conditions.

Table 12 shows the impact of including a speed-dependent adhesion assumption on values of μ. Where a single value is taken by Stadler a lower value of μ is used. For example, for a 4-axle locomotive Stadler use as single value 0.33 whereas Germany uses 0.36 for μ_0 with a speed dependency for modern locomotive types. Similarly, for a 6-axle locomotive Stadler uses a single value of 0.35 whereas a value of 0.38 for μ_0 with a speed dependency for modern locomotive types is used by AREMA in North America.

Table 12 also show differences in μ values for 4 and 6-axle locomotives:

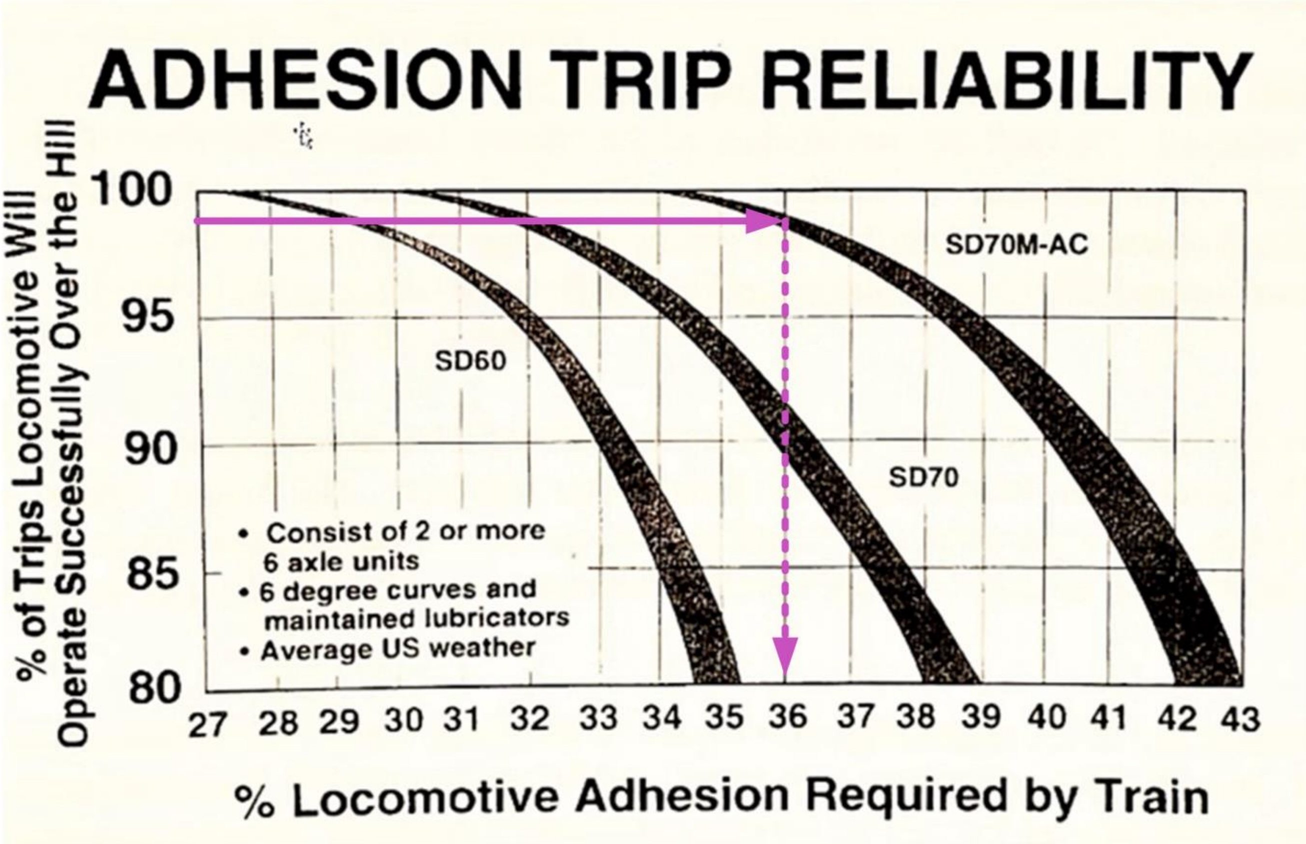
- Stadler: μ is 0.02 greater for 6-axle locomotives (where a single maximum adhesion value is used)
- For US 6-axle locomotives adhesion cap on μ is 0.02 greater than German 4-axles locomotives (where speed-dependent adhesion formulae are used)

Where data are available, there is a very clear common theme that the maximum adhesion assumption for 6-axle locomotives is 0.02 greater than for 4-axle locomotives.

Steerable bogies significantly reduce the level of wheel slip. The chart in Figure 27 below was developed by the American locomotive manufacturer EMD and shows the benefits of steerable bogies when fitted to their SD60 locomotive, in comparison with their similar SD70 (improved DC traction electronics and steerable bogies compared to SD60) and SD 70M-AC (whole-bogie control AC traction electronics and steerable bogies compared to SD60) locomotives. Note the assumed radius of track curvature for this chart is 292 m albeit with flange lubrication. A much lower coefficient of friction is required on these locomotives to achieve the same trip reliability. The annotation in Figure 27 (magenta arrows) shows the commonly used 99% all-weather definition which for the SD70M-AC aligns with μ=0.36. The curve for a modern locomotive with individual axle control (with or without steerable bogies) would be expected to be shifted by about 2% further to the right than the SD70M-AC curve. Individual axle control (whether via separate excitation DC systems (for example, Class 60) or three-phase AC drives (for example, GB Classes 68, 70, 88, 93, and 99, and numerous examples overseas) provides significant improvements in adhesion but these improvements are mostly not additive to any improvements from steerable bogies. Hence the adhesion benefits of steerable bogies are reduced if individual axle control is also fitted. The residual benefits of steerable bogies on adhesion can be achieved with simpler passive, rather than the more complex active, steering technologies.

A more detailed discussion of the impact of traction electronics is provided in the appendix (Section 14); the focus in this section is on higher level transferable understandings on the impact of traction electrical equipment on adhesion.

Figure 27 Comparison of adhesion levels and probability of successful operation for three EMD locomotives with different traction electrical equipment (from SD70M-AC technical sales literature, EMD, 1994)



For older traction electrical equipment types, steerable bogies can improve adhesion by 0.03 to 0.04. However, for modern traction systems with individual axle control, especially those with three-phase drives, the improvement in adhesion is much reduced. MT19 only contains appropriate adhesion values for older locomotive types (Classes 20-58 & 73). It does not contain relevant adhesion assumptions and data for modern locomotive types. Key learnings to fill these gaps are available from international practice.

For Class 60 FTLB calculations a starting adhesion value of 0.34 has been used and this is still felt by operators to be too low given real-world performance. Looking at international comparators in Table 12 above suggests that a value of 0.36 may be more appropriate.

For newer locomotive types (for example, Classes 68, 70 and 88 and future Classes 93 and 99), assumptions on the maximum adhesion level deliverable from 4-axle and 6-axle locomotives with three-phase AC traction equipment and individual axle control need to be made. International comparators in Table 12 above suggest that a value of 0.36 is appropriate for 4-axle locomotives and 0.38 for 6-axle locomotives based on American and European experience.

International practice suggests that appropriate starting adhesion values should be:

Class 60: 0.36 (revised upwards from current 0.34)

Classes 68, 88 and 93 (4-axle locomotives): 0.36

Classes 70 and 99 (6-axle locomotives): 0.38.

4.3.1.4 Weather and track conditions

Starting adhesion values inherently contain assumptions about weather conditions and the probability of successfully completing a journey. This relationship can be seen in the general shape of the three curves in Figure 27 where the probability of successful completing a journey decreases as the required adhesion level increases. The default assumption in North America is to use the 99% probability assumptions for the route geometry with sanding used as required. Different assumptions for adhesion as well as locomotive and wagon resistance are used when temperatures fall substantially below 0°C with snow and /or ice.

General track conditions affect both 1) adhesion levels and 2) locomotive and wagon resistances with some track parameters affecting both (for example, continuously welded versus jointed track, railhead wear, and good general track geometry) and some factors only the affecting locomotive and wagon resistances (for example, rail section, sleeper spacing (closer is better), and type (concrete is better)). Different countries have different ways of including the effects of track quality in the trailing load calculations. Some countries do not include variability in either track condition on adhesion or locomotive and wagon resistances. While other countries just include variable track quality in adhesion calculation (for example, in MT19 and the FTLB in Great Britain) and some counties include the impacts on both adhesion as well as locomotive and wagon resistances (for example, North America, Australia, and former Soviet Union states).

In Great Britain the correct classification of a section of route between mainline and secondary, based on current track condition, has potentially significant impacts on the maximum trailing load on a section of route. It is currently unclear how up to date the mainline and secondary route assumptions used in the FTLB are.

Weather conditions can affect adhesion levels and assumed starting adhesion values have implicit assumptions around all but the most unfavourable weather conditions included within them (including the use of sanding as and when needed). Requiring virtually 100% probability of successful journey when making adhesion assumption would significantly reduce calculated TLLs. Including the effect of steeper gradients which leads to reduced adhesion will help mitigate against this risk.

High adhesion levels that define the maximum TLL are only typically required on relatively short sections of a route, and these may or may not be prone to weather-related poor adhesion issues. The use of sanding in isolated locations such as this is plausible without risking locomotive sandbox capacity becoming exhausted.

Adhesion levels have a much lower impact at medium and higher speeds where train performance is usually limited by a locomotive’s maximum power and hence tractive effort at those speeds (where the tractive effort is usually lower than any speed-related adhesion cap values at those speeds).

In Britain, variation in track quality is only included in adhesion assumptions and calculations for TLLs. We suggest retaining this approach as the data needed to apply variability to locomotive and track resistance is currently not available.

The continued use of starting adhesion levels being 0.02 lower on secondary routes compared to mainline routes remains appropriate.

Key assumptions in the adhesion values are that the track is regularly used and in good condition; this may not the case on some routes.

4.3.1.5 Recommended locomotive adhesion values and their implications

A number of useful lessons can be derived from international practice where the existing GB practices in MT19 or FTLB TLL calculations have not kept up with changes in locomotive design. Most countries use a speed-dependent formula-based approach to define the value of μ used, with a capped starting value and a calculated decreasing value with speed. Many modern manufacturers (Stadler, EMD, GE) install a software limit on tractive effort equivalent to a μ value of between 0.45 and 0.46.

<u>North America</u>

- 0.38 cap built into the AREMA (2022) rules from 2020 (previously 0.37).
- Default value is based on a 6-axle locomotive.
- Acceptable μ values have substantially increased over time.

<u>Germany (plus Benelux, France, Denmark)</u>

- 0.36 cap built into the German rules (established ~20 years ago).
- Default value is based on a 4-axle locomotive.
- Acceptable μ values have substantially increased over time.

<u>India</u>

- Larger values but accept a higher failure assumption. Also wagon resistances and track resistances are higher (some monsoon related).

<u>Australia</u>

- No cap, location specific definition based on measured data.

Much higher values of μ are used internationally for UK-comparable locomotives compared to the UK default value of 0.33.

Current issues in the Britain and potential lessons from international practice to address them are now discussed.

In MT19 the Class 60 starting adhesion values of 0.33 (mainline) and 0.30 (secondary route) were adopted for the calculation of maximum TE (and hence TLLs) before a full understanding of the levels of adhesion deliverable with the technologies installed on this locomotive was available. For Class 60 FTLB calculations a higher revised value of 0.34 has been used, but this is still felt by operators to be too low given real-world performance.

For newer locomotive types (for example, Classes 60, 59, 66 (75-mph geared), 66 (65-mph geared), 68, 70, 88, 90 and 92 and future Classes 93 and 99), assumptions on the maximum adhesion level will need to be made, as variability in local conditions can have a significant impact. In the FTLB for newer locomotive types, the Class 60 MT19 assumptions are reused for gradient, curvature, and wagon values along with Class 60 locomotive resistance assumptions, so just the locomotive specific TE and adhesion assumption vary from the Class 60 values. For timetabling purposes the values for newer locomotives in RailSys® are the same as those used in FTLB calculations for new locomotive types.

We therefore propose the modified μ values for more modern UK traction as shown in Table 13.

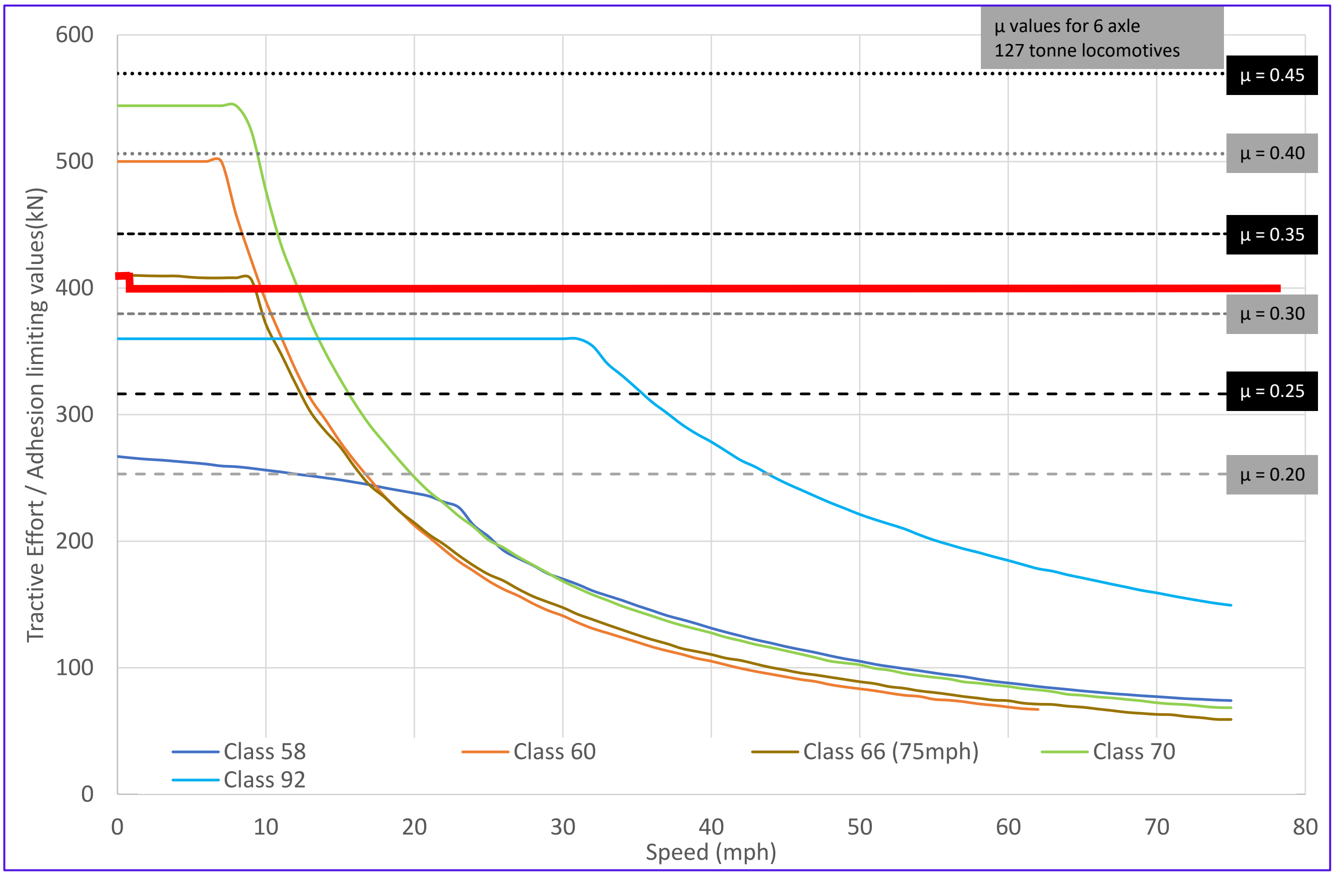
Table 13 Revised μ values for modern UK traction

Locomotive	Drive	Axles	MT19 μ_0	FTLB μ_0	Recommended μ_0	International comparator
59	DC, Paired axle control, WSP	6		0.34	0.34	Existing GB performance
60	DC, SepEx individual axle control, WSP	6	0.33	**0.34**	**0.36**	US EMD SD-40-2 retrofit
66 (standard)	DC, Paired axle control, WSP	6		0.33	0.33	Existing GB performance
66/6 (low geared)	DC, Paired axle control, WSP	6		0.35	0.35	Existing GB performance
68	AC, VVSD with individual axle control	4			0.36	European 4-axle assumption
70	AC, VVSD with individual axle control	6			0.38	US 6-axle assumption
88	AC, VVSD with individual axle control	4			0.36	European 4-axle assumption
90	AC single phase	4			0.31	Existing performance

Locomotive	Drive	Axles	MT19 μ_0	FTLB μ_0	Recommended μ_0	International comparator
92	AC, VVSD with individual axle control	6			0.29	Existing performance (software limited)
92 (boost mode)	AC, VVSD with individual axle control	6			0.29	Existing performance (software limited)
93	AC, VVSD with individual axle control	4			0.36	European 4-axle assumption
99	AC, VVSD with individual axle control	6			0.38	US 6-axle assumption

The value of the coefficient of friction effectively caps the maximum tractive effort which a locomotive can apply, based on a 6-axle 127 tonne locomotive. Figure 28 below shows this.

Figure 28 Selected 6-axle locomotive tractive effort curves (125-139 tonnes locomotive mass) and the MT19 µ cap value of 0.33 starting / 0.32 rolling used for the Class 60 on mainline routes in MT19 (thick red line)



For more powerful locomotives increasing the µ value gives the beneficial effect of increased starting TE compared to the 75-mph Class 66 baseline (Table 14).

Table 14 Increase in available starting TE with increasing values of µ

µ	Max TE (kN)	Uplift from 6-axle 127 tonne locomotive baseline
0.33	411	1.0
0.35	436	1.06
0.36	449	1.09
0.38	473	1.15
0.40	498	1.21

In Table 15, recommended starting adhesion and other aligned data for adhesion calculation for newer locomotives are set out. Further information on how traction electrical technology affects μ is given in the appendix (Section 14).

Table 15 Recommended adhesion limits assumptions and TE values for newer locomotives

Locomotive	Weight (tonnes)	Axles	Recommended μ_0 (Mainline)	Recommended μ_0 (Secondary)	Max TE (kN)	Increase TE (at starting) compared to current value
59	124	6	0.34	0.32	413	0
60	130	6	0.36	0.34	455	6%
66	127	6	0.33	0.31	409	0
66/6 (low geared)	127	6	0.35	0.33	436	0
68	85	4	0.36	0.34	300	9%
70	129	6	0.38	0.36	480	15%
88	85	4	0.36	0.34	300	9%
90	84.5	4	0.31*	0.29*	258	0
92 (boost mode)	126	6	0.33**	0.31**	400	0
92 (normal mode)	126	6	0.29**	0.29**	360	0
93	88	4	0.36	0.34	311	9%
99	113	6	0.38	0.36	421	15%

Notes:
*Class 90 – low TE at low speed but high TE (relative to other locomotives) at mid and high speeds due to original design assumptions for attainable μ values along with optimising mid and high-speed TE for their mixed-traffic (passenger and freight) role.
**Class 92 – no simple change possible due to hard-coded software configuration and EuroTunnel 34.5 tonne coupler restrictions.

Simplification of the evaluation of μ leads to an overly conservative value being taken.

A speed-specific formula should be adopted to model the reduction in μ with increasing speed and we recommend adoption of the latest German CK curve.

Since there are no statistics for freight train adhesion values for modern traction types at starting or low speeds (μ_0) in Great Britain, we recommend use of μ values in line with the US or Europe as appropriate. This will lead to increase in the available tractive effort for larger 6-axle vehicles, although the increases will be up to 15%.

In low (starting) speed circumstances a technology-specific value of µ needs to be taken:

- For a 3-phase AC 6-axle motor drive a value of 0.38 should be taken (Classes 70, 99)
- For a 3-phase AC 4-axle motor drive a value of 0.36 should be taken (Classes 68, 88, 93)
- For a separate excitation DC drive a value of 0.36 can be taken (Class 60)
- For the Class 66 (75-mph geared) the existing FTLB value of 0.33 remains appropriate
- For the Class 66 (65-mph geared) the existing FTLB value of 0.35 remains appropriate
- For the Class 59 the existing FTLB value of 0.34 remains appropriate.

4.3.2 Locomotive TE

Locomotive TE varies with speed and, under some circumstances, with performance reduction due to thermal degradation of the traction electrical equipment. Two specific cases are usually examined: Starting, and Rolling with continuous-rated thermal degradation. The STE values from MT19 are shown in Table 16 (note that the provisional Class 60 data shown in red from 1989 was subsequently revised in 1991) and all values apart from the provisional Class 60 value have been retained. STE values for newer locomotives and the revised Class 60 value are shown in Table 17.

Table 16 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 60	*409*
Class 73/0	165
Class 73/1	160

Table 17 Additional and revised locomotive starting tractive effort values used in the calculation tool

Locomotive class	Locomotive rolling TE (kN)
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 88 (AC)	317
Class 88 (diesel)	317
Class 90 (single headed)	258
Class 90 (double headed)	258
Class 92 (AC)	360
Class 93 (AC)	278
Class 93 (diesel)	278
Class 99 (AC)	500
Class 99 (diesel)	500

The rolling 1-hour and continuous-rated thermal degradation TE values and associated speeds from MT19 are shown in Table 18 (note that the provisional Class 60 data shown in red from 1989 was subsequently revised in 1991) and all values apart from the provisional Class 60 value have been retained. Continuous-rated thermal degradation tractive effort and related speed values for newer locomotives and revised Class 60 values are shown in Table 19. The only 1-hour values shown in Table 19 are those used in the FTLB '66-H' case (see Section 6.5).

Table 18 Locomotive rolling tractive effort rolling values (continuous and 1-hour cases) 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 60	*-*	*-*	*336*	*11.6*
Class 73/0	-	-	73	10.0
Class 73/1	-	-	60	11.5

Table 19 Additional and revised locomotive rolling tractive effort values (continuous and 1-hour cases) used in the calculation tool

Locomotive class	Locomotive rolling TE (kN)			
	1-hour (just FTLB '66-H' case)		Continuous	
	TE (kN)	Speed (mph)	TE (kN)	Speed (mph)
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 88 (AC)	-	-	258	34.3

Locomotive class	Locomotive rolling TE (kN)			
	1-hour (just FTLB ‘66-H’ case)		Continuous	
	TE (kN)	Speed (mph)	TE (kN)	Speed (mph)
Class 88 (diesel)	-	-	258	5.3
Class 90 (single headed)	-	-	244	53.7
Class 90 (double headed)	-	-	244	45.8
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

The UIC continuous assumption is based a combination of the level of thermal degradation from continuous running alongside available cooling at 40°C at an altitude of 305 m (1,000’). That temperature at that altitude has never been reached in Britain. Full-power operating periods approaching continuous running are almost impossible to achieve on the GB network as the high-power levels required for the sustained periods rarely happen (especially for modern locomotive types) and the levels of cooling available in Britain are usually substantially better than the standard UIC conditions. Hence a 1-hour rating (as used for the FTLB 66-H case in place of continuous) and under more typical worst British case cooling conditions may be more relevant. The continuous case has effectively become a conservative ‘worse than worst’ real-world case assumption, though this may still have some relevance as a conservative starting assumption for further analysis.

Newer locomotives have less thermal degradation in their traction electrical equipment performance. The limiting case usually becomes the starting case; it is very difficult to obtain a continuous case fail in any TLL calculation. Consequently there is limited justification for considering the continuous case for modern locomotives – this case no longer relevant for TLL calculations for modern locomotives.

The starting and continuous cases are not sufficient to evaluate timings and whether SRTs can be complied with. To do so involves looking at a range of speeds. Incremental testing of set speeds can provide insights, for example Corus (2009) assessed TLLs at fixed speeds of 0, 10, 20, 30, 40, 50 mph. In reality, speeds of 20 mph or greater do not result in thermal degradation so these speeds are above the range of the continuous case. At the medium and higher speeds (that is, 20 mph and greater) the locomotive and wagon resistances go up and the available (non-thermally limited) tractive effort goes down, resulting in lower TLLs as the speed increases.

In other countries rolling speeds other than the continuous rolling speed are routinely used in TLL calculations. For instance, in India a minimum rolling speed of 20 mph is assumed for network capacity and timetabling purposes. This is higher than the continuous rated speeds of diesel locomotives used in India, so the continuous case is not examined in India.

It is much more useful to do be able to calculate TLLs at any speed to better understand all potential rolling cases rather than just the single, very limited continuous rolling subcase. Furthermore, this would allow consistent and aligned timetabling calculations to be performed with the same inputs and methodology; indeed, such an approach would follow what is already done in the FTLB for electric traction. As part of this project tractive effort data has been compiled for 19 locomotive types, based primarily on OEM data. This compilation, which is available in the associated Excel maximum trailing load calculation tool, represents a significant step forward by making this data freely available in a digitised table format containing TE value for each 1 mph speed increment. As well as enabling understanding of the starting and continuous cases, a full range of data are now available so TLL calculations can be done at any speed, thus enabling evaluation of SRTs.

Tractive effort data for the following locomotive types in increments of 1 mph are contained within the 'Loco TE Data' tab in the associated Excel calculation tool described in Section 6:

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

Modern locomotive types have lower thermal degradation and therefore the continuous case is effectively of limited relevance for TLL calculations. The ability to look at TE across the full speed range for SRT calculation purposes is essential and data has now been compiled to do this.

4.3.3 Locomotive rolling resistance

In this section we review British and international approaches to locomotive mechanical and curvature resistance with recommendations laid out for mechanical resistance in Section 4.3.3.3 and curvature resistance in Section 4.3.3.5.

For locomotive resistance (for both rolling or starting) in MT19 there is no explicit inclusion of curvature resistance for locomotives in the calculation methodology. However, there may have been some implicit inclusion of curvature resistance within the locomotive resistance through the use of higher speed independent resistance equation values (see Section 4.3.3.2). Sections 4.3.3.4 and 4.3.3.5 contain our recommendation to include locomotive curvature resistance (including for steerable bogies) in the calculation methodology. Due to lack of available data we have not made any attempt to reduce locomotive mechanical resistance due to the inclusion of locomotive curvature resistance. This may mean that there is some potential double counting in the new locomotive resistance methodology although this would have very small impact on calculated TLLs, as changes in locomotive resistances have very small impact on calculation results.

Current international methodologies result in lower locomotive mechanical resistances than those in MT19, especially at speeds relevant to timetabling calculations (that is, speeds above those examined in the MT19 continuous or 1-hour cases). However, the overall impact on maximum trailing load calculations is small (as there is typically only one locomotive per train and wagon resistances dominate).

4.3.3.1 British locomotive resistance approaches

A key recommendation in Headech (1982) was to move to a universal approach to calculate locomotive resistance for both maximum trailing load and timetabling calculations. In Headech (1982) several options were examined, and it was recommended that best-fit equations, developed from measurements carried out in the early 1970s of Class 86 (4-axle) and Class 47 (6-axle) locomotives, form the default for locomotive mechanical resistance where better data is not available.

The Class 86 and Class 47 are analysed and further compared with other British Rail research and international research in this section. Locomotive resistance is a small component of the overall train resistance at low speeds when calculating the TLL for diesel locomotives at starting and continuous conditions (typically 1/80th to 1/150th of the total available tractive effort for a modern diesel locomotive on the level at those low speeds). As the wagon resistances dominate the overall train resistance, in MT19 it was reasonable to apply some simplifications to locomotive resistance compared to wagon resistance. Some of these simplifications may have been made to make computation in the late 1960s easier and less computer memory intensive and/or some may have been due to lack of available data or confidence levels in that data at the time.

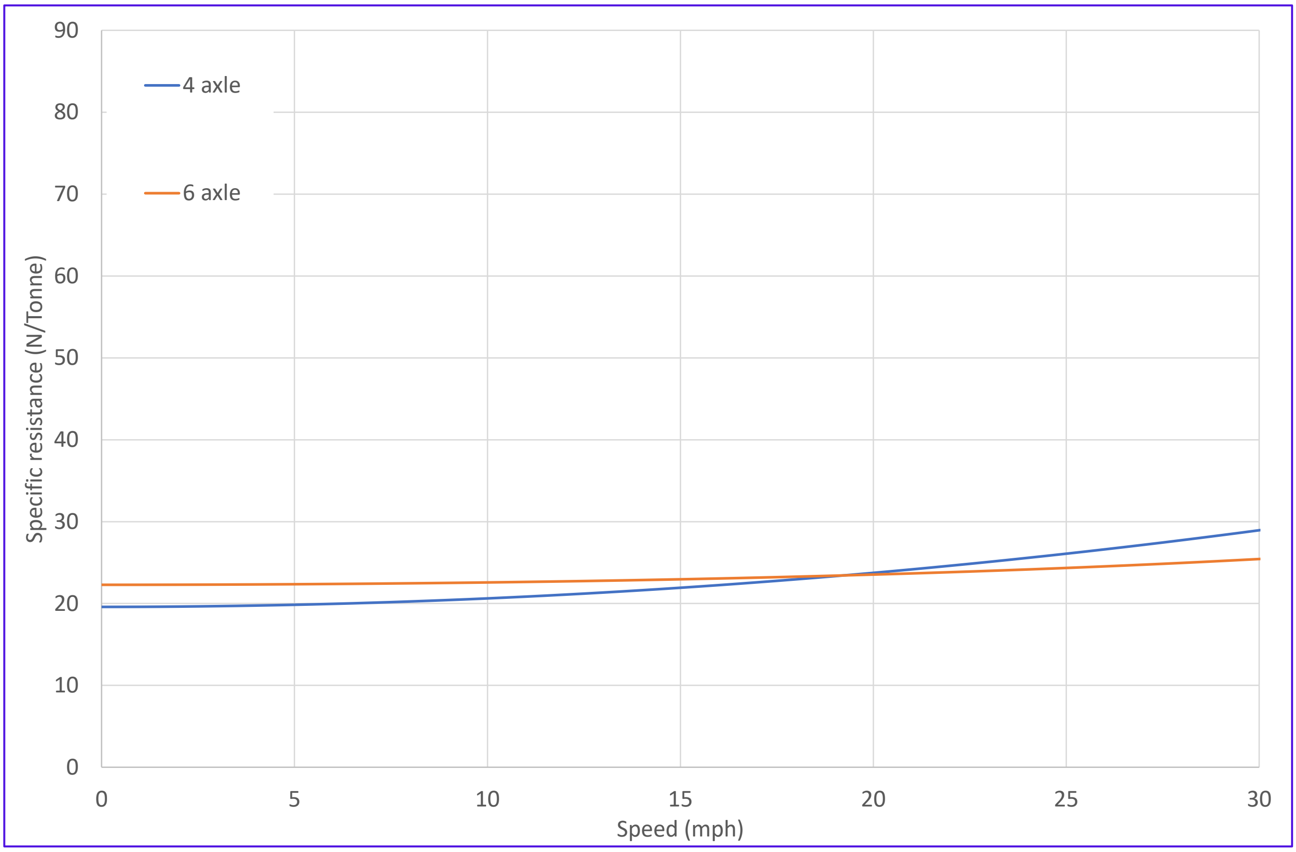
Locomotive mechanical resistance increases rapidly with speed due to the large aerodynamic loads on the leading vehicle of a train (for example, on the level the locomotive mechanical resistance is typically ~7% and ~17% of the locomotive maximum TE at 50 mph and 75 mph, respectively). Thus, more accurate locomotive mechanical resistance data and assumptions are needed, especially for higher speeds. This is particularly important for electric freight locomotives which were not included in MT19. For electric freight locomotives an alternative timing-based approach is used for regional FTLB based on maximum train speeds of 60 mph (Class 6 freight train) or 75 mph (Class 4 freight train). This results in lower TLLs in order to keep to required timing paths over very long route sections. Electric freight locomotives tend to have significantly higher TE at medium and higher speeds than diesel locomotives (due to greater power) and therefore timing performance calculations need more accurate resistance data. The locomotive resistance approach used in MT19 is a much older V^2 + constant type formula (with no V term). This slightly simpler approach persists. For instance, Siemens still use the German V^2 + constant type formula.

In MT19 curvature resistance was not applied to locomotives, and it is unclear as to why this is so. However, the impact on calculated TLLs is very small and this approach yields a reasonable representation (probably because of the simplifications to adhesion, curvature, and/or locomotive resistances). Excluding curvature resistance for locomotives means that the benefit for locomotives with steerable axles (which reduce locomotive curvature resistance, as applied to Class 59 and 66) cannot be utilised.

Higher speed train operation or operation on higher curvature track can both occur but not concurrently. This is because vehicles are at risk of overturning if operated fast around tight curves, given limits to applied cant (the ‘banking’ of the track): the maximum train speed on uniformly curved track is proportional to the square root of the track’s radius of curvature. Hence on track with a high radius of curvature (and high curvature resistance), the maximum potential line speed is lower and therefore the maximum mechanical resistance (proportional to V^2 and V) is lower because of the lower train speeds. On straighter track (where the radius of curvature is far higher), the curvature resistance is minimal, but train speeds are higher so the maximum mechanical resistance (if the train is travelling fast enough) can be higher than the maximum curvature resistance. Hence mechanical and curvature resistances are not entirely independent - curvature resistance and mechanical resistance at medium to higher speeds cannot both have high values at the same time.

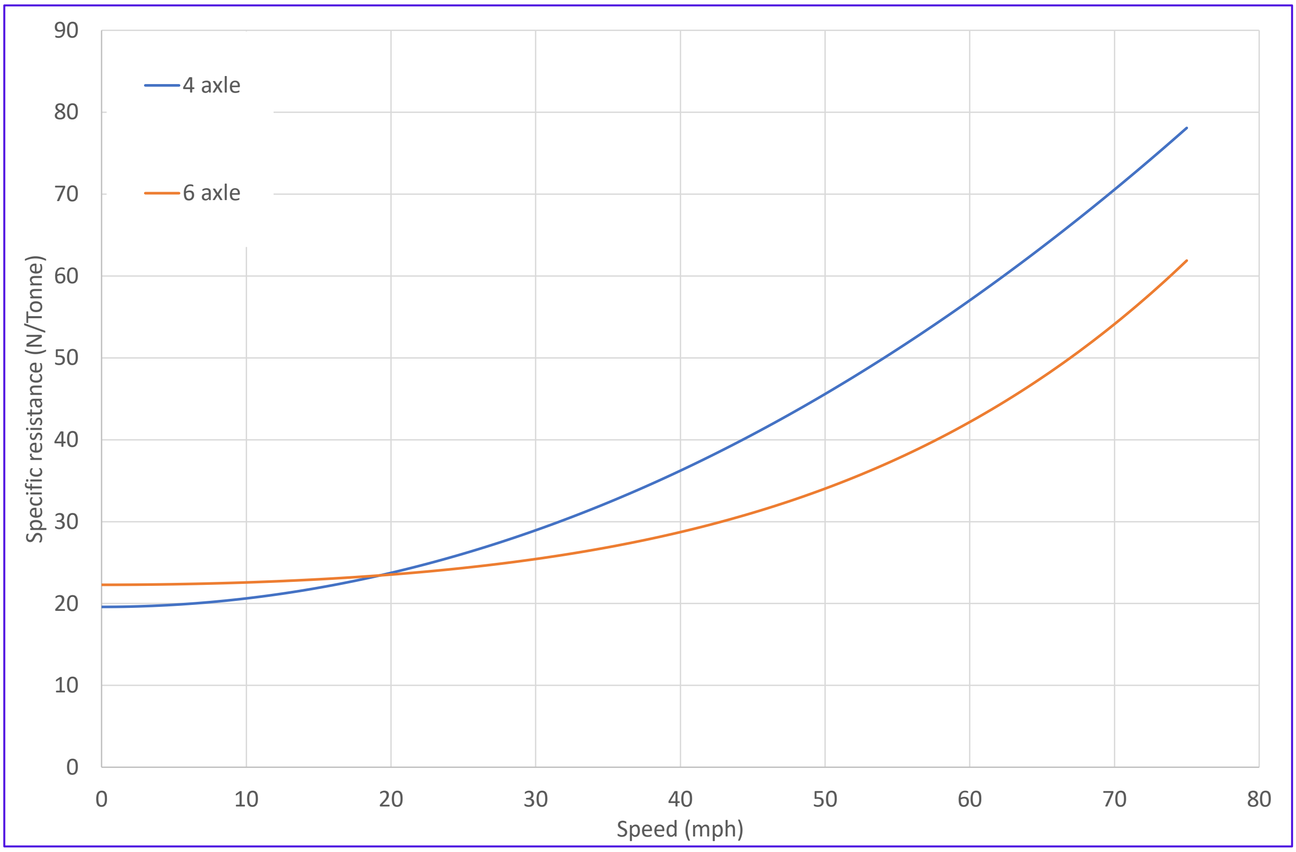
Figure 29 below shows the specific locomotive resistance equations used for MT19 4-axle and 6-axle locomotive resistance at low speeds, and there is very little difference between the specific resistance for 4 and 6-axle locomotives at these low speeds for which the curves were derived.

Figure 29 Low speed locomotive specific rolling resistance from MT19



However, when the chart in Figure 29 is extended to higher speeds there is a significant divergence between the 4-axle and 6-axle locomotive specific rolling resistance curves at the higher speeds (see Figure 30).

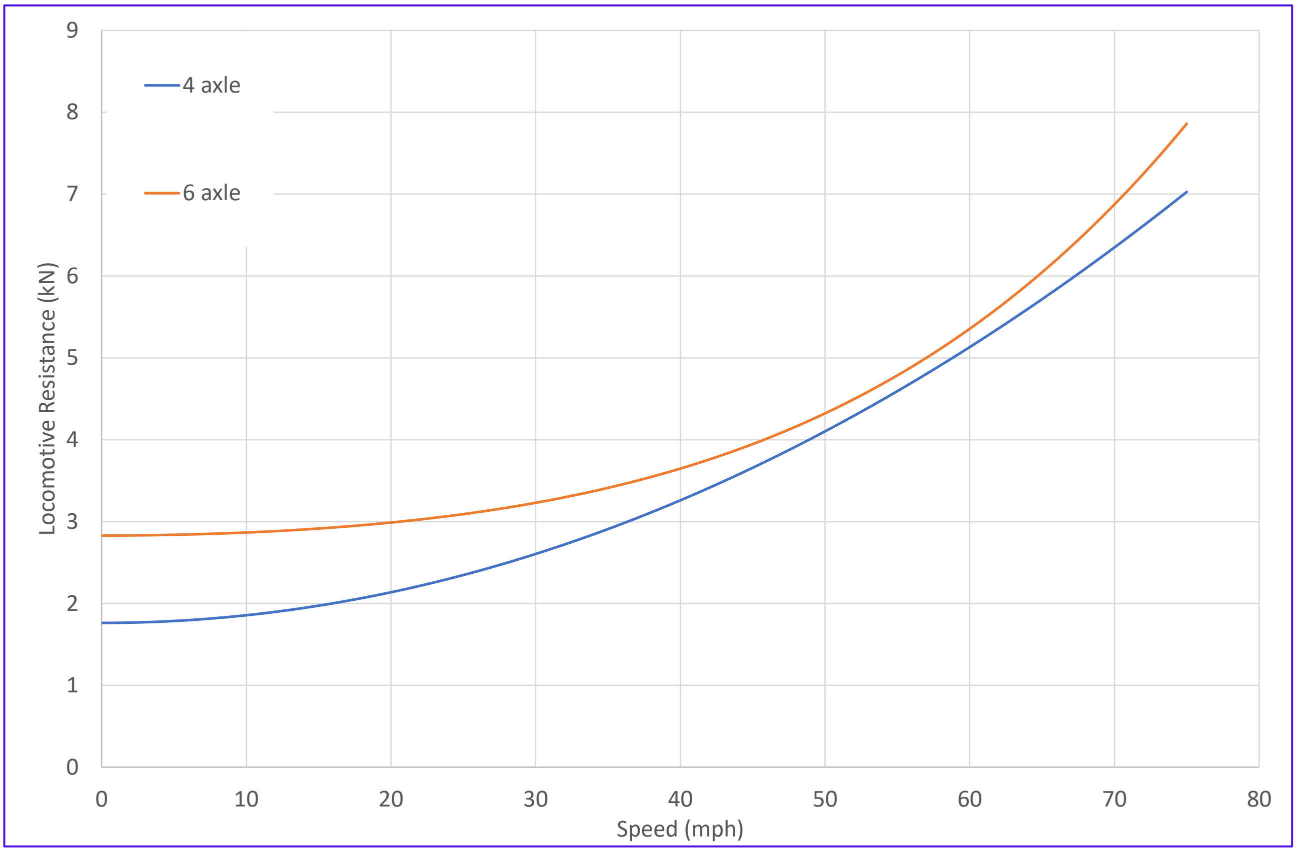
Figure 30 Locomotive specific rolling resistance from MT19



In Figure 31 below the overall mechanical resistances using the MT19 formula are plotted assuming typical RA7 axle load for the 6-axle locomotive and RA8 axle load for the 4-axle locomotive. This show a substantial difference at lower speeds between 4 and 6 axle locomotives as expected; however, there is an unexpected convergence between the resistances predicted at higher speeds. So, is this convergence at higher speeds real or is it an artifact of using formulae derived for low-speed calculation being extended well beyond the speed range they were derived for? We discuss this question further in the section below.

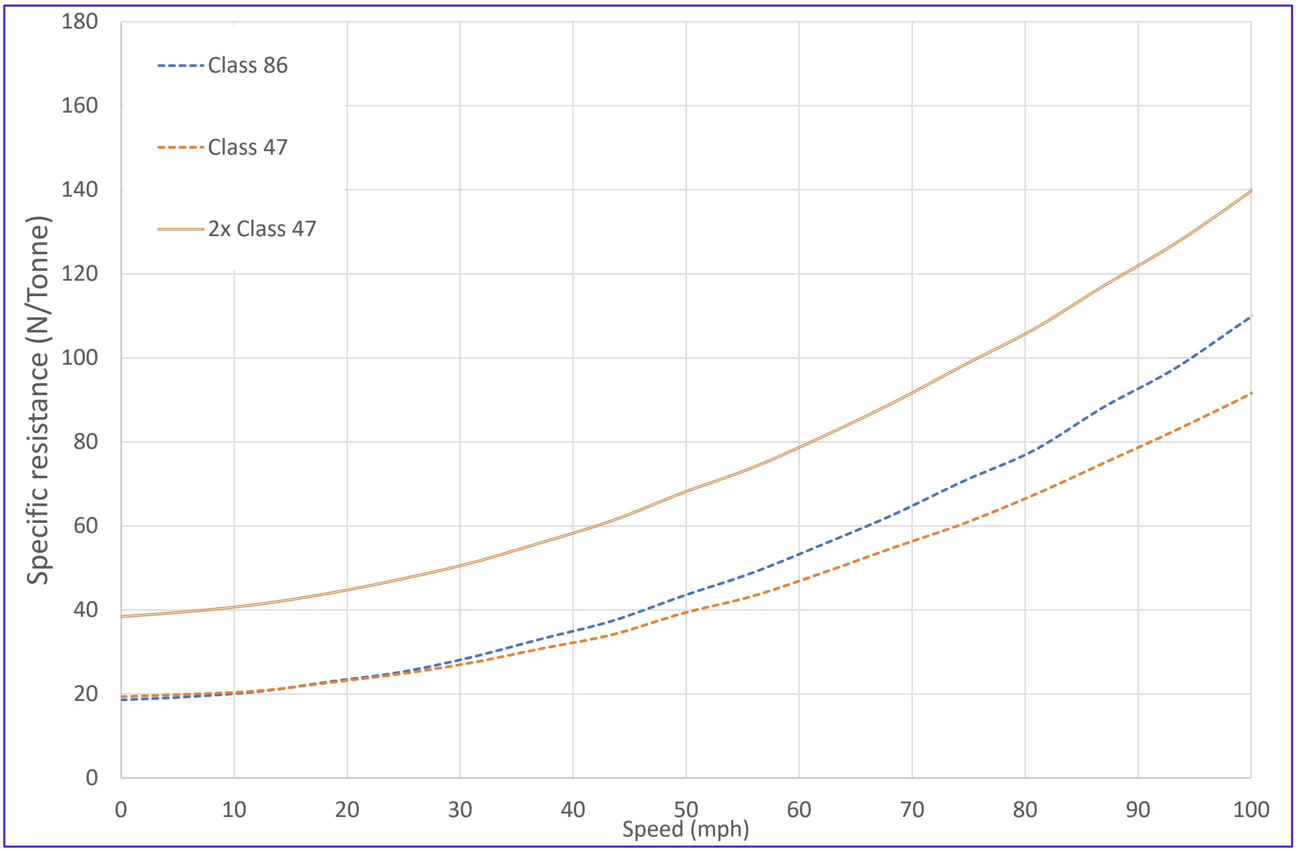
The 4 and 6-axle total locomotive mechanical resistances at high speed are similar with most of the resistance being due to aerodynamic drag. However, the curves in Figure 31 are too similar to each other at higher speeds which would not be consistent with other mechanical resistance components.

Figure 31 High speed locomotive total rolling resistance from MT19



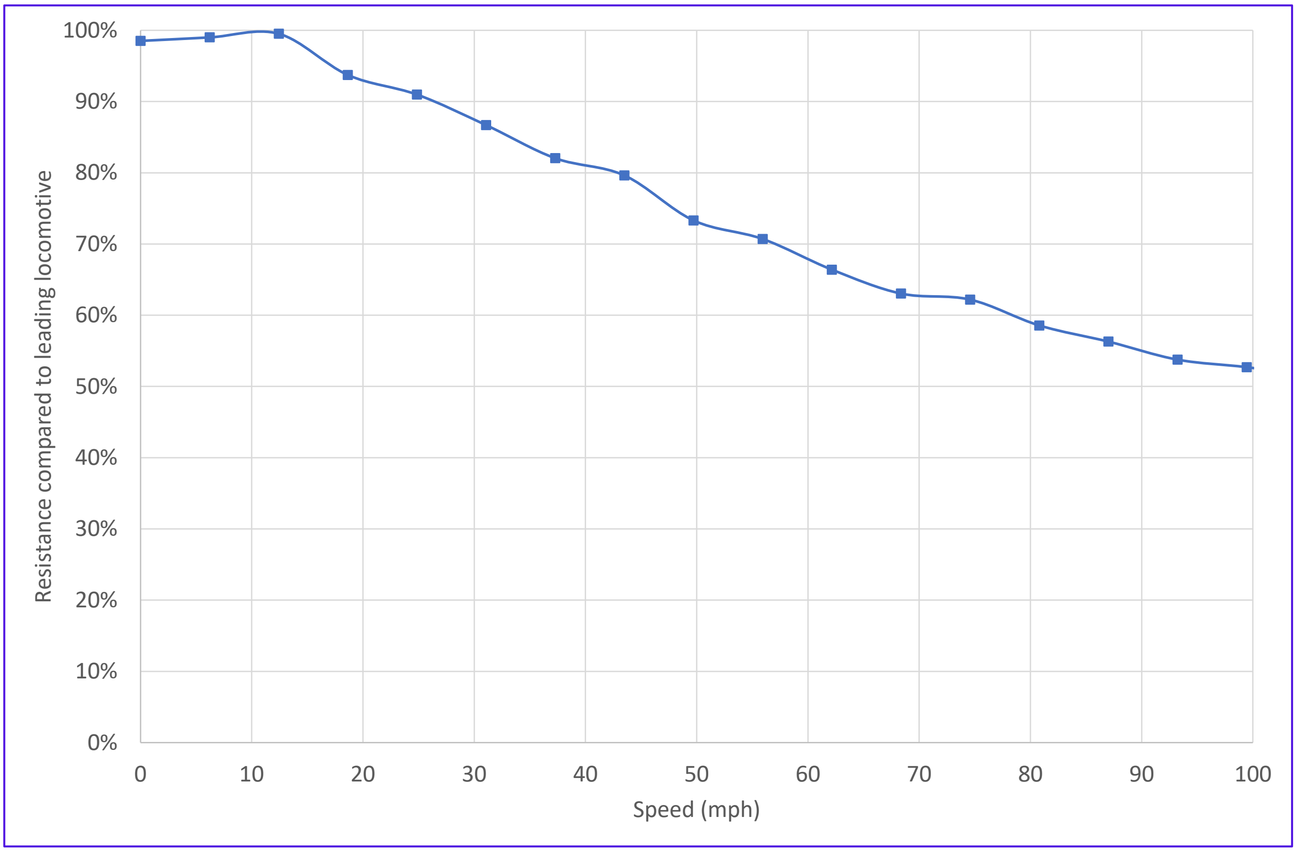
In the early 1970s, British Rail had already been gathering substantial data sets on train dynamics, including improved resistance data sets. These improved resistance data sets started to be used for timing calculations from 1974 onwards (Hargraves, 1974). In the 1982 British Rail report (Headech, 1982) the various resistance data sets were reviewed with the aim of working towards a unified set of resistance data that could be used for all purposes (that is, for freight TLL and timetabling calculations). Gaps in the data sets or data quality issues were identified and recommendation made for further work. Some of the data included in Headech (1982) were the results of British Rail trials on how locomotive (as well as other rolling stock) resistance varied with speed. The locomotive resistance curves from the trial have been redrawn below in Figure 32. There are three curves: a single Class 86 locomotive (4-axle), a single Class 47 (6-axle), and a double-headed Class 47 combination (two 6-axle locomotives). At low speeds the single Class 47 and Class 86 overall resistances are very similar but as the speed increases there is a divergence with the Class 86 resistance increasing at a faster rate than the Class 47, almost the exact opposite of the locomotive resistance equations deduced from MT19. One potential reason for this divergence is due to increased aerodynamic resistance from the electric Class 86 locomotive having a pantograph. At low speed the resistance of two Class 47s is effectively double that for a single locomotive. However, as speed increases the overall resistance of two locomotives is less than double that of a single locomotive, which is in line with expectations as the aerodynamic resistance of the following vehicle is reduced as a result of the low-pressure slipstream generated by the leading vehicle. The recommendation of Headech (1982) was to use best-fit curves developed from the measured Class 86 and Class 47 for resistance curves for 4-axle and 6-axle locomotive resistances, respectively.

Figure 32 Class 86 (4-axle) and Class 47 (6-axle) locomotive specific rolling resistance from Headech (1982)



The benefit of double-heading on locomotive resistance is shown in Figure 33 where the resistance of the second locomotive is compared with the first locomotive. The resistance of the second locomotive is very similar at low speeds but falls to almost half that of the first locomotive at 100 mph.

Figure 33 Resistance of second Class 47 as a proportion of the resistance of the leading locomotive



Using the three sets of measured data, we developed the following best-fit equations for a single Class 86 locomotive, a single Class 47 and double-headed Class 47s:

$$\text{Class 86 (4 axle) specific locomotive rolling resistance [N per } tonne] = 0.00839 \times V^2 + 0.0698 \times V + 18.649$$

$$\text{Class 47 (6 axle) specific locomotive rolling resistance [N per } tonne] = 0.00655 \times V^2 + 0.0607 \times V + 19.157$$

$$\text{Second Class 47 (6 axle) specific locomotive rolling resistance [N per } tonne] = 0.00188 \times V^2 + 0.102 \times V + 18.999$$

The relative coefficient values for the second Class 47 locomotive compared to a single locomotive are:

- V^2: 28.8%
- V: 147.9%
- Constant: 99.1%.

The non-speed dependent coefficient being virtually identical is as expected and the speed dependent coefficients based on Figure 32 would be expected to be lower however while the V^2 coefficient is lower, the V

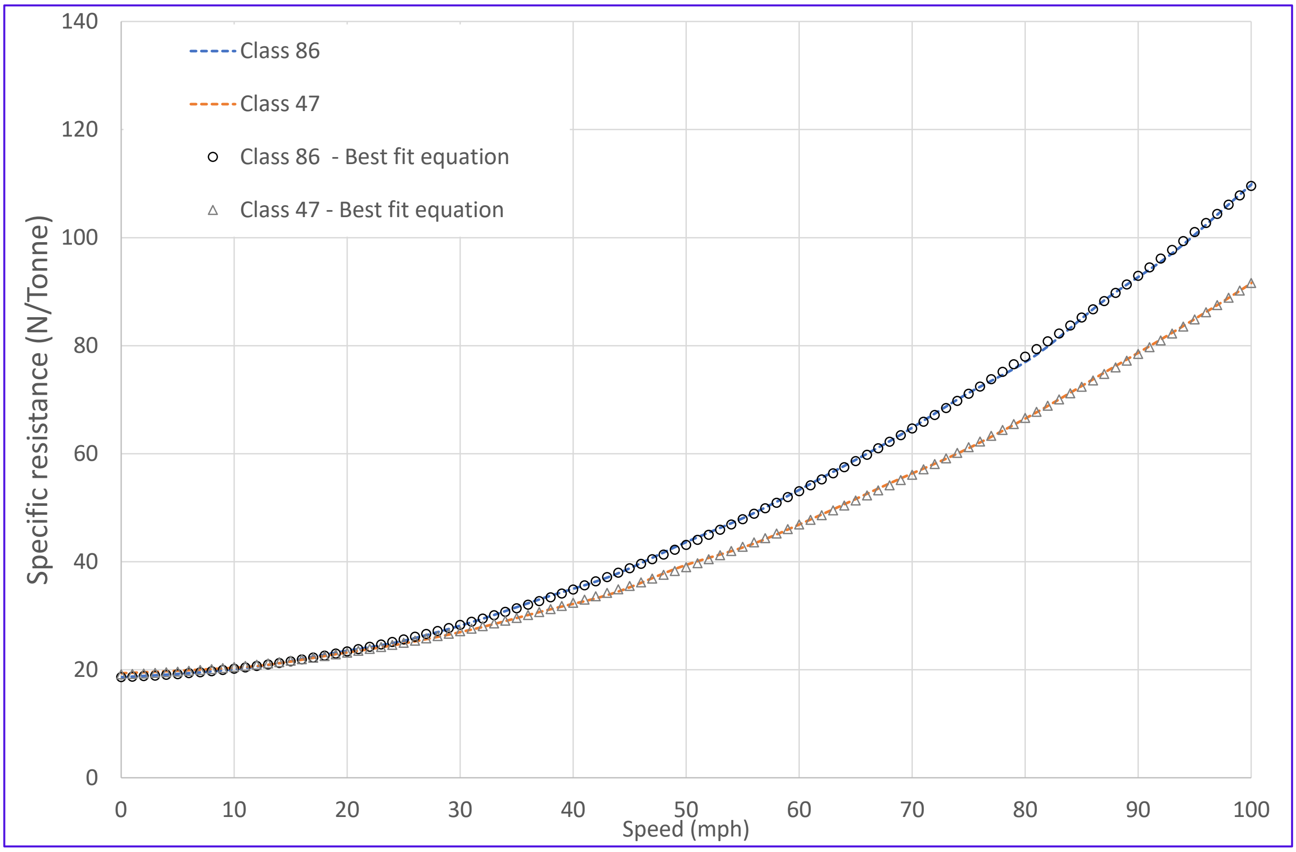
coefficient is higher. This does not appear to be an artifact of the best-fit equation calculation process however, as the maximum difference between the single and double Class 47 curves is around 45-55 mph indicating that the increase in the V coefficient does match the underlying data and also aligns with the slight curvature in the chart above ~12 mph in the curve in Figure 33 above. There are two potential approaches that could be taken for adjusting the first (leading) locomotive factors to be used for a second locomotive:

- Use % values of the first locomotive's coefficients for both 4 and 6-axle locomotives (as outlined above).
- Derive a simple speed-dependent function based on Figure 33 where the resistance of the second locomotive reduces linearly with speed above 12 mph.

The first approach aligns more closely with existing calculation methodologies as the three coefficients are being adjusted and could be viewed as coefficients for a different locomotive type (that is, different values for leading and non-leading locomotives which could be updated fairly readily). It does however assume that the aerodynamics of locomotives generally are broadly comparable. Given the constraints of loading gauge, vehicle length, and operational considerations (for example, forward visibility from the cab) this is taken to be a reasonable assumption. The second approach introduces new calculation logic and is harder to update as new data become available, or for new locomotive types if they are substantially different. Therefore, we recommend use of the first approach.

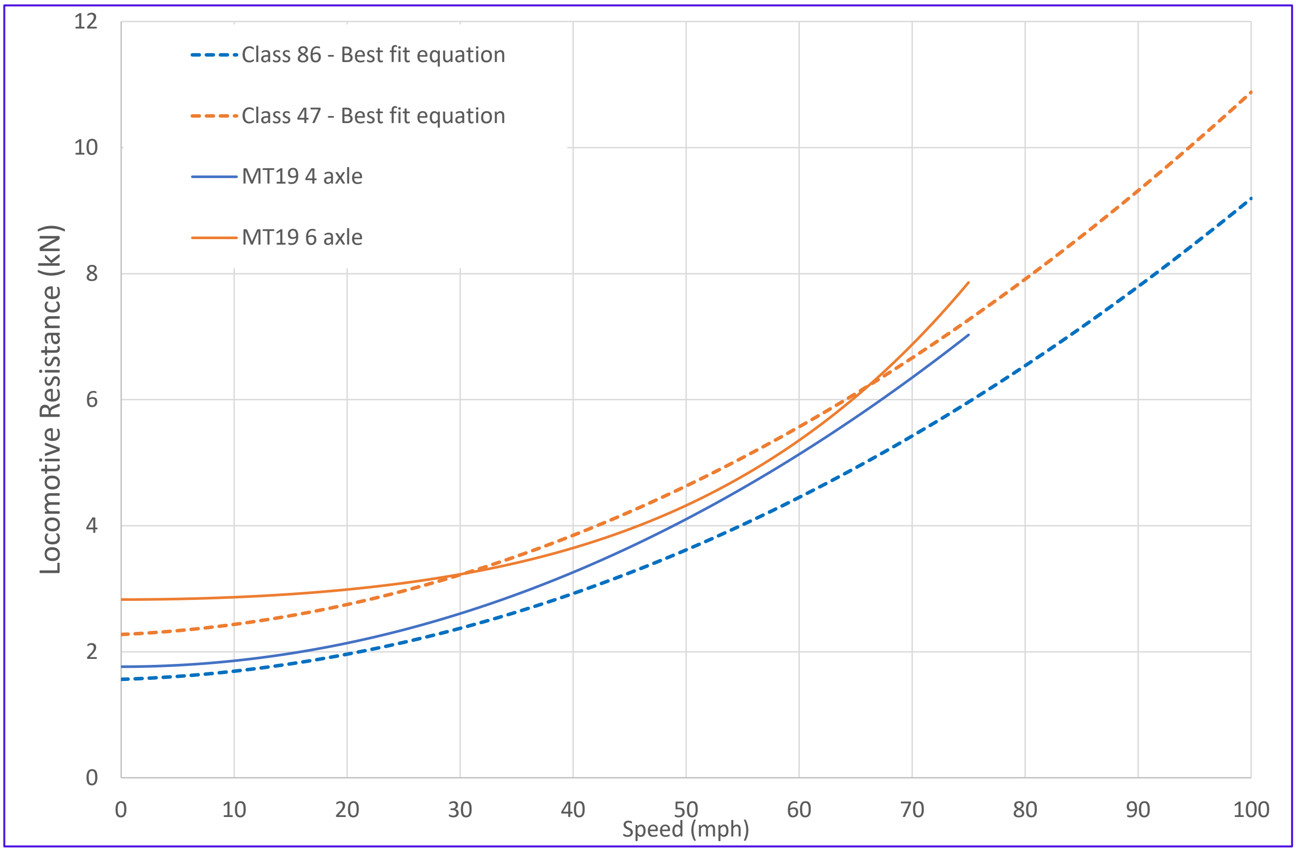
The measured data (dashed lines) and best-fit curves (circles or triangles) for single locomotives are plotted in Figure 34 below, with the best-fit curves providing a good match to the measured data.

Figure 34 Class 86 (4 axle) and Class 47 (6-axle) locomotive rolling resistance



The total locomotive rolling resistances for both 4 and 6 axles using the MT19 equations and Class 86 (4 axle) and Class 47 (6 axle) are compared in Figure 35. While there are broad similarities, the variance between the two approaches for 4 and 6 axles can be up to 30%.

Figure 35 Comparison of total locomotive rolling resistances in MT19 and other BR work



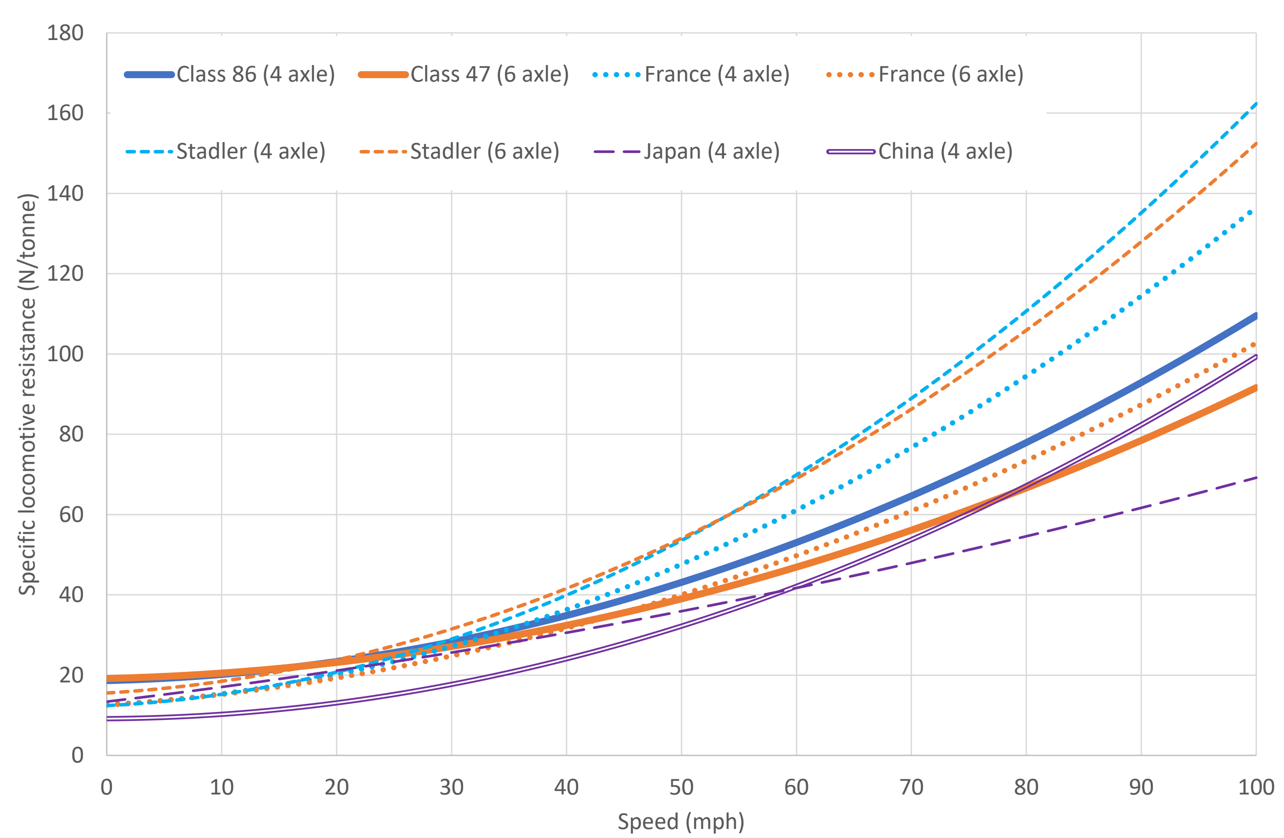
Use of the BR Class 86 (4 axles) and Class 47 (6 axles) data is recommended for default locomotive resistances where other data are not available. Use of the $V^2 + V +$ constant equation format allows OEM data for newer locomotive types to replace the default values. Data sets are available for single and double-headed locomotive use.

4.3.3.2 Overseas locomotive resistance comparisons

The British Rail 1982 report (Headech, 1982) referenced comparisons with European and US data for both 4-axle and 6-axle locomotives but did not state which European countries the data came from, or provide the raw data, but it did provide best-fit curves for the European data. The US data for 4-axle and 6-axle locomotives was not analysed in detail due to the substantial larger locomotive frontal area and aerodynamic drag of North American locomotives resulting in high locomotive rolling resistances, and the Headech (1982) conclusion that the data was not readily transferable to the GB or many European networks.

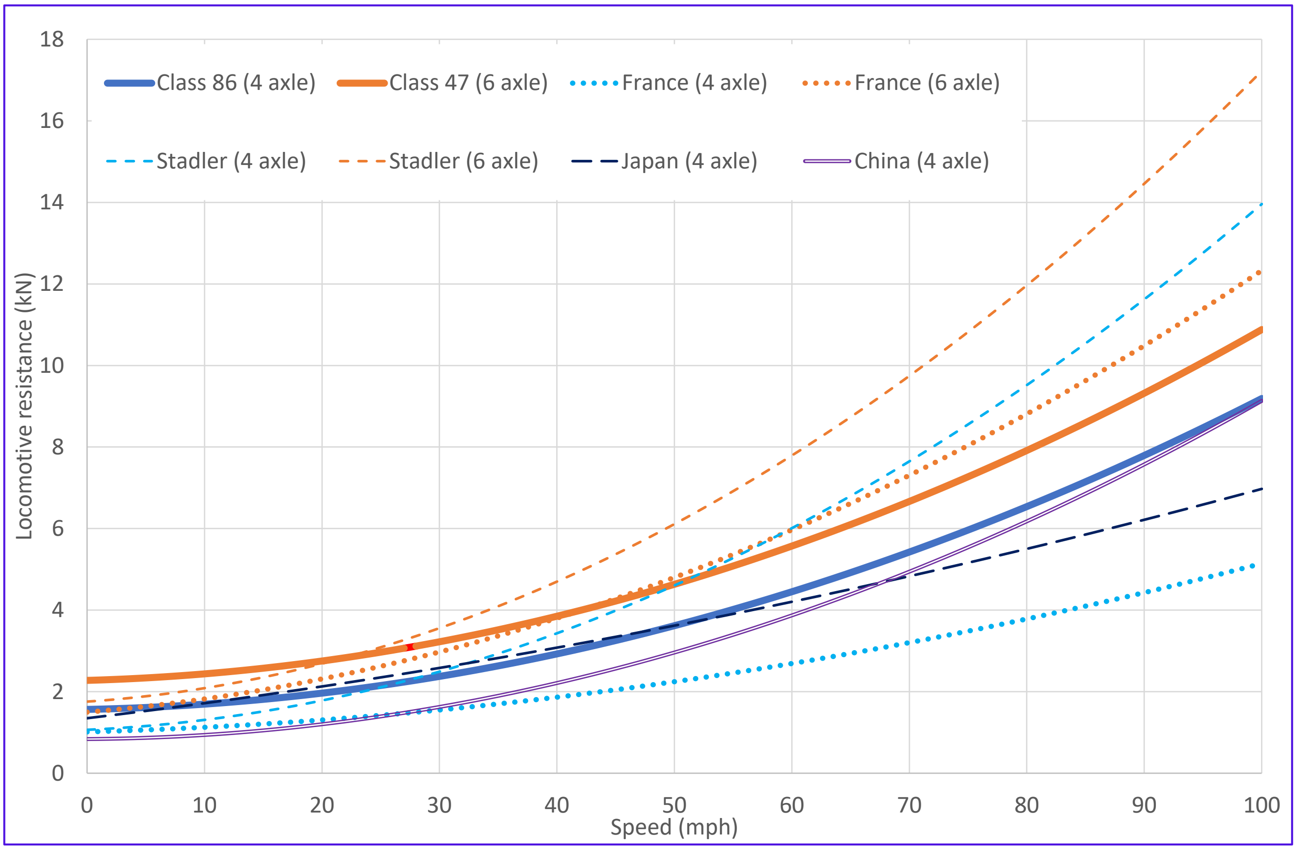
Specific mechanical resistance data from France, Japan, China, and Stadler have been found and are presented in Figure 36 below, alongside the Class 86 and 47 best-fit equations based on the BR Class 86 (4 axles) and Class 47 (6 axles) data.

Figure 36 International specific locomotive rolling resistances comparisons



Overall mechanical resistance data from France, Japan, China, and Stadler are presented in Figure 37 below, alongside the Class 86 and 47 best-fit equations. This figure shows that the BR locomotive resistances are higher than international comparators at low speeds and similar at typically middle of the range compared against international comparators:

Figure 37 International locomotive rolling resistances comparisons



International formulae plotted in Figure 36 and Figure 37 above are presented below in standardised units of N/tonne and mph. Some formula have been adapted from the original formula but with modified coefficient values for unit conversion reasons to enable comparison between formulae. Some formulae are best-fit equations based on published curves (where formulae for those curves have not been published).

$$\text{SNCF (4 axle) specific locomotive rolling resistance [N per } tonne\text{]} = 0.01079 \times V^2 + 0.1594 \times V + 12.683$$

This formula has been derived from a curve derived from measurements in 1962/63 (Allenbach, 2012), with unit conversion from km/h to mph.

$$\text{SNCF (6 axle) specific locomotive rolling resistance [N per } tonne\text{]} = 0.00704 \times V^2 + 0.1985 \times V + 12.507$$

This formula has been derived from a curve derived from measurements in 1962/63 (Allenbach, 2012), with unit conversion from km/h to mph.

$$\text{Stadler (4 axle) specific locomotive rolling resistance [N per } tonne\text{]} = 0.01353 \times V^2 + 0.1470 \times V + 12.395$$

This formula has been derived from a manufacturer formula of unknown history (Stadler, personal communication), with unit conversion from kg/tonne to N/tonne and km/h to mph. The values the formula produces are similar to several older published Swiss Railways (CFF) 4-axle locomotive curves derived from measurement in the 1950s and 1960s (Allenbach, 2012), so the formula may have been derived to be a best fit of these curves.

$$\text{Stadler (6 axle) specific locomotive rolling resistance [N per } tonne\text{]} = 0.01196 \times V^2 + 0.1726 \times V + 15.563$$

This formula has been derived from a manufacturer formula of unknown history (Stadler, personal communication), with unit conversion from kg/tonne to N/tonne and km/h to mph. The values the formula produces are similar to several older published Swiss Railways (CFF) 6-axle locomotive curves (for both Co-Co and Bo-Bo-Bo 6-axle locomotives) derived from measurement in the 1950s and 1960s (Allenbach, 2012), so the formula may have been derived to be a best fit of these curves.

$$\text{Japan (4 axle) specific locomotive rolling resistance [N per } tonne\text{]} = 0.00214 \times V^2 + 0.3437 \times V + 13.375$$

This formula has been derived from a JR East formula of unknown history (Harada, 1967), with unit conversion from km/h to mph.

$$\text{China (4 axle) specific locomotive rolling resistance [N per } tonne\text{]} = 0.00881 \times V^2 + 0.0210 \times V + 9.130$$

This formula has been derived from a China Railway formula of unknown history, with unit conversion from km/h to mph. This formula is believed to be of more recent origin than the other formulae.

Overseas approaches outside of North America using the V^2 + V + constant format with a similar range of values to Class 86 and Class 47 values.

4.3.3.3 Recommendations for locomotive mechanical resistance

For rolling resistance, the recommendation of Headech (1982) was to use formulae derived from best-fit curves from the measured Class 86 and Class 47 resistance curves for default 4 and 6-axle locomotive mechanical resistance calculations. This continues to be the best approach based on available GB data sets as defined in Section 4.3.3.1.

Ideally data for both starting and rolling mechanical resistance should be collected and coefficients calculated for current GB locomotive types, particularly as modern bogie designs are likely to have lower track forces and resistance than older designs and real locomotive starting resistance lower than the conservative assumptions used in MT19. However locomotive resistances of all types are a small part of overall freight train resistances, so any changes with new data set, if this were to be collected, would only result small changes in maximum trailing loads calculated.

Equations for locomotive mechanical resistance based on the learnings derived in Section 4.3.3.1 are presented below.

Mechanical component (leading locomotive):

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:

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

Mechanical component (non-leading locomotive):

All coefficients and values remain the same, except for the V^2 coefficients of K_{LMR7} and K_{LMR8} which are reduced by ~66%:

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

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

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.

4.3.3.4 Locomotive curvature resistance

In the MT19 methodology, curvature resistance is not applied to the locomotive; however, it is applied in calculations overseas.

There are three cases to consider:

- Locomotives with 4 axles (2 x 2-axle bogies, Bo-Bo)
- Locomotives with 6 axles (2 x 3-axle non-steerable bogies, Co-Co)
- Locomotives with 6 axles (2 x 3-axle steerable bogies, Co-Co).

For 4-axle locomotives overseas, the curvature resistance is treated as being the same as bogie wagon curvature resistance.

For 6-axle locomotives, the initial US approach was to assume that the curvature resistance of each 3-axle bogie was equivalent to two 2-axle bogies, hence the curvature resistance for a 6-axle locomotive being double that for a 4-axle bogie wagon.

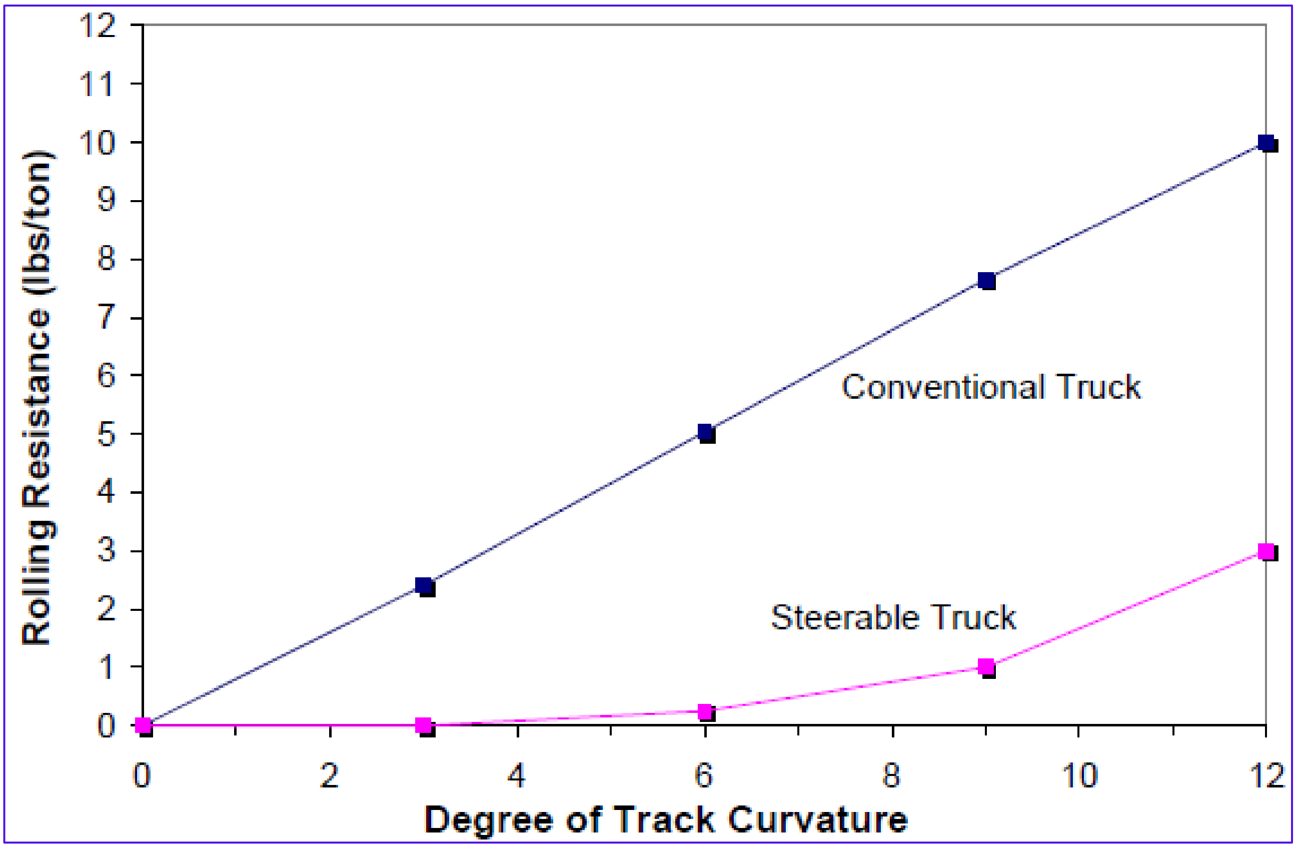
$$R_{LC\ (US\ 2-axle\ bogie)} = \frac{780}{track\ radius\ [m]}\ [\mathrm{kg/tonne}]$$

$$R_{LC\ (US\ 3-axle\ non-steerable\ bogie)} = \frac{1{,}560}{track\ radius\ [m]}\ [\mathrm{kg/tonne}]$$

Bogies with radially steerable axles have been developed in both the US and Europe for both 2 and 3-axle bogies in order to reduce curvature resistance as well as wheel and track wear. Hence being able to incorpoate reduction in curvature resistance due to steerable bogie designs requires incorporating locomotive curvature resistance in calculations.

Figure 38 below shows the difference in curvature resistance for steerable and non-steerable (‘conventional’) bogies (referred to as ‘trucks’ in US terminology) used by the Federal Railroad Administration (FRA) in the US (FRA, 2009).

Figure 38 Comparison of locomotive curvature resistance for 3-axle steerable and non-steerable bogies from FRA, 2009



The best-fit equations below were derived for the two curves in Figure 38 based on the five available data points for each curve:

$$R_{LC(US\ non-steerable\ 3-axle\ bogie)} = \frac{1,480}{track\ radius\ [m]} - 0.15\ [\mathrm{N/tonne}]$$

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

In the non-steerable bogie case, the curvature resistance is effective equal to 95% of the value assumed in the US approach of doubling the 2-axle bogie resistance (1,480 versus 1,560).

In the case of the 3-axle steerable bogie, the resistance is substantially lower (0.1 N/tonne versus 1.56 N/tonne at R1,000 m) and is therefore negligible, unless the radius of curvature is R300 m or sharper.

4.3.3.5 Recommendations for locomotive curvature resistance

We recommend incorporating locomotive curvature resistance in the trailing load calculations (MT19 currently only includes it for wagons). While this theoretically reduces the maximum trailing load by a small amount if there are no other changes, the incorporation makes the overall calculation more realistic in that the benefits of steerable bogies can be included. The inclusion of locomotive curvature resistance is needed to align with using higher adhesion values which do not include an underlying adjustment for adhesion curvature dependency at tight curvatures.

It is recommended that the approach outlined below is taken for both rolling and starting locomotive curving resistance.

For 4-axle locomotives, use the existing curvature resistance for wagons (that is, use the same assumption used in other countries but with a GB value; see Section 3.3.1.2 and Section 4.4.5.3):

$$R_{LC(2-axle\ bogie)} = \frac{753.6}{r}\ [\mathrm{kg/tonne}]$$

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

For 6-axle locomotives with conventional non-steerable bogies, use the US approach of doubling existing curvature resistance for a 4-axle bogie wagons (see Section 4.3.3.4 and Section 4.4.5.3):

$$R_{LC\ (3-axle\ non\ steerable\ bogie)} = \frac{2\ \times 753.6}{r}\ [\mathrm{kg/tonne}]$$

$$R_{LC\ (3-axle\ non\ steerable\ bogie)} = \frac{2\ \times\ 7{,}390}{r}\ [\mathrm{N}/\mathrm{tonne}]$$

For 6-axle locomotives with steerable bogies (that is, Classes 59 and 66), use the best-fit equation produced from the US FRA data (see Sections 3.3.1.2 and Section 4.4.5.3):

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

4.3.3.6 Future research for locomotive curving resistance

Locomotive manufacturers have to carry out detailed track force calculations (for example, using the Vampire® simulation package) for rolling stock acceptance testing, hence some more accurate data may be available for certain new locomotive types to improve calculation methodologies and values for locomotive curvature resistance. However locomotive resistances of all types are a small part of overall freight train resistances, so any changes due to a new data set would only result small changes in maximum trailing loads calculated.

Further research and gathering or existing data on locomotive curving resistance is recommended.

4.3.4 Locomotive starting resistance

Internationally, locomotive starting resistance is often very poorly and inconsistently addressed with a far greater focus on rolling resistance. Therefore, continued use of the MT19 approach is recommended (see Section 3.2.4. The equations below are presented in metric format.

Locomotive mechanical starting resistance: $R_{LMS} = K_{LMS1}\ [N/tonne]$

K_{LMS} = Locomotive mechanical starting resistance factor = 87.5230 (N/tonne)

$$K_{LMS1} = 87.5230\ [{}^{N}/_{tonne}]$$

$$\text{Locomotive starting resistance } (R_{LMS})[\text{N}] = 87.5230 \times \text{locomotive mass [tonnes]}$$

The locomotive starting assumptions in MT19 can be used since these do not have a significant impact on the overall outcomes, and a better data set is not available to revise these assumptions.

For starting resistance, the recommendation is to use the existing MT19 approach and values for starting resistance outlined in Section 3.2.4.

4.4 Wagon factors

4.4.1 Types of wagon resistance formulae

In this section we step through the development of wagon resistance formula (and whole train formulae where applicable).

Stephenson and Wood conducted tests to determine the resistance of wagons on the Killingworth Railway in 1818. Tests were carried out on the Liverpool and Manchester Railway in 1834, and Gooch used an early form of dynamometer car to measure drawbar forces on the Great Western Railway in 1847. Early in this period it was established that mechanical drag was related to weight (and axle load), but independent of speed. **Thus, resistance formulae include implicit assumptions on weight/axle load**. Lardner in 1838 and Bessemer in 1845 (referred to in Johansen, 1936) determined that air resistance was closely (but not completely) proportional to the square of the speed. Thus, by the 1850s, resistance equations were established. These equations consisted of two terms in the format of:

$$R = A + C \times V^2$$

This format is still in use in some countries, for example, Germany, France, and Czechia. As the laws of mechanical and aerodynamic resistance became better understood and more accurate measuring instruments were devised and introduced, it was realised by several teams working independently in Europe (Britain and Russia) and in North America in the early 1900s that the two-term equation was not complete. The three-term equation for different vehicle types was therefore introduced in the now familiar format of:

$$R = A + B \times V + C \times V^2$$

The detail and complexity of the three-term formulae developed in Britain, Russia, and North America varies significantly. The simplest formulation in Britain is from Carus-Wilson (1907) for a given vehicle type (with axle load assumptions implicit in the coefficient values) due to concerns over the quality and quantity of available data being insufficient to make more detailed conclusions, for example, to be able to incorporate axle load variability or quantify the difference in aerodynamics between difference vehicle types. This formulation also introduced the common (outside America) A, B, and C coefficient definitions. The British format is:

$$R = A + B \times V + C \times V^2$$

Others in Russia (Petrov, 1898; Lomonosov, 1898) and the United States (Davis, 1904) included axle load dependencies but did so in ways that were later shown not to reflect the underlying physics. These were initial approaches that included axle load, and in some cases aerodynamic and track construction dependencies, in the resistance formulae.

The Petrov formula format is:

$$R = A + \frac{B \times v}{M^{\sim}} + \frac{C_1 \times V^2}{M^{\sim}} + \frac{C_2 \times V^2}{M_T} \; [{}^{kg}/_{tonne}]$$

where:

R = the specific resistance to the movement (kg/tonne)

v = speed (km/h)

M_T = the train weight (tonne)

$M^{\sim}$ = average vehicle weight (tonne).

In 1904, W.J. Davis published his first iteration of train resistance equation based on his experimental research designing General Electric's first electric locomotives (Davis, 1904). These were the first complex tests to determine the resistance of electric locomotives at higher speeds and the influence of the number of carriages or wagons were carried out in 1900 on the Buffalo & Lockport railway, with a maximum speed of 60 mph. (This first iteration should not be confused with his final iteration published in 1926 which is generally referred to as *the* Davis equation.) Utilizing his experimental data, Davis (1904) suggested the following formula for calculating the resistance of trains with the electric traction:

$$R = B + C \times V + \frac{d \times V^2}{M_T} \times \left(A_1 + m(A_2 + A_3 + \ldots + A_n)\right) \, [{}^{lb}/_{US\ ton}]$$

where:

R = the specific resistance to the movement (lb/ton)

V = speed (mph)

M_T = the train weight (US ton)

B = 3.5 for freight trains, 4.0 for standard passenger train carriages and long electric trains, 5.0 - 6.0 for lightweight electric trains

C = the complex friction coefficient when rolling, 0.11 for heavy track construction, 0.13 for average track construction

d = the wind pressure coefficient, = 0.0024 - 0.0035 – depending on carriage/wagon aerodynamic characteristics especially vehicle end and cross section

m = the proportionality coefficient showing the effect of each carriage / wagon on the overall aerodynamic movement resistance, = 0.10

A1, A2, … An = the cross-sectional areas of the locomotive (A1) and carriages / wagons (A2, … An).

The three formats above proposed by Carus-Wilson, Petrov and Lomonosov, and Davis, provided the three main formats that others later used as the basis to develop resistance formulae until the 1960s.

At this stage no formulae had complex axle or wagon weight adjustments for the non-velocity dependent component (which would come later to all three formulae formats). The key persistent difference between the American-type formats which do not use axle/wagon weight adjustments of the V coefficient in specific formulae (which is consistent with the underlying physics) and the Russian, Soviet, and post-Soviet formats which use axle/wagon weight adjustments of the V coefficient (which is not consistent with the underlying physics) can be seen at this early stage.

Total and specific resistance formulae

Resistance formulae are either expressed as total vehicle resistance (for example, [N]) or specific formula with resistance per unit weight of vehicle (for example, [N/tonne]). In the former the coefficients are always derived for a given vehicle weight. The latter can also be derived for a single given vehicle weight with axle load scaling applied (hence the formula validity may be poor apart from the derivation conditions) or coefficients developed from data for several different vehicle weights with a best-fit approach used to set the coefficients so that they are better matched across a range of different vehicle masses (albeit with a focus on more closely matching resistance data for heavier axle loads where accuracy is more critical).

Categories of resistance formulae

Four categories of formula for wagon rolling resistance are used internationally are outlined below according to their key characteristics, and their relative advantages and disadvantages are discussed in detail in Section 4.4.20:

- Non-axle load dependent two-term formulae, with single fixed wagon load assumptions (covered below in Section 4.4.2.1) in the format $R = A + C \times V^2$ are used in:
    - Czechia
    - France
    - Germany.
- Non-axle load dependent formulae three-term formulae, with single fixed wagon load assumptions (covered below in Section 4.4.2.1) are mostly in the format $R = A + B \times V + C \times V^2$ are used in:
    - Schmidt (1910-1927 work)
    - Australia (some instances)
    - China
    - Serbia
    - Switzerland.
- Simplified axle load-dependent formulae (covered below in Section 4.4.2.2) are used in:
    - MT19, both 2-axle and 4-axle formulae
    - Headech (1982) interim recommendation for both 2-axle and 4-axle wagons
    - India

- USSR and successor states (format evolved to equations for each wagon type, resulting in a very large number of individual equations)
- Looking forward to our recommendation, the BR 2-axle TRFR07 equation (same as used in MT19 and Headech's (1982) recommendation for 2-axle).

- Complex formulae approaches with variation in axle load and in wagon type and aerodynamics (covered in Section 4.4.2.3) are used in:
  - Davis (1904)
  - Davis (1926), generally known as *the* Davis equation
  - Totten (1937), modified Davis equation (first roller bearing formula)
  - Tuthill (1948), modified Davis equation
  - Erie-Lackawanna Railroad (1966), modified Davis equation with more aerodynamic variations
  - Canadian National (1980 to 2021, and ongoing), modified Davis equation, at least eight iterations over four decades to date. Used for vehicle resistance in FRA, AAR, operator and most third-party models for vehicle resistance calculation in North America
  - Headech (1982), report's ideal future equation format recommendation
  - Szanto (2016), Australian modification of Canadian National equation
  - The formula proposed in this report for 4-axle based on Australian modification of Canadian National equation (covered in Sections 4.4.2.3 and 4.4.2.4).

There are four main categories of wagon rolling resistance equation format.

The simple format equations (the first two categories above), which have no axle load or aerodynamic variations in the formula) can either be specific resistance or overall wagon resistance formulas.

More complex wagon resistance equation formats (the latter two categories above) with axle load and variation in wagon aerodynamics are always specific resistance formulae.

In contrast to rolling resistance, wagon starting resistance calculation is often treated in much simpler ways, and there is far less published information on starting resistances. There are two common categories of approach (covered below in Section 4.4.4):

- Simple value (most)
- Multiple of the rolling value at 0 mph (rare).

Approaches to starting resistance should align with the chosen rolling resistance methodology, else there will be some implausible calculation results with some chosen inputs resulting in starting resistances being lower than rolling resistances calculated at 0 mph for low axle loads.

4.4.2 Wagon mechanical rolling resistances

While use of the simplest formulation has often been preferred, this can lead to highly inaccurate wagon resistance values under some circumstances. In this section issues and problems associated with each type of resistance equation are discussed.

Relevant significant previous reviews include:

Muhlenberg (1977) is a review for the US Department of Transport and Federal Railroad Administration of 'Resistance of a freight train to forward motion'. This report lays out different types of approaches to resistance equations and approaches to computer modelling using those resistances. This report laid the groundwork for the Canadian National (CN) approach to vehicle resistance equations from 1980 onwards (latest revision in 2021) and the modelling approaches used by the FRA, AAR, operators, and most third-party models including vehicle resistance calculation in North America. It makes several key recommendations, including the need for:

- Formulae being physically consistent
- Including axle load dependencies in formulae
- Including variations in vehicle (locomotive and wagon) aerodynamics in formulae
- A systematic approach to addressing gaps in the required data (mainly for the two point above).

This report also has a better understanding of some of the history and assumptions for the British Rail wagon resistance equations (for example, TRFR08) used in MT19 than the Headech (1982) report as more history and assumptions are often better discussed in Muhlenberg (1977) and are available in external publications.

Headech (1982), seemingly unaware of the Muhlenberg (1977) report, comments in this substantial British Rail report on MT19 and its problems and how to address them. Gaps in data sets and assumptions were identified, and key requirements for future locomotive and wagon resistance equations were set out, including the formats (formulae being physically consistent, including axle load dependencies and vehicle (locomotive and wagon) aerodynamics) and what the ideal formats would be (requiring further research to fill gaps in data and assumptions. It also set out some recommended interim resistance formula based on best available data without the need for further research, though these interim recommendations were not always fully thought through.

British Rail (1983) followed on from Headech (1982) by trying to fill in some of the easier and quicker to address gaps in assumptions and data sets identified in Headech (1982) with several potential improvements outlined in this report being used in MT19.

4.4.2.1 Non axle-load dependent formulae, single fixed wagon load assumptions

These are the simplest type of equation. However, they are only valid for single wagon types and loading assumptions.

The are two main groups of non-axle-load dependent formulae still in use today, the larger group is of three-term equations developed from early work in Britain, Russia, and USA in the late 1890s and 1900s (as initially laid out in Section 4.4.1):

$$R = A + B \times V + C \times V^2$$

A smaller group of two-term equations follows the work done by Strahl in 1913:

$$R = A + C \times V^2$$

This variation is still used in Germany, France, and Czechia with updated A and C values. Later work by Strahl (1925) highlighted the lower resistance of wagons in block trains compared to the earlier work on trains with mixed wagon types which tend to have higher aerodynamic resistances, resulting in a lower C value for wagon in block trains. This is the simplest possible approach resulting in an easier calculation.

Schmidt (1910) published a series of formulas for total train resistance, each formula being applicable to a train of a specific average carriage/wagon weight. The formulas were based upon empirical data, and the user was advised not to apply them to trains at velocities higher than 40 mph. At the time Schmidt developed this series of formulas, there seems not to have been much general recognition that aerodynamic drag was particularly appreciable, probably because normal freight train velocities were relatively slow, and no distinction was made between vehicles on the basis of their aerodynamic shape or their position in the consist.

The above series of formulas applied to all vehicles and gave the specific resistance of the train in lb/US ton. For a train consisting of wagons of gross weight of 75 US tons each, the Schmidt formula for the train resistance in lb per ton of train weight is:

$$R = 2.87 + 0.019 \times V + 0.00113 \times V^2 \ [{}^{lb}/_{US\ ton}]$$

where:

V = speed in mph.

The total train resistance in lb, is obtained from this expression by multiplying by the total train weight. Since this formula is predicated upon the average weight of the cars in the train, the expression may also be looked upon as yielding the specific resistance of a single wagon, in lb/ton of wagon weight. It should be noted, however, that this expression, even though on a lb/ton basis, is not applicable to wagons or trains of other weights and applies only to a 75 US ton wagon, or to a train whose average weight per wagon is 75 tons; thus a different expression would be applicable to a wagon of 100 tons, or a train whose average weight is 100 tons per car, but the increase in total resistance would not be proportional to the increase in train weight.

As the Schmidt formulas were not to be used at velocities above 40 mph, after World War II, Tuthill (1948) produced another series of similar formulas, based upon a series of tests conducted by the University of Illinois in 1937. These are basically extensions of the Schmidt formulas to be used at higher velocities. Tuthill's formulas were also directed toward total train resistance based upon average car weight and yielded the resistance in lb/ton, but, as with the Schmidt formulae, they may also be interpreted as yielding the specific resistance of a single car, in lb/ton of car weight. Tuthill's formula for the resistance of a single car of 75 tons gross weight, in lb/ton of car weight, would be:

$$R = 0.53 + 0.009 \times V + 0.0029 \times V^2 \left[{}^{lb}/_{US\ ton}\right]$$

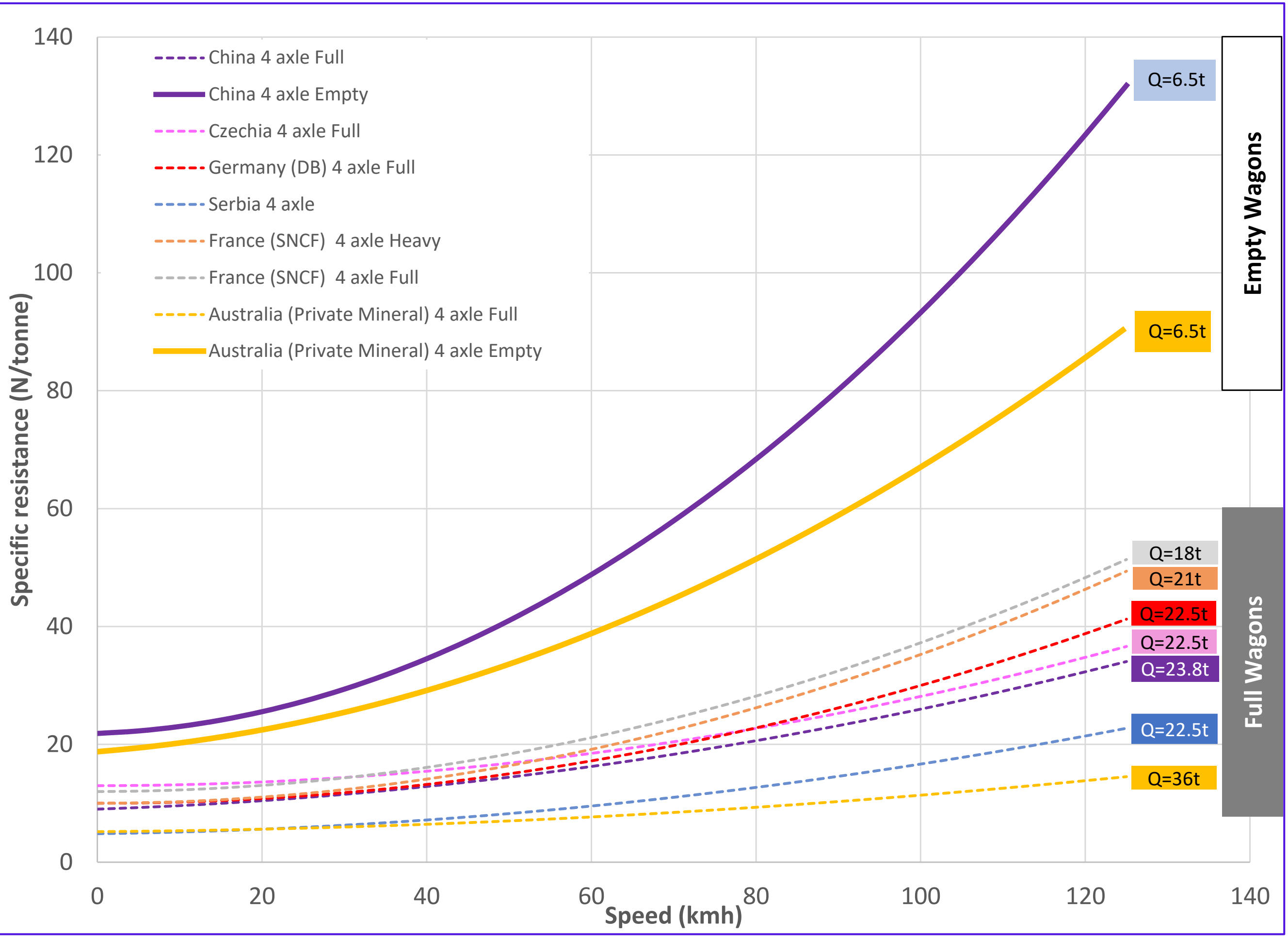
It is worth noting that if the expressions are placed on an absolute basis, so that the resistance is measured in lb, the coefficient of the V^2 dependent terms varies with the weight; as the weight increases, the coefficient increases. It has been noted by Hammitt (1976) that this is illogical, since the coefficient reflects the aerodynamic drag coefficient which is unrelated to weight. A possible explanation is that both Schmidt's and Tuthill's expressions are based upon average characteristics: average wagon weights and average consist makeup of actual trains. One can plausibly infer that the average density of the load, given a sufficient number of wagons, was constant. In such a case, for a constant average cross-section, a heavier wagon will be longer, and the heavier trains will be longer trains for the same number of wagons. It is known (see later discussions on aerodynamics in Section 4.4.2.3) that longer wagons or trains have more aerodynamic drag than shorter ones, other things being equal, since much of the air drag is skin friction, a factor dependent upon train length. Unfortunately, it is impossible to demonstrate the validity of this explanation, since only the weights were considered to be important in these experiments and no information was given on lengths of wagons or trains.

Coefficient values used in current non axle-load dependent formulae are shown in Table 20 along with loading cases and axle loads if known.

Table 20 Currently used A, B, C coefficients for non-axle load dependent formulae for 4-axle wagons

Country	Load case	A coefficient	B Coefficient	C Coefficient	Axle Load (tonnes) if known)
Australia (Private Mineral)	Full	5.2	0.0110	0.00051	36
Australia (Private Mineral)	Empty	18.7	0.1111	0.00372	5.5
China	Full	9.0	0.0471	0.00123	23.8
China	Empty	21.9	0.0520	0.00662	6.5
Czechia	Full	13	-	0.0015	22.5
France	Heavy	10	-	0.0022	21
France	Full	12	-	0.0025	18
Germany	Full	10	-	0.002	22.5
Serbia	Full	4.8	0.0183	0.001	22.5
Switzerland	Full	13.5	0.0981	0.00128	22.5

Figure 39 Comparison of international specific non axle-load dependent wagon rolling resistances formulae



As can be seen in Figure 39 above, empty wagons (dotted lines) have much higher specific resistances than fully loaded wagons (dashed lines) and there is a reasonable range of specific resistance values between different formulae for similar axle loadings. Heavier axle loads typically lead to lower specific resistances, there are also considerable differences in specific resistance values at lower speeds between formulae which are largely a function of bearing resistance assumptions.

4.4.2.2 Simplified axle-load dependent formulae

Axle load or train mass dependencies are included in some or all of the A, B, or C terms by various authors, however many implementations do not align with the underlying physics. Sighard Hoerner carried out extensive work in fluid-dynamic drag and the correct forms of resistance equations for land (including some rail work), sea and air vehicles (Hoerner, 1965). While showing considerable similarities to Davis (1926) and the Totten (1937) and Tuthill (1948) adaptations of the Davis equation for higher speed running and later roller bearings, there are some small changes in the equation format from gross wagon weight to axle load for some terms, so the equation format reflects underlying physics (including roller bearings). Hoerner had insufficient data to assess the detailed roll of wagon types in aerodynamics, so his format of formula was just a simplified axle-load formula in the following format:

$$R = A_1 + \frac{A_2}{Q} + B \times V + \frac{C \times V^2}{Q \times n}$$

where:

R = the specific resistance to the movement (lb/ton)

V = speed (mph)

A_1 = non-velocity dependent coefficient, non-axle load dependent

A_2 = velocity dependent coefficient, non-axle load dependent

B = V coefficient

C = V^2 (aerodynamic) coefficient.

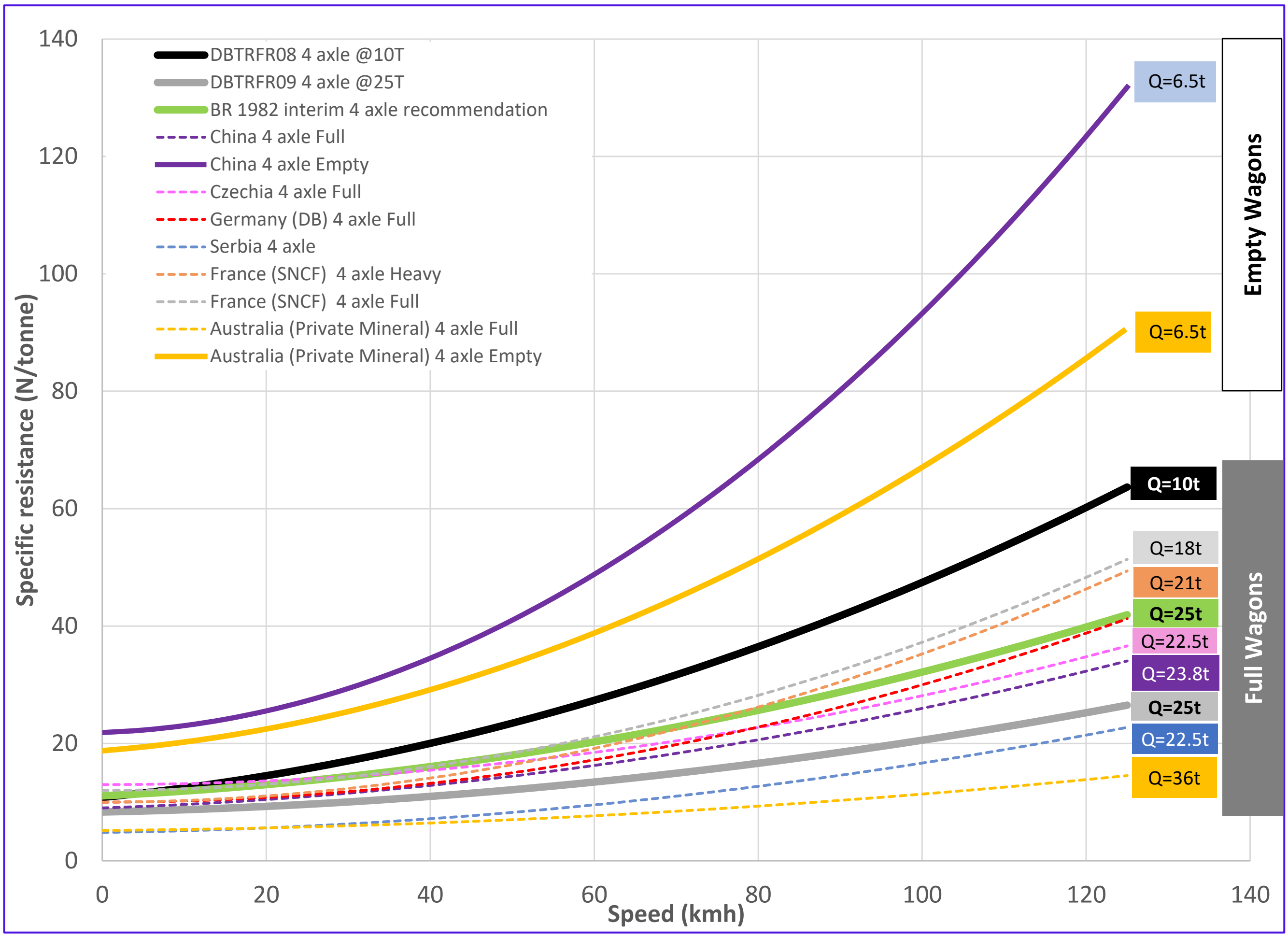
This format was used by British Rail, albeit slightly simplified from the 1960s onwards, including the TRFR07 and TRFR08 data sets used in MT19 and the interim recommendations for the freight resistance equation in Headech (1982). It also formed the basis of the more modern formats of complex formulae with both axle load and wagon type aerodynamics (modified Davis equation formats) in North America, initially by Erie-Lackawanna Railroad (1966) and later by Canadian National (1980 onwards). These more complex formulae formats split out the C coefficient into multiple individual coefficients.

With the Hoerner-type format, one of the key elements is that there is no axle load or vehicle weight scaling of the scaling of the V coefficient, which is reflected in all the formats of America equations for the last six decades. The Russian, Soviet, and post-Soviet formats continue to use axle or wagon weight adjustments of the V coefficient (which is not consistent with the underlying physics), this means that accurate complex formulae with both axle load and wagon type aerodynamics are not possible to derive.

In Figure 40 below the BR 4-axle wagon resistance formulae have been added for comparison:

- TRFR08 – the default MT19 formula which was derived for 10 tonne axle load container wagons in 1964. This formula was subsequently used for heavier axle loads (thick black line).
- TRFR09 – A 4-axle formula for 25 tonne axle loads believed to be developed by BR as part of international consultancy work in Australia in the later 1970s (thick grey line).
- Headech's interim recommendation for a 4-axle variable axle load formula, with the axle load set to 25 tonnes in this case (thick green line). Despite being categorised as an axle load independent formula, it only produces sensible results with axle loads between 15 and 25 tonnes. The resistance at low speed for axle loads below 12 tonnes are much higher than any other formulae.

Figure 40 Comparison of British Rail wagon rolling resistances formulae international specific non-axle-load dependent wagon rolling resistances formulae



4.4.2.3 Complex formulae with both axle load and wagon type aerodynamics

Between 1908 and 1916 a large series of experiments was carried out in the experimental laboratory of the University of Illinois under the guidance of Professors E. Schmidt and H. Dunn to determine the resistance of freight and passenger trains with steam and electric traction. The results were obtained in the range of speeds between 10 and 55 mph during experimental travel and were published in the *Bulletin of the Engineering* Experiment Station of the University of Illinois, Urbana between 1910 and 1927 (for example, Schmidt, 1910; Schmidt and Marquis, 1912; Dunn, 1914; Schmidt and Dunn, 1916, 1918; Schmidt, 1927). These experiments showed the with greater clarity the underlying factors in experimental data in rail vehicles resistance (including curvature resistance) that needed to be included in potential equations. The work often focused on individual learnings from the data rather than proposing overall equations. Two key themes for the development of equations from the data were the need to include for axle load variation in the non-velocity dependent components and the need for be able to include the difference in aerodynamics between different vehicles which would require multiple V^2 coefficients.

However, the most common used fundamental formula for the movement resistance is still called the Davis equation. In 1926 in a brochure Davis (1926) suggested an improved empirical formula to calculate the resistance of single vehicles (rather than the whole train in his first 1904 iteration) on straight horizontal track, the whole train resistance being the sum of the individual vehicle resistances. The expression included the number of axles as well as the weight and velocity, the original formula being:

$$R = 1.3 + \frac{29}{Q} + B \times V + \frac{C \times A \times V^2}{Q \times n} \; [^{lb}/_{US\ ton}]$$

where:

R =the specific resistance to the movement (lb/ton)

V =speed (mph)

A = cross sectional area of the vehicle (square feet)

B = experimental derived constant

C = aerodynamic coefficient

n = number of axles per vehicle

Q = the axle train load (US ton).

Davis gave recognition to differing velocity-dependent resistances and aerodynamic drags for various vehicles and published an accompanying table of recommended values for cross-sectional areas 'A', the coefficient 'B', and the aerodynamic drag coefficient 'C'. Values were provided for locomotives, passenger cars, freight cars and a few other miscellaneous vehicles.

There have been many, often gradual, improvements to the 1926 Davis equation that addressed specific issues. These have included Totten (1937), Tuthill (1948) for non V^2 coefficient values, Erie-Lackawanna Railroad (1966) for V^2 coefficient values, and Hoerner (1965) for range for issues around axle load variation in formulae.

The Muhlenberg (1977) review directly laid the groundwork for the Canadian National (CN) approach to vehicle resistance equations which addresses all the relevant recommendation of the review. From 1980 onwards there have been at least eight iterations of the CN formula, datasets, and assumptions with the latest public revisions in 2021. The CN formula and associated learnings provides the most tested and utilised basis for a wagon rolling resistance formula currently available; however, there are a few minor issues with the approach, and it requires adaptation for GB rolling stock.

<u>CN Equation with metric and GB specific values:</u>

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

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} = 7.355

K_{WMR2} = 80.068

K_{WMR3} = 0.147

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

K_{WMR5} = 'C' coefficient as defined in Table 21

K_{WMR6} = 1024.081

A_W = wagon frontal area as defined in Table 21 (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:

$$R_{WMR} = 7.355 + \frac{80.068}{Q} + 0.147 \times V + \frac{K_{WMR5} \times A_w \times V^2}{1024.081 \times M_w} \; [^{N}/_{tonne}]$$

Values of K_{WMR5} and A_w for relevant British wagon types are shown in Table 21. The selected wagon types were chosen where the wagon type used in North America and Great Britain have sufficiently similar characteristics for the K_{WMR5} values to be used and the wagon frontal area have been calculated for GB wagons including varying platform heights for container wagons. K_{WMR5} values have a dependency on wagon length, with longer wagon typically having larger values as the non-frontal surface area of the wagons is a function of wagon length. For example, iron ore box wagons are shorter than coal box wagons, and due to the greater density of iron ore, the maximum cargo mass has a smaller volume enabling shorter wagons to be used. A similar situation exists with petroleum product tanker length which is greater than for coal box wagons. In this instance, although petroleum product densities are broadly equivalent to coal, the need to employ cylindrical tanks for liquids for reasons of strength as opposed to hoppers or box wagons for bulk materials which have a usable cross-sectional profile much closer to that of the loading gauge results in longer wagon lengths for tanker wagons for the same mass of cargo. Derivation of values of K_{WMR5} and A_w for other GB wagon types substantially different from the types shown in Table 21, such as car carriers, will need analysis of real world data following one of the methodologies outlined in Rochard and Schmid (2000).

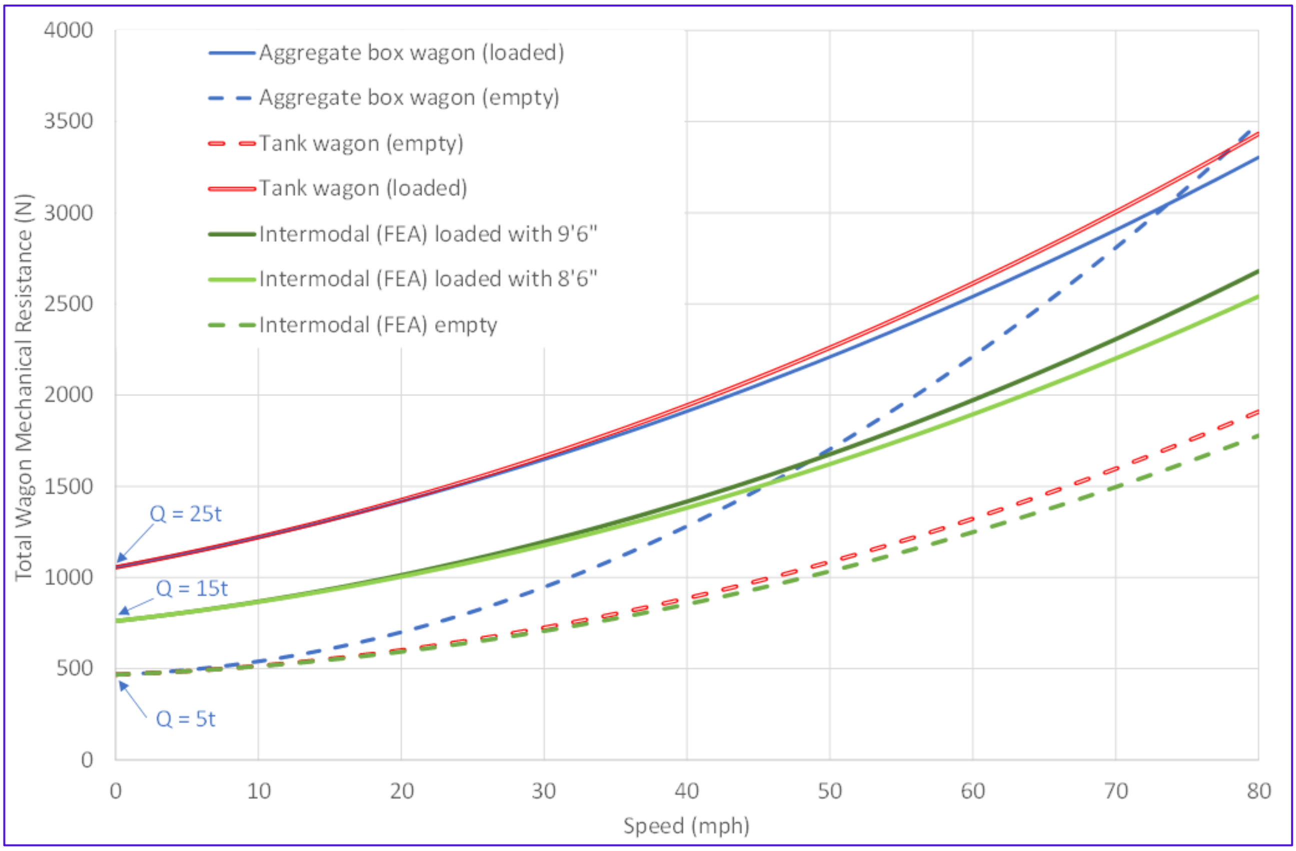
Table 21 K_{WMR5} and A_W values for selected wagon types

Wagon type	K_{WMR5} 'C' coefficient [N/tonne]	A_W wagon frontal area (m^2)	Notes
Aggregate box wagon (loaded)	18.683	8.361	
Aggregate box wagon (empty)	53.379	8.361	
Tank wagon	24.465	7.890	
Intermodal (FEA) loaded with 9'6"	22.241	9.443	Platform height 980 mm
Intermodal (FEA) loaded with 8'6"	22.241	8.699	Platform height 980 mm
Intermodal (FEA) empty	22.241	2.391	Platform height 980 mm

The total wagon rolling resistances using the coefficients from Table 21 are compared in Figure 41 with axle loads (Q) of 5 tonnes for empty wagons, 15 tonnes for loaded intermodal wagons, and 25 tonnes for loaded aggregate box and tank wagons.

Unloaded wagon mechanical resistances are generally between 40% and 55% of the loaded wagon resistances. The exception is the empty box wagon, where the rear face and any internal dividers of the unloaded wagon significantly increase the aerodynamic loading. Wagon resistance increases significantly with speed, but this increase is non-linear, reflecting the increased effect of aerodynamic loading as higher speeds and this increase in resistance with speed is most extreme for unloaded box wagons. The tractive effort required to haul unloaded box wagons on straight level track at 60 mph is only 15% less than for a loaded wagon; however, the difference will increase significantly on uphill section of route where the loaded wagon resistance due to gravity is far greater than all other factors combined.

Figure 41 Comparion of proposed 4-axle wagon mechanical rolling resistances (R_{WMR}) for different wagon types versus speed



Several studies in North America and Australia have observed that the non-velocity dependent terms in the US (CN) approach did not match values from calculations based on OTMR data in North America or Australia. However, calculations based on OTMR analysis shows close matches with velocity-dependent terms in the CN equation including for different coefficient values for different wagon types (Stehly, 2008; Szanto, 2016). Overall non-velocity dependent resistance is slightly too high for loaded/high axle loads and slightly too low for low axle loads (which causes issues with many potential approaches for wagon mechanical starting resistance for low wagon axle loads; see Section 4.4.4). Very few of the studies that note the issue either attempt to analyse the potential underlying reasons or to propose potential solutions to the problem, but there are two useful sources that do. The first was Mark Stehly's work at BNSF (Stehly, 2008), noting the issue and suggesting that the chosen K_{WMR1} and K_{WMR2} values in the CN equation are likely due to wanting to prioritise a simplified treatment that accurately covers the North American worst resistance case with high axle loads at very low temperatures (down to -30°F/-34°C) at the expense of accurate treatment of (empty) wagons with low axle loads which is a much lower priority in comparison for North American operators. The second is work by Frank Szanto at Downer Rail in Australia (EMD's local manufacturing partner in Australia for many decades) who has gone further in presenting revised K_{WMR1} and K_{WMR2} values that align with resistance data derived from OTMR and GPS datasets. The Szanto (2016) analysis looked at loaded and unloaded, out and return runs with identical locomotive and wagons on several different routes and with different cargo types, initially individually for each journey and then together in a coherent way to propose K_{WMR1} and K_{WMR2} values that provide a good fit with resistance data for both high and low axle load permutations. The original and changed values are shown in the bold below.

CN equation (in metric form):

$$R_{WMR} = \mathbf{7.355} + \frac{\mathbf{80.068}}{Q} + 0.147 \times V + \frac{K_{WMR5} \times A_w \times V^2}{1024.081 \times M_w} \; [{}^{N}/_{tonne}]$$

CN revised with alternative K_{WMR1} and K_{WMR2} values suggested by Szanto (2016):

$$R_{WMR} = \mathbf{4.0} + \frac{\mathbf{100}}{Q} + 0.147 \times V + \frac{K_{WMR5} \times A_w \times V^2}{1024.081 \times M_w} \; [{}^{N}/_{tonne}]$$

Overall non-velocity dependent resistance is lower slightly for heavily loaded wagons (high axle loads) and slightly higher for lightly loaded wagons (low axle loads). These alternative values also help address issues with starting resistance calculation for low axle loads; see Section 4.4.4).

The same issues with K_{WMR1} and K_{WMR2} values for low and high axle loads for the non-velocity dependent resistance are seen in the 4-axle resistance equation suggested in Headech (1982), with noticeable issues below axle loads of 12 tonnes, and similar issues with simple starting resistance approaches.

Szanto (2016) also confirmed cargo density effects in the V^2 coefficients for which the K_{WMR5} term contains a scaling factor for vehicle length. Shorter vehicles with denser cargos (for example, iron ore or roadstone) have lower K_{WMR5} values. Lower density cargo (for example, brown coal or wood pellets) with longer wagons have larger K_{WMR5} values.

> Resistance formulae need to reflect the underlying physics.
>
> Resistance formulae need to be specific formulae (that is, N or kN per tonne of wagon) which are also scalable for different axle loads.
>
> The non-velocity dependent coefficients used in the formulas need to be consistent for the same wagon types across the full range of loadings.
>
> The Szanto (2016) adaptation of the CN equation ensures consistency across the full range of loadings in non-velocity dependent coefficients.

4.4.2.4 Recommended approach for 4-axle wagon rolling resistance

We recommend using the CN formula and coefficients with the Szanto (2016) adaptation of K_{WMR1} and K_{WMR2} values with conversion of unit to metric (apart from mph), the GB vehicle cross-sectional area, and the curving resistance approach from the GB values for the UK (but the rest of the US formula for mechanical).

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 3.1.1

R_A = acceleration resistance from Section 3.1.2 = 0 N/tonne (as acceleration = 0 m/s^2).

Mechanical Component (R_{WMR})

From Section 4.4.2.3:

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

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} = 0.147

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

K_{WMR5} = 'C' coefficient as defined in Table 21

K_{WMR6} = 1024.081

A_W = wagon frontal area as defined in Table 21 (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:

$$R_{WMR} = 4.0 + \frac{100}{Q} + 0.147 \times V + \frac{K_{WMR5} \times A_w \times V^2}{1024.081 \times M_w} \ [{}^{N}/_{tonne}]$$

The values of K_{WMR5} and A_w for relevant British wagon types are shown above in Table 21. The selected wagon types were chosen where the wagon type used in North America and Great Britain have sufficiently similar characteristics for the K_{WMR5} values to be used, and the wagon frontal areas have been calculated for GB wagons, including varying platform heights for container wagons.

4.4.3 Wagon mechanical rolling resistance, 2-axle

The 'TRFR07' equation was used for 2-axle wagon mechanical rolling resistance for eight years before MT19 was developed (see Section 3.4.2.1; this equation is presented below in metric form). Since that time the whole nature of operation of the freight fleet has changed. Trains of short wheelbase, lightly loaded wagons of different designs marshalled in random fashion have largely changed to block trains, often with single or virtually identical wagon types. In almost all cases, these trains consist of vehicles of a single design. In many cases the wagons are of modern design with a longer wheelbase. Hence the coefficients are unlikely to be relevant for the current 2-axle wagon fleet or typical current usage.

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

where:

R_{WMR} = specific resistance (N/tonne)

V = speed (mile/h)

Q = axle load (tonne)

Headech (1982) concluded '*Thus the above equation, produced originally for mixed trains of short-wheelbase, lightly loaded wagons is generally inappropriate. With the emergence of freight trains consisting entirely of oil tank wagons or aggregate, covered, open, hopper etc. wagons each train has a different drag characteristic and consequently should have a different drag equation*.'

The original criticism of the BR TRFR07 equation remains as it can only be used reliably when considering mixed, short-wheelbase, 2-axle wagon freight trains with plain journal bearings, a particular train category that does not operate today. However, there are still 2-axle wagon types in use today which represent just under 10% of the total GB wagon fleet (compared to 85% in 1982). There are a number of relevant characteristics of these current wagons which have different impacts on the resistance:

- These current wagons all have roller bearings, so the net impact is that resistances are lower than calculated by the above equation.
- Revenue 2-axle wagons (as opposed to Network Rail departmental 2-axle wagons) tend to be identical and so resistances should be lower than the above equation predicts.
- These current wagons all have longer wheelbases than typical wagons in 1957, so the net impact is that resistances are slightly higher than calculated by the above equation.

The overall shape of the resistance versus speed curve is noticeably flatter than any other wagon resistance equation used internationally, so the limited speed dependency of this equation is questionable. However, the results for predicted resistances are broadly in line with expectations for empty and fully laden conditions.

Headech (1982) was unable to find any datasets to refine this equation and this appears to remain the case. It was not seen as a priority for further work at the time (that is, compared to 4-axle bogie wagons). Headech (1982) noted that the '*BR equation, better than any other, serves the need for drag calculations in this category. Its reliable use, however, is restricted to mixed trains of 2-axle vehicles. Block or unit trains would have a lower aerodynamic drag and, in such cases, the above equation could be used to provide 'first look' but pessimistic values.*' Headech (1982) therefore recommended continuing to use the equation as it was expected to be slightly conservative for then-current 2-axle wagons. This situation still holds today.

The British Rail TRFR07 equation used in MT19 should continue to be used as there are no alternatives. This equation will slightly overestimate wagon resistance values for the current 2-axle wagon fleet, wagon types and operational practices. The size and relevance of the 2-axle wagon fleet has reduced over time and continues to reduce, so producing an updated equation or coefficients may be of low value.

4.4.4 Wagon mechanical starting resistance

British Transport Commission (1954), British Rail (1978), Headech (1982) and British Rail (1983) indicated a range of mechanical starting resistances values between 1.3x and 1.49x the comparable value of mechanical rolling resistances at low speed from both experiments and formulas with the same conditions. However at low axle loadings (below ~12 tonnes/axle especially below 8 tonnes/axle), for the proposed future 4-axle wagon mechanical rolling resistance formulae proposed by Headech (1982) some choices of non-velocity dependent formula coefficients can produce very high resistance values. At low speeds the rolling resistance can be higher than the experimental starting mechanical resistance values (with no axle load dependency). This indicates that either:

- The non-velocity dependent rolling resistance coefficient values are incorrect.
- The limited range of starting resistance measurements is incorrect (unlikely).
- The traditional simplistic fixed value approach to specific starting resistances is incompatible with wagon mechanical rolling formulae with complex variable axle load adjustment.

This could be rectified by:

- Changing the non-velocity dependent rolling resistance coefficient values (as recommended for other reasons in Section 4.4.2.4);
- Adopting a starting resistance methodology that is compatible with wagon mechanical rolling formulae with complex variable axle load adjustment by including complex variable axle load adjustment in the starting resistance formula; or
- Both of the above, which we recommend.

The modifications to CN rolling mechanical resistance formula based on Australian learnings (see Section 4.4.2.4) provides the first step of the solution; the second step involves using a wagon mechanical starting resistance approach where the starting resistance is a multiple of the wagon mechanical rolling resistance at 0 mph:

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

where:

R_{WMR} = wagon mechanical resistance from Section 4.4.4

? = is the selected multiplier value that is used

Without the modification to the CN formula based on Australian learnings, a multiplier value of ~1.5 needs to be used, so the formula generates similar results to older experimentally measured starting resistances at low and medium wagon axle loads, but very high starting resistances at high axle loads (far higher than MT19). However, with the modification to the CN formula based on Australian learnings, a multiplier value of 1.4 (the average difference between of BR experimental starting and rolling resistance measurements for range of axle loads), the formula generates similar results to older experimentally measured starting resistances at low, medium and high wagon axle loads for both 2-axle and 4-axle wagons. The wagon starting resistance values generated by the formula are similar to MT19 at medium and high axle loads, and it generates safe (and sensible) wagon starting resistance values for low axle loads (empty wagons) unlike MT19 or the proposed solutions proposed in Headech (1982). We therefore recommend the use of:

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

to calculate wagon mechanical starting resistances under all conditions.

Recommendation for both 2 and 4 axle Wagon Mechanical starting resistance (R_{WMS}):

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

where:

R_{WMR} = wagon mechanical resistance from Section 4.4.4

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)

A formula that calculates wagon mechanical starting resistances and produces sensible results for all axle loadings must replicate (or closely replicate) the axle load dependencies used in for wagon mechanical rolling formulae in order to produce sensible and safe results across the full range of axle load values.

4.4.5 Wagon curving resistance

Our research has identified that, internationally, there is no difference in the treatment of wagon curving resistance between starting or rolling conditions. There are two variants of a 'simple' (speed independent) curvature resistance formula used internationally as discussed below. Curving resistance was traditionally expressed in units of kg.m/tonne outside of North America so this has been used for most comparisons, with conversion to N.m/tonne where appropriate.

4.4.5.1 Simple curve resistance, $R_{WC,simple}$

This 'simple' format is used in GB, US, Canada, Australia, France, Italy, China, USSR (and successor states Belorussia, Kazakhstan, Russia, and Ukraine) and is based on the Schmidt (1927) review paper:

$$R_{WC,simple} = \frac{Constant\ 1}{track\ radius\ [m]}$$

The various international constants are shown in Table 22.

Table 22 Comparison of international curve resistance constants

Country	Constant 1 [kg.m/tonne]	Source of data
China	573.0	Sapronova et al. (2017)
Australia	623.7	Spiryagin et al. (2016), Szanto (2016)
USSR	700	Grebenyuk et al. (1985)
British Rail (1983) approach	753.6	British Rail (1983)
North America	779.4	AREMA (2022)
France	800	SNCF LGV track standards
Italy	800	Sapronova at al. (2017)

The British Rail (1983) value of 753 kg.m/tonne (7,390 N.m/tonne) is consistent with most of the European and North America values which are in the 700 to 800 kg.m/tonne range.

China and Australia use lesser values of 573 and 587 kg.m/tonne, respectively. This is believed to be due to track construction recommendations prohibiting curvatures less than R300 m.

4.4.5.2 Roeckl curve resistance, $R_{WC,Roeckl}$

The second format is used in Austria, Czechia, Croatia, Germany, Hungary, Romania, Serbia, Slovakia, Slovenia, and Switzerland, with a format initially developed in 1885 by Roeckl of the Bavarian State Railways (Roeckl, 1885):

$$R_{WC,\mathrm{Roeckl}} = \frac{Constant\ 1}{(track\ radius\ [m] - Constant\ 2)}$$

The Roeckl type formula(e) is widely used on Europe and can be either a single formula (Sweden) or a set multiple formulae for different ranges of track radii (other countries).

The equation utilises two constants, with one set of constants for tighter radii of curvature and one for more relaxed radii of curvature. However, the traditional constant values utilised for 1,435 mm gauge leads to a distinct discontinuity at track radii around R300 m leading to a lack of a smooth transition between the results of two formulae at this value. Therefore, two formulae are used either side of this threshold value.

$$R_{WC,\mathrm{Roeckl}}[for\ track\ radius \geq 300m] = \frac{Constant\ 1}{(track\ radius\ [m] - Constant\ 2)}$$

$$R_{WC,\mathrm{Roeckl}}[for\ track\ radius < 300m] = \frac{Constant\ 1'}{(track\ radius\ [m] - Constant\ 2')}$$

The Roeckl formulae used in Austria, Czechia, Croatia, Germany, Hungary, Romania, Serbia, Slovakia, Slovenia, and Switzerland is:

$$R_{WC,Germany}[for\ track\ radius \geq 300m] = \frac{650}{(track\ radius\ [m] - 55)}$$

$$R_{WC,Germany}[for\ track\ radius < 300m] = \frac{500}{(track\ radius\ [m] - 30)}$$

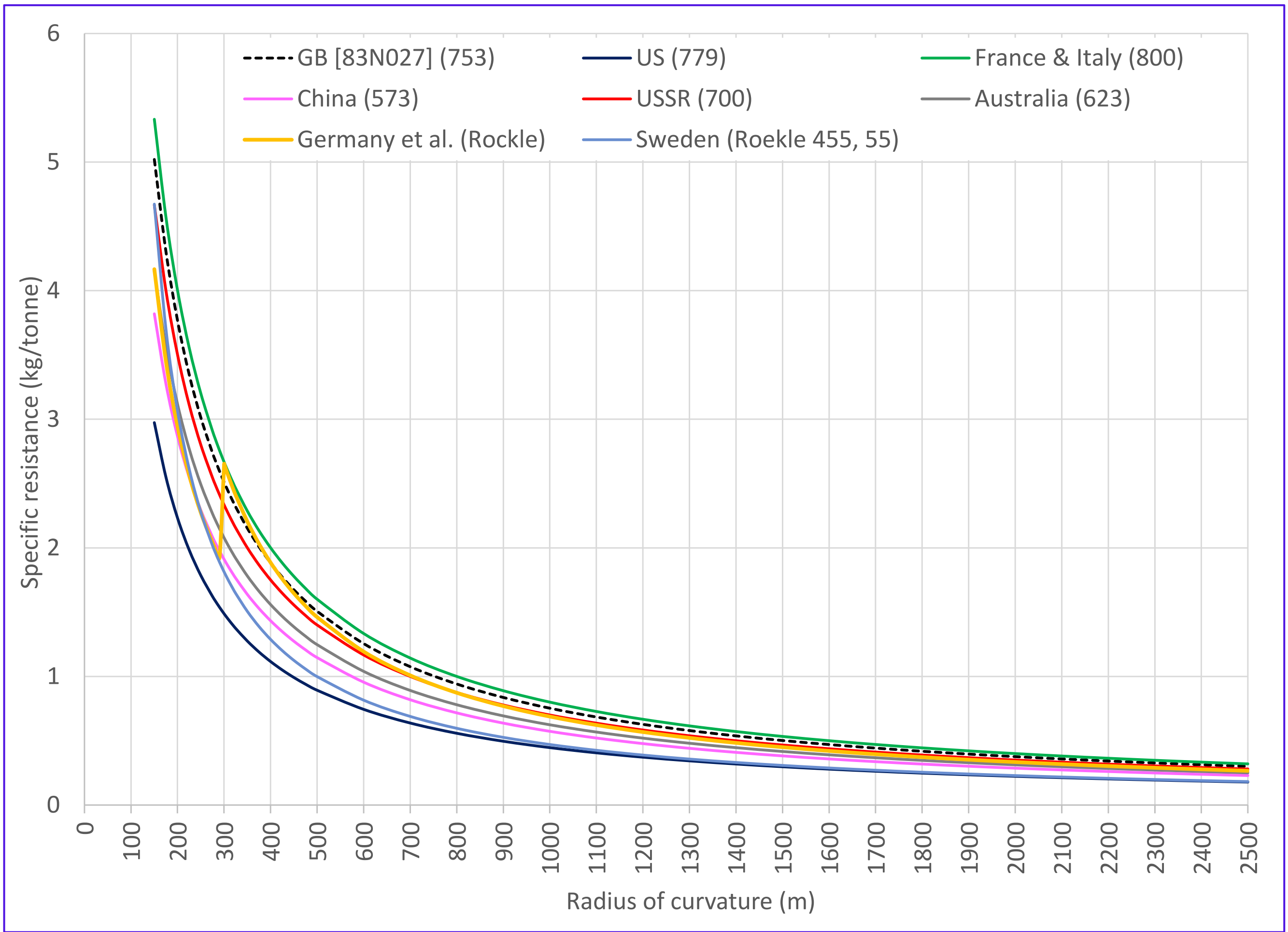
Sweden uses a derivation of this formula for all track radii. This has been recently verified as producing reasonable resistance values for freight on the Kiruna-Narvik Iron Ore Railway:

$$R_{WC,Sweden} = \frac{455}{(track\ radius\ [m] - 55)}$$

4.4.5.3 Curve resistance comparison and recommendation

The graph in Figure 42 below maps the curving resistances of the different methods discussed above. As can be seen, the British Rail (1983) method produces results where the track is similar to overseas approaches that produce higher curvature resistance values (that is, France, Italy, USA], and USSR) but does not produce the highest values itself.

Figure 42 Comparison of simplified curve resistances (for indicated curvature radius)



Use of the British Rail (1983) and MT19 methodology in Sections 3.3.1.2 and 3.3.2.2, that is, 753.6 kg.m/tonne (7,390 N.m/tonne), is recommended for both starting and rolling wagon curving resistance.

Recommendation for wagon curvature resistance:

Wagon curving starting resistance, for both 2-axle and 4-axle wagons (R_{WCS}) based on section 3.3.2.2**:**

R_{WCS} 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).

Wagon curving rolling resistance, for both 2-axle and 4-axle wagons (***R_{WCR}***) based on Section 3.3.2.2**:**

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

where:

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

R = curve radius (m).

5 Proposed new methodology

Based on the analysis and discussion within Section 3 (Detailed assessment of MT19 methodology) and Section 4 (Review of other sources), a new methodology is proposed for determining TLLs in terms of new formulae and factors. These are 'road mapped' in Table 23.

Table 23 Subsections describing components of the proposed new methodology

Tractive effort and adhesion	Resistances							
Locomotive	All vehicles		Locomotive		Each wagon (4 axle)		Each wagon (2 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 Section 3 and 4 where learning was derived or a decision made.

5.1 All vehicles factors

The factors influencing all vehicles are given below.

5.1.1 Gradient

From Section 3.1.1:

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

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:

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

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 deliverable 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.

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. Recommended starting tractive effort values are presented in Table 24 and Table 25.

Table 24 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 25 Additional and revised locomotive starting tractive effort values used in the calculation tool

Locomotive class	Locomotive rolling TE (kN)
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 88 (AC)	317
Class 88 (diesel)	317
Class 90 (single headed)	258
Class 90 (double headed)	258
Class 92 (AC)	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 26 and Table 27. The only 1-hour values shown in Table 27 are those used in the FTLB ’66-H’ case (see Section 6.5).

Table 26 Locomotive rolling tractive effort values (continuous and 1-hour cases) 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

Locomotive class	Locomotive rolling TE (kN)			
	1-hour		Continuous	
	TE (kN)	Speed (mph)	TE (kN)	Speed (mph)
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 27 Additional and revised locomotive rolling tractive values (continuous and 1-hour cases) used in the calculation tool

Locomotive class	Locomotive rolling TE (kN)			
	1-hour (just FTLB ’66-H’ case)		Continuous	
	TE (kN)	Speed (mph)	TE (kN)	Speed (mph)
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 88 (AC)	-	-	258	34.3
Class 88 (diesel)	-	-	258	5.3
Class 90 (single headed)	-	-	244	53.7
Class 90 (double headed)	-	-	244	45.8

Locomotive class	Locomotive rolling TE (kN)			
	1-hour (just FTLB '66-H' case)		Continuous	
	TE (kN)	Speed (mph)	TE (kN)	Speed (mph)
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

TE data for the following locomotive types in increments of 1 mph is contained within the 'Loco TE Data' tab in the associated Excel calculation tool described in Section 6:

- Class 37
- Class 47
- Class 56
- Class 58
- Class 59
- Class 60
- Class 66 (75-mph geared)
- Class 66 (65-mph geared)
- Class 69
- Class 70
- 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 4.3.1.2.

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

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 28. Adhesion values at 0 mph (μ_0), for different locomotive types based on locomotive characteristics are set out in Table 29 below for newer locomotive types not covered in MT19 or else revised in this report (see section 4.3.1).

Table 28 μ_0 and locomotive weight values retained from MT19 for older locomotive types

Locomotive class	Adhesion Weight (tonnes)	Axles	Recommended μ_0 (Mainline)	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 29 μ_0 and locomotive weight for newer locomotive types

Locomotive	Weight (tonnes)	Axles	Recommended μ_0 (Mainline)	Recommended μ_0 (Secondary)
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 68	85	4	0.36	0.34
Class 70	129	6	0.38	0.36
Class 88	85	4	0.36	0.34
Class 90	84.5	4	0.31**	0.29**
Class 92 (boost mode)	126	6	0.33***	0.33***
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 Mainline and Secondary route assumption due to the impact of the software configuration.

5.3 Locomotive resistance factors

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 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:

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

K_{LMS} = Locomotive mechanical starting resistance factor = 87.5230 (N/tonne)

$$K_{LMS1} = 87.5230\ [^{N}/_{tonne}]$$

$$\text{Locomotive starting resistance } (R_{LMS})[\text{N}] = 87.5230 \times \text{locomotive mass [tonnes]}$$

5.3.1.2 Curving component (R_{LC})

From Section 4.3.3.5:

For 2-axle bogies (4-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 3-axle bogies (6-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 3-axle bogies (6-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

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

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

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

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 ($\boldsymbol{R_{LCR}}$)

From Section 4.4.5.3:

For 2-axle bogies (4-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 3-axle bogies (6-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 3-axle bogies (6-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 4-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 4-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 ($\boldsymbol{R_{WMS}}$)

From Section 4.4.4:

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

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 ($\boldsymbol{R_{WCS}}$)

From Section 4.4.5.3:

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 4-axles

Rolling resistance for 4-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 ($\boldsymbol{R_{WMR}}$)

From Section 4.4.2.4:

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

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} = 0.147

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

K_{WMR5} = ‘C’ coefficient as defined in Table 30

K_{WMR6} = 1024.081

A_W = wagon frontal area as defined in Table 30 (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:

$$R_{WMR} = 4.0 + \frac{100}{Q} + 0.147 \times V + \frac{K_{WMR5} \times A_w \times V^2}{1024.081 \times M_w} \; [N/tonne]$$

Table 30 summarises the recommended values of K_{WMR5} and A_w for typical wagons in use on the GB network. Regarding the lack of data for other wagon types, refer to Section 4.4.2.4.

Table 30 K_{WMR5} and A_W values for selected wagon types

Wagon type	K_{WMR5} 'C' coefficient [N/tonne]	A_W wagon frontal area [m^2]	Notes
Aggregate box wagon (loaded)	18.683	8.361	
Aggregate box wagon (empty)	53.379	8.361	
Tank wagon	24.465	7.890	
Intermodal (FEA) loaded with 9'6"	22.241	9.443	Platform height 980 mm
Intermodal (FEA) loaded with 8'6"	22.241	8.699	Platform height 980 mm
Intermodal (FEA) empty	22.241	2.391	Platform height 980 mm

5.4.2.3 Curving component (R_{WCR})

From Section 4.4.5.3:

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

where:

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

R = curve radius (m).

5.5 Wagon factors for 2-axle wagons

The 2-axle wagon resistance factors are given in Sections 5.5.1 (starting) and 5.5.2 (rolling) below.

5.5.1 Wagon starting resistances for 2-axles

Starting resistance for 2-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

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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 ($\boldsymbol{R_{WMS}}$)

From Section 4.4.4:

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

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 ($\boldsymbol{R_{WCS}}$)

From Section 4.4.5.3:

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 2-axles

Rolling resistance for 2-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 (R_{WMR})

From Section 4.4.5.3:

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

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 (R_{WCR})

From Section 4.4.5.3:

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

where:

K_{WCR1} = 7,390

R = curve radius (m).

6 Maximum trailing load calculation tools

This section describes the calculation tools developed to calculate trailing loads, initially in Excel and then in 'R'.

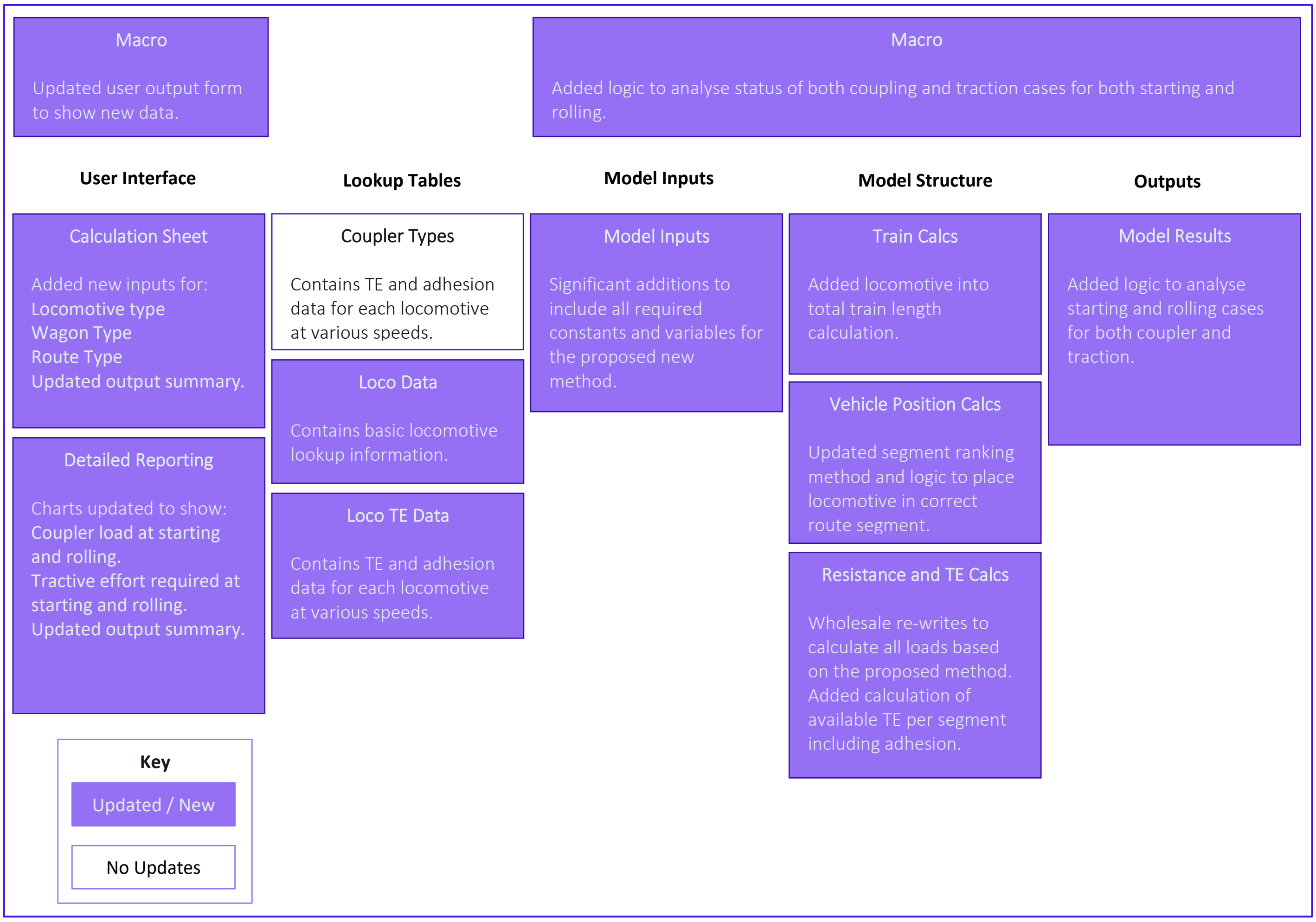
6.1 Extend the T1256 calculation tool to consider tractive effort

Following the creation of the proposed new method outlined in Section 5, the existing T1256 coupler-strength tool was updated to incorporate calculations for analysing the tractive effort. The additions are summarised in Figure 43.

The proposed new method required a wholesale update to the tool, including updates to the T1256 method for calculating coupler loads. This enabled the calculation of the following data at all track positions:

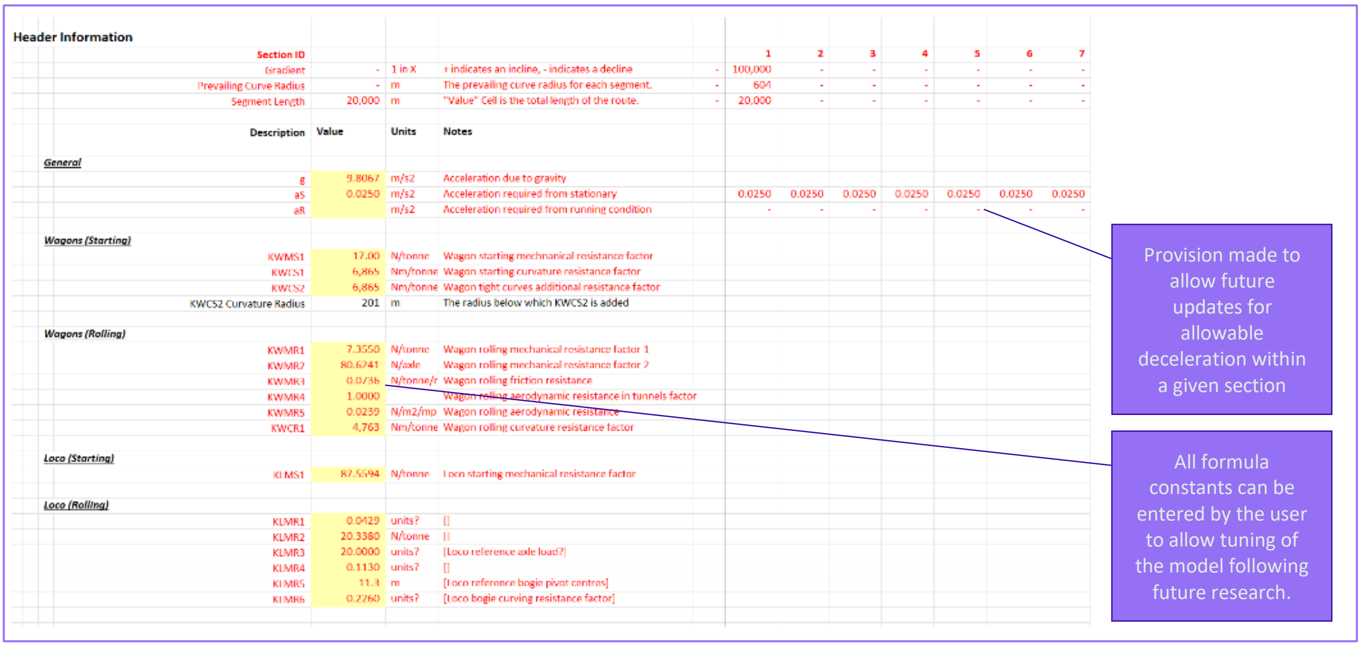
- Available starting tractive effort (accounting for adhesion limits)
- Available rolling tractive effort (accounting for adhesion limits)
- Coupler loads at starting
- Coupler loads at rolling speeds
- Traction loads at starting
- Traction loads at rolling speeds.

Figure 43 Changes to the T1256 model



To enable updates of the tool constants (for example, wagon aerodynamic resistance values) based on future research, these were added as user inputs on the ‘Model Inputs’ sheet within the model. Nomenclature used here aligns with that used in Section 5 as shown in Figure 44.

Figure 44   Updated model inputs sheet



Header Information

Description	Value	Units	Notes		1	2	3	4	5	6	7
Section ID					1	2	3	4	5	6	7
Gradient	-	1 in X	+ indicates an incline, - indicates a decline	-	100,000	-	-	-	-	-	-
Prevailing Curve Radius	-	m	The prevailing curve radius for each segment.	-	604	-	-	-	-	-	-
Segment Length	20,000	m	"Value" Cell is the total length of the route.	-	20,000	-	-	-	-	-	-
Description	**Value**	**Units**	**Notes**								
General											
g	9.8067	m/s2	Acceleration due to gravity								
aS	0.0250	m/s2	Acceleration required from stationary		0.0250	0.0250	0.0250	0.0250	0.0250	0.0250	0.0250
aR		m/s2	Acceleration required from running condition		-	-	-	-	-	-	-
Wagons (Starting)											
KWMS1	17.00	N/tonne	Wagon starting mechnanical resistance factor								
KWCS1	6,865	Nm/tonne	Wagon starting curvature resistance factor								
KWCS2	6,865	Nm/tonne	Wagon tight curves additional resistance factor								
KWCS2 Curvature Radius	201	m	The radius below which KWCS2 is added								
Wagons (Rolling)											
KWMR1	7.3550	N/tonne	Wagon rolling mechanical resistance factor 1								
KWMR2	80.6241	N/axle	Wagon rolling mechanical resistance factor 2								
KWMR3	0.0736	N/tonne/r	Wagon rolling friction resistance								
KWMR4	1.0000		Wagon rolling aerodynamic resistance in tunnels factor								
KWMR5	0.0239	N/m2/mp	Wagon rolling aerodynamic resistance								
KWCR1	4,763	Nm/tonne	Wagon rolling curvature resistance factor								
Loco (Starting)											
KLMS1	87.5594	N/tonne	Loco starting mechanical resistance factor								
Loco (Rolling)											
KLMR1	0.0429	units?	[]								
KLMR2	20.3380	N/tonne	[]								
KLMR3	20.0000	units?	[Loco reference axle load?]								
KLMR4	0.1130	units?	[]								
KLMR5	11.3	m	[Loco reference bogie pivot centres]								
KLMR6	0.2260	units?	[Loco bogie curving resistance factor]								

6.2 Develop new input sheet and lookup tables

In addition to updating the core of the tool, the user interface sheets were also modified to provide the necessary inputs as shown in Figure 45 and Figure 46. Other than the addition of new data input cells, and an updated reporting section, the use of this section of the tool remains the same as in the T1256 coupler-strength model.

Figure 45 Updated input sheet

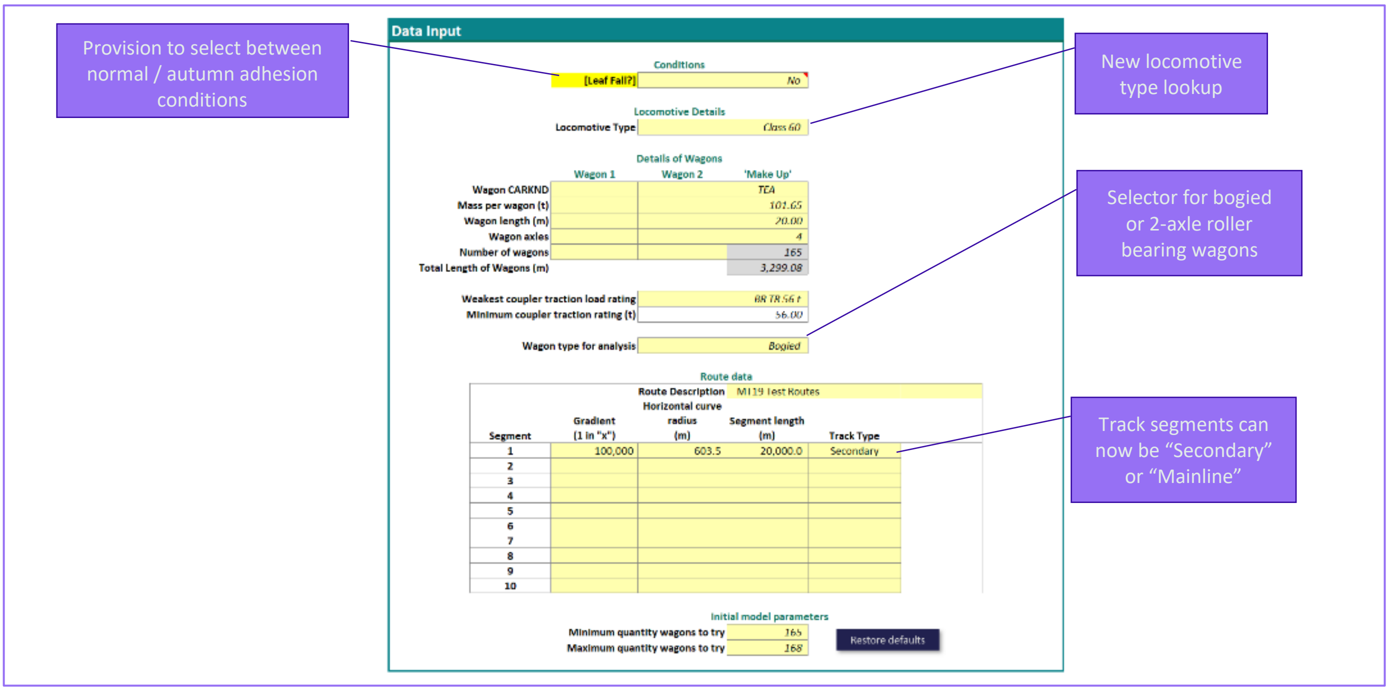
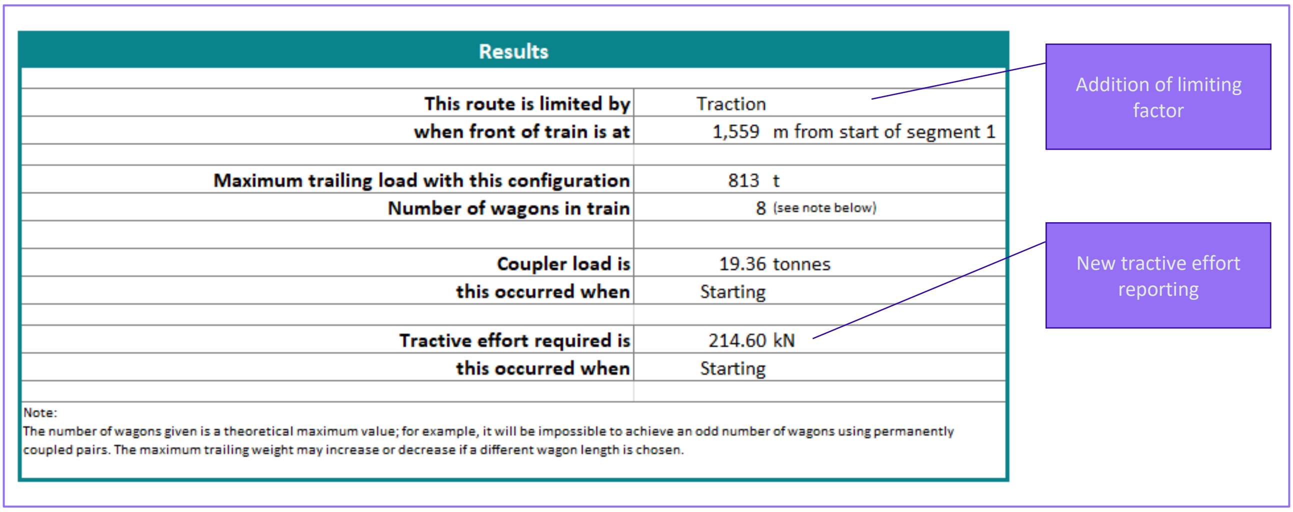
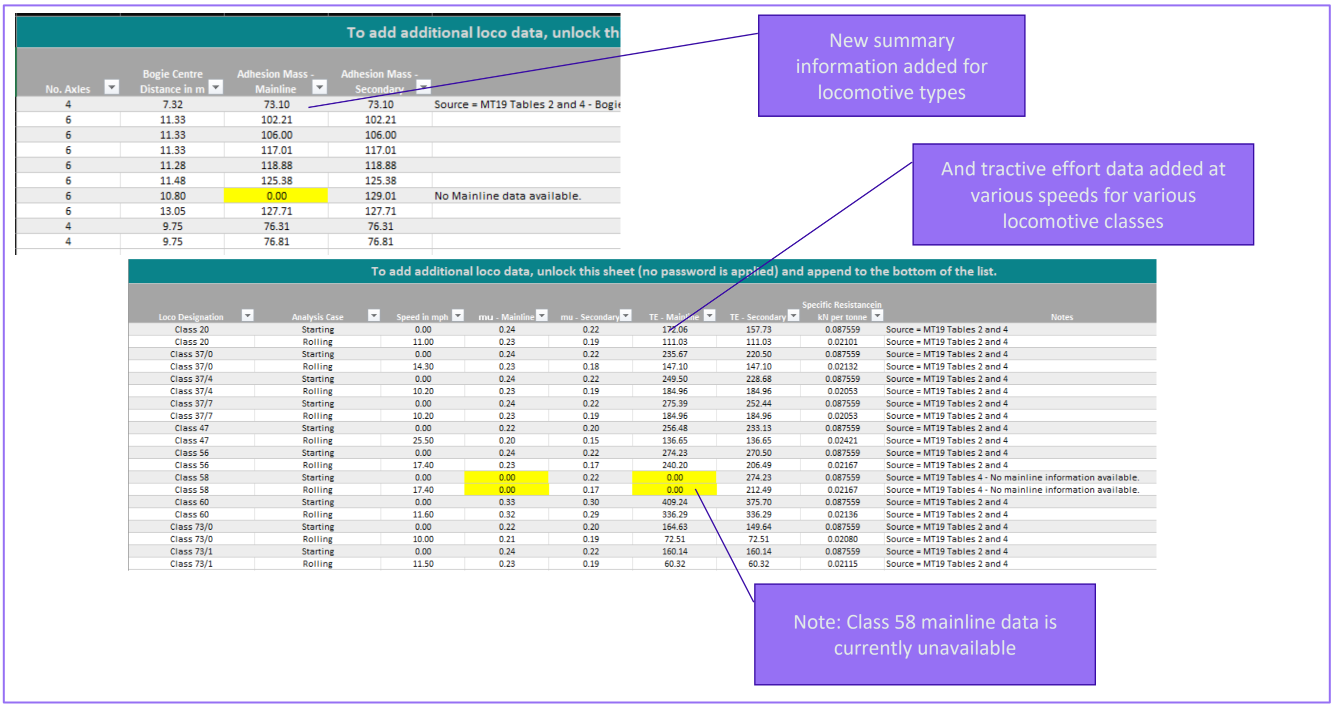


Figure 46 Updated results section



In addition to the updates to the tool's input and reporting sections, new sheets were added containing the locomotive data necessary for calculating tractive effort. The initial tables shown in Figure 47 were based on the values extracted from MT19 Tables 2 and 4.

Figure 47 New locomotive lookup tables



To add additional loco data, unlock th

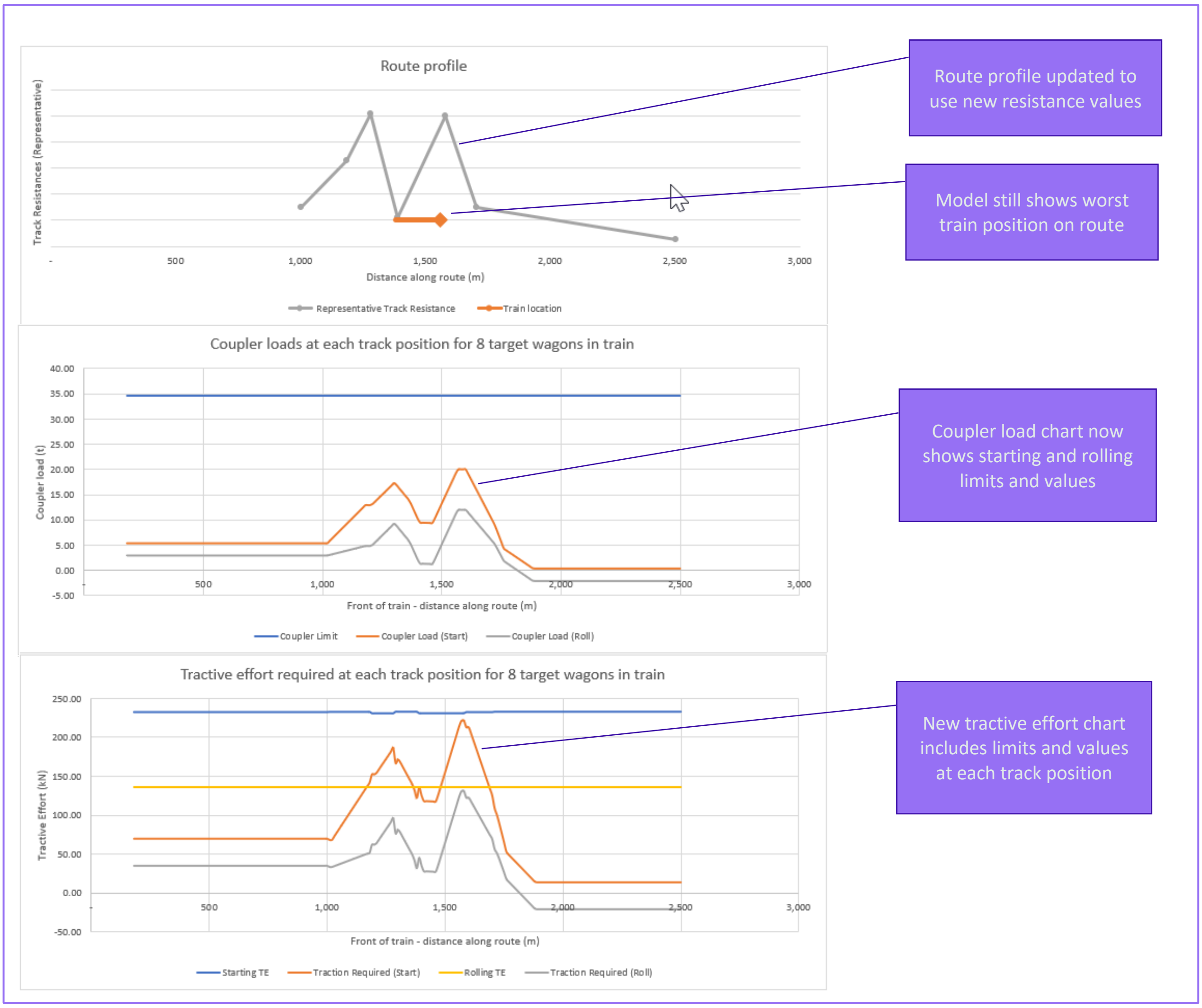
No. Axles	Bogie Centre Distance in m	Adhesion Mass - Mainline	Adhesion Mass - Secondary	
4	7.32	73.10	73.10	Source = MT19 Tables 2 and 4 - Bogie
6	11.33	102.21	102.21	
6	11.33	106.00	106.00	
6	11.33	117.01	117.01	
6	11.28	118.88	118.88	
6	11.48	125.38	125.38	
6	10.80	0.00	129.01	No Mainline data available.
6	13.05	127.71	127.71	
4	9.75	76.31	76.31	
4	9.75	76.81	76.81	

To add additional loco data, unlock this sheet (no password is applied) and append to the bottom of the list.

Loco Designation	Analysis Case	Speed in mph	mu - Mainline	mu - Secondary	TE - Mainline	TE - Secondary	Specific Resistancein kN per tonne	Notes
Class 20	Starting	0.00	0.24	0.22	172.06	157.73	0.087559	Source = MT19 Tables 2 and 4
Class 20	Rolling	11.00	0.23	0.19	111.03	111.03	0.02101	Source = MT19 Tables 2 and 4
Class 37/0	Starting	0.00	0.24	0.22	235.67	220.50	0.087559	Source = MT19 Tables 2 and 4
Class 37/0	Rolling	14.30	0.23	0.18	147.10	147.10	0.02132	Source = MT19 Tables 2 and 4
Class 37/4	Starting	0.00	0.24	0.22	249.50	228.68	0.087559	Source = MT19 Tables 2 and 4
Class 37/4	Rolling	10.20	0.23	0.19	184.96	184.96	0.02053	Source = MT19 Tables 2 and 4
Class 37/7	Starting	0.00	0.24	0.22	275.39	252.44	0.087559	Source = MT19 Tables 2 and 4
Class 37/7	Rolling	10.20	0.23	0.19	184.96	184.96	0.02053	Source = MT19 Tables 2 and 4
Class 47	Starting	0.00	0.22	0.20	256.48	233.13	0.087559	Source = MT19 Tables 2 and 4
Class 47	Rolling	25.50	0.20	0.15	136.65	136.65	0.02421	Source = MT19 Tables 2 and 4
Class 56	Starting	0.00	0.24	0.22	274.23	270.50	0.087559	Source = MT19 Tables 2 and 4
Class 56	Rolling	17.40	0.23	0.17	240.20	206.49	0.02167	Source = MT19 Tables 2 and 4
Class 58	Starting	0.00	0.00	0.22	0.00	274.23	0.087559	Source = MT19 Tables 4 - No mainline information available.
Class 58	Rolling	17.40	0.00	0.17	0.00	212.49	0.02167	Source = MT19 Tables 4 - No mainline information available.
Class 60	Starting	0.00	0.33	0.30	409.24	375.70	0.087559	Source = MT19 Tables 2 and 4
Class 60	Rolling	11.60	0.32	0.29	336.29	336.29	0.02136	Source = MT19 Tables 2 and 4
Class 73/0	Starting	0.00	0.22	0.20	164.63	149.64	0.087559	Source = MT19 Tables 2 and 4
Class 73/0	Rolling	10.00	0.21	0.19	72.51	72.51	0.02080	Source = MT19 Tables 2 and 4
Class 73/1	Starting	0.00	0.24	0.22	160.14	160.14	0.087559	Source = MT19 Tables 2 and 4
Class 73/1	Rolling	11.50	0.23	0.19	60.32	60.32	0.02115	Source = MT19 Tables 2 and 4

As an additional feature to aid visualisation of the model outputs and inform the work for task 2, additional charts were created within the detailed reporting sheet of the model as shown in Figure 48. These provide a visual summary of the various loads and limits as the train progresses along the route.

Figure 48 New charts on detailed reporting sheet



6.3 Testing the tool

On completion of the tool's development, testing and verification was performed on its outputs by comparison with manually calculated values. This confirmed that the calculated outputs matched the expected outputs for the changes made to incorporate the new tractive effort calculations.

6.4 Implementation in ‘R’ to model longer routes

6.4.1 Introduction

The Excel tool described above is limited to a fixed maximum number of track segments[3] (currently 56) to be analysed in any single running of the tool. In order to assess trailing load limits for the full lengths of real-life case-study routes (see Section 6.5), a much greater number of track segments than this limit needs to be handled while running the tool. Therefore, the calculations and model structure from the Excel tool were replicated in the ‘R’ programming language[4] (hereafter referred to as the R tool), which enables a route of any length and number of track segments to be iteratively processed through the model. The R tool consists of a family of ‘scripts’ (text files) which are run in the open-source R environment.

The R tool was validated against the Excel tool for several short test routes and wagon combinations to ensure that the results yielded were identical.

6.4.2 Defining track segments on case-study routes

Three case-study routes consisting of sections of particularly acute gradient and/or curvature were chosen to be modelled in full by the R tool. These are listed below:

i. West London Line (ELR WLL; from Falcon Junction to West London Junction)

ii. Lancaster to Carlisle (ELR CGJ7; from Lancaster to Carlisle)

iii. Reading West (central and eastern curves from Southcote Junction to Reading Main Station, and western curve from Southcote Junction to Tilehurst).

To analyse TLLs for each of the case-study routes, the trailing load calculations require input in the form of a sequence of track segments of constant gradient and curvature, each of a specified length.

The process used to build the sequence of track segments was the following:

i. Given a known start and end point, use the Network Rail track centreline shapefile to determine a sequence of ELR(s) and start mileage and end mileage of the route, as well as the most appropriate track ID (a code assigned to each track defining its directionality and status such as main/relief/crossover/loop).

ii. Based on the chosen sequence of ELR(s), track ID(s) start and end mileages, extract the appropriate data on gradients and track curvature.

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[3] One track segment here is defined as one distinct combination of track gradient and curvature. Therefore, each time either the gradient or curvature changes along a route, this defines the start of a new track segment.

[4] https://cran.r-project.org/

iii. Combine the ELR(s) start and end mileages of sections of constant gradient and curvature, to produce a sequence of segments of constant gradient and curvature, then measure the length of these.

However, there were challenges encountered when building the route, relating to gaps in the gradient and curvature data available. These challenges and solutions are described briefly below.

6.4.2.1 Dealing with missing gradient data

Gradient data is available from Network Rail, with the ELR, start mileage, and end mileage of each section of constant gradient defined at the route level.

6.4.2.2 Dealing with missing curvature data

Track curvature data (at the track level) was obtained from a Network Rail Freedom of Information request (FOI202201043). However, on inspection it became clear that a substantial fraction of curvature data is missing from this dataset, including for the routes chosen as case studies (data completely missing at the route level for Reading West Curve, and partially missing for the West London Line).

It was also noticeable that a large degree of rounding had been applied to the radius of curvature numbers in the Network Rail curvature file.

Therefore, a new curvature dataset was built based on the geometry of the Network Rail track centreline shapefile, giving complete coverage of the whole rail network as defined in that dataset. The brief methodology (more detail can be provided on methodology if requested) undertaken was as follows:

- Each individual network link is represented digitally as a series of closely spaced nodes (on a curve, nodes are usually digitised c.10-30 metres apart), joined by straight-line arcs.
- Taking the sequence of straight-line arcs making up one link, a GIS process was developed to:
    - Calculate the change in bearing from one to the next and the distance between nodes assign a 'local curvature' value to each arc.
    - Group together runs of consecutive arcs with similar 'local curvature', to define longer sections of constant curvature.
    - Break up the original links at the start and end points of the constant curvature sections to create smaller track sections, assigning new start and end mileages to each end of these.

The newly-created curvature dataset was validated against the Network Rail curvature dataset for parts of the rail network covered by the latter, and from visual inspection there was a good correspondence between the two. Rounding of the Network Rail radius of curvature numbers, and a lack of predictability in how the sign ('left/right handing' or direction) of curvature was allocated in the Network Rail dataset, prevented a robust quantitative comparison.

6.4.2.3 Modelled routes

Maps of the route geography for each of the modelled case-studies are presented below.

Figure 49 West London Line (WLL)

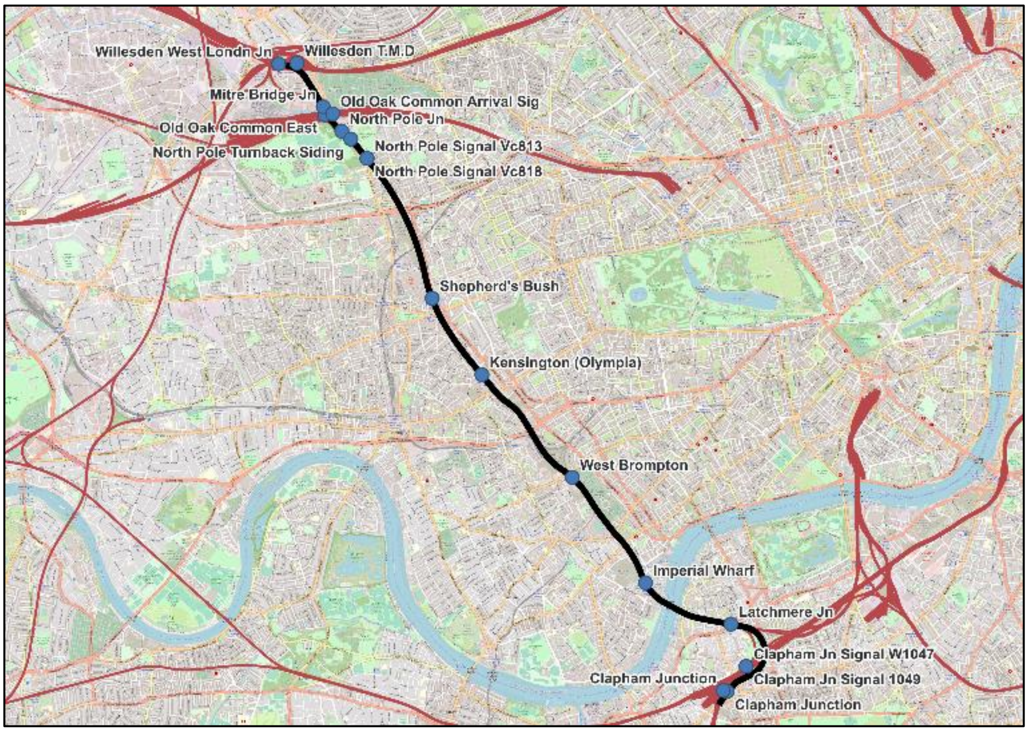


Figure 50 Lancaster to Carlisle (CGJ7)

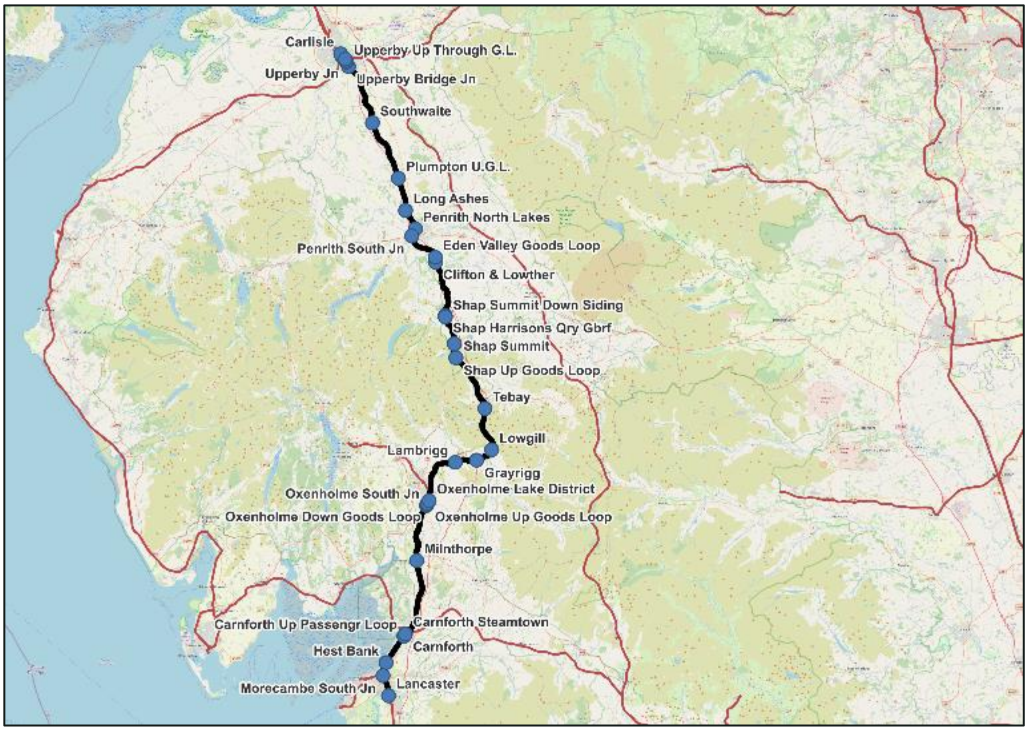
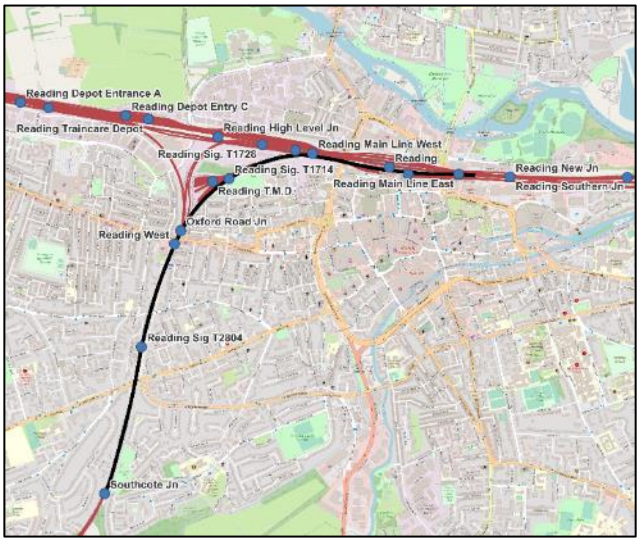
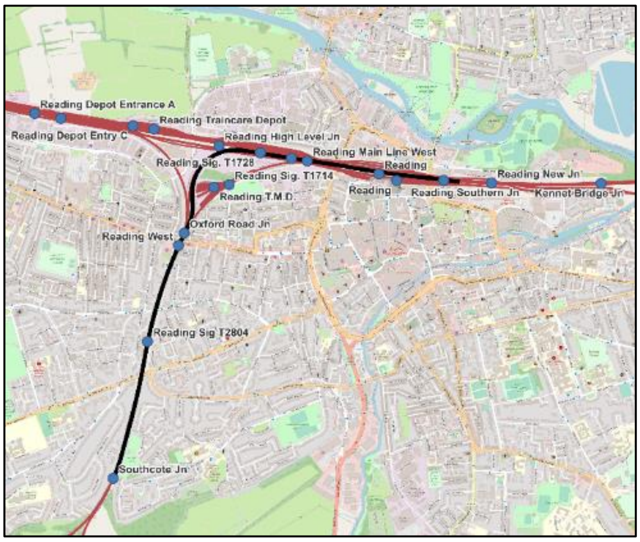


Figure 51 Reading West

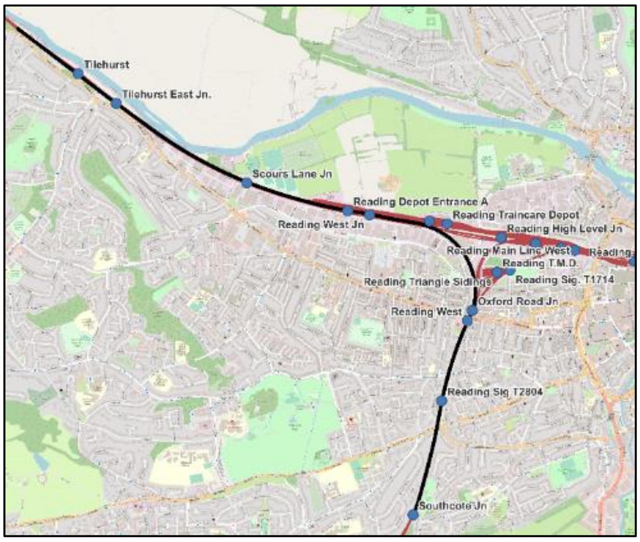
Eastern curve:



Central curve:



Western Curve:



6.4.3 Results

The R tool was used to simulate and perform trailing load calculations at fixed intervals of half the wagon length along each case-study route. Multiple configurations of different loco designations, coupler types, and wagon ranges were tested in order to find the optimal number of wagons for each loco-coupler combination. The results generated by the R tool are presented in this section.

Table 31 R tool results for West London Line (WLL)

Route	Locomotive	Coupler	Max Coupler Rating (t)	Min Wagons	Max Wagons	Optimum Wagons	Limiting Factor
WLL_down-forward	Class 60	BR TR 34.5 t (Original Rating)	34.55	9	25	14	Coupler
WLL_down-forward	Class 66 (65 mph geared)	BR TR 34.5 t (Original Rating)	34.55	9	25	13	Traction
WLL_down-forward	Class 66 (75 mph geared)	BR TR 34.5 t (Original Rating)	34.55	9	25	11	Traction
WLL_down-forward	Class 70	BR TR 34.5 t (Original Rating)	34.55	9	25	14	Coupler
WLL_down-forward	Class 93 Diesel	BR TR 34.5 t (Original Rating)	34.55	9	25	10	Traction
WLL_down-forward	Class 93 Electric	BR TR 34.5 t (Original Rating)	34.55	9	25	9	Traction
WLL_down-forward	Class 99 Diesel	BR TR 34.5 t (Original Rating)	34.55	9	25	14	Coupler
WLL_down-forward	Class 99 Electric	BR TR 34.5 t (Original Rating)	34.55	9	25	14	Traction
WLL_down-forward	Class 60	BR TR 56 t	56	9	25	15	Traction
WLL_down-forward	Class 66 (65 mph geared)	BR TR 56 t	56	9	25	13	Traction
WLL_down-forward	Class 66 (75 mph geared)	BR TR 56 t	56	9	25	11	Traction
WLL_down-forward	Class 70	BR TR 56 t	56	9	25	19	Traction
WLL_down-forward	Class 93 Diesel	BR TR 56 t	56	9	25	10	Traction
WLL_down-forward	Class 93 Electric	BR TR 56 t	56	9	25	9	Traction
WLL_down-forward	Class 99 Diesel	BR TR 56 t	56	9	25	16	Traction
WLL_down-forward	Class 99 Electric	BR TR 56 t	56	9	25	14	Traction
WLL_up-back	Class 60	BR TR 34.5 t (Original Rating)	34.55	9	25	18	Coupler
WLL_up-back	Class 66 (65 mph geared)	BR TR 34.5 t (Original Rating)	34.55	9	25	17	Traction
WLL_up-back	Class 66 (75 mph geared)	BR TR 34.5 t (Original Rating)	34.55	9	25	14	Traction
WLL_up-back	Class 70	BR TR 34.5 t (Original Rating)	34.55	9	25	18	Coupler
WLL_up-back	Class 93 Diesel	BR TR 34.5 t (Original Rating)	34.55	9	25	13	Traction
WLL_up-back	Class 93 Electric	BR TR 34.5 t (Original Rating)	34.55	9	25	11	Traction

Route	Locomotive	Coupler	Max Coupler Rating (t)	Min Wagons	Max Wagons	Optimum Wagons	Limiting Factor
WLL_up-back	Class 99 Diesel	BR TR 34.5 t (Original Rating)	34.55	9	25	18	Coupler
WLL_up-back	Class 99 Electric	BR TR 34.5 t (Original Rating)	34.55	9	25	18	Coupler
WLL_up-back	Class 60	BR TR 56 t	56	9	25	21	Traction
WLL_up-back	Class 66 (65 mph geared)	BR TR 56 t	56	9	25	17	Traction
WLL_up-back	Class 66 (75 mph geared)	BR TR 56 t	56	9	25	14	Traction
WLL_up-back	Class 70	BR TR 56 t	56	9	25	24	Traction
WLL_up-back	Class 93 Diesel	BR TR 56 t	56	9	25	13	Traction
WLL_up-back	Class 93 Electric	BR TR 56 t	56	9	25	11	Traction
WLL_up-back	Class 99 Diesel	BR TR 56 t	56	9	25	21	Traction
WLL_up-back	Class 99 Electric	BR TR 56 t	56	9	25	18	Traction

Table 32 R Tool Results for Lancaster to Carlisle (CGJ7)

Route	Locomotive	Coupler	Max Coupler Rating (t)	Min Wagons	Max Wagons	Optimum Wagons	Limiting Factor
CGJ7_down-forward	Class 60	BR TR 34.5 t (Original Rating)	34.55	15	30	18	Coupler
CGJ7_down-forward	Class 66 (65 mph geared)	BR TR 34.5 t (Original Rating)	34.55	15	30	18	Traction
CGJ7_down-forward	Class 66 (75 mph geared)	BR TR 34.5 t (Original Rating)	34.55	15	30	16	Traction
CGJ7_down-forward	Class 70	BR TR 34.5 t (Original Rating)	34.55	10	30	18	Coupler
CGJ7_down-forward	Class 93 Diesel	BR TR 34.5 t (Original Rating)	34.55	10	30	14	Traction
CGJ7_down-forward	Class 93 Electric	BR TR 34.5 t (Original Rating)	34.55	10	30	14	Traction
CGJ7_down-forward	Class 99 Diesel	BR TR 34.5 t (Original Rating)	34.55	10	30	18	Traction
CGJ7_down-forward	Class 99 Electric	BR TR 34.5 t (Original Rating)	34.55	10	30	18	Traction
CGJ7_down-forward	Class 60	BR TR 56 t	56	15	30	21	Traction

Route	Locomotive	Coupler	Max Coupler Rating (t)	Min Wagons	Max Wagons	Optimum Wagons	Limiting Factor
CGJ7_down-forward	Class 66 (65 mph geared)	BR TR 56 t	56	15	30	18	Traction
CGJ7_down-forward	Class 66 (75 mph geared)	BR TR 56 t	56	15	30	16	Traction
CGJ7_down-forward	Class 70	BR TR 56 t	56	10	30	21	Traction
CGJ7_down-forward	Class 93 Diesel	BR TR 56 t	56	10	30	14	Traction
CGJ7_down-forward	Class 93 Electric	BR TR 56 t	56	10	30	14	Traction
CGJ7_down-forward	Class 99 Diesel	BR TR 56 t	56	10	30	18	Traction
CGJ7_down-forward	Class 99 Electric	BR TR 56 t	56	10	30	18	Traction
CGJ7_up-back	Class 60	BR TR 34.5 t (Original Rating)	34.55	15	30	22	Coupler
CGJ7_up-back	Class 66 (65 mph geared)	BR TR 34.5 t (Original Rating)	34.55	15	30	22	Coupler
CGJ7_up-back	Class 66 (75 mph geared)	BR TR 34.5 t (Original Rating)	34.55	15	30	20	Traction
CGJ7_up-back	Class 70	BR TR 34.5 t (Original Rating)	34.55	10	30	22	Coupler
CGJ7_up-back	Class 93 Diesel	BR TR 34.5 t (Original Rating)	34.55	10	30	17	Traction
CGJ7_up-back	Class 93 Electric	BR TR 34.5 t (Original Rating)	34.55	10	30	17	Traction
CGJ7_up-back	Class 99 Diesel	BR TR 34.5 t (Original Rating)	34.55	10	30	22	Traction
CGJ7_up-back	Class 99 Electric	BR TR 34.5 t (Original Rating)	34.55	10	30	22	Traction
CGJ7_up-back	Class 60	BR TR 56 t	56	15	30	25	Traction
CGJ7_up-back	Class 66 (65 mph geared)	BR TR 56 t	56	15	30	23	Traction
CGJ7_up-back	Class 66 (75 mph geared)	BR TR 56 t	56	15	30	20	Traction
CGJ7_up-back	Class 70	BR TR 56 t	56	10	30	25	Traction
CGJ7_up-back	Class 93 Diesel	BR TR 56 t	56	10	30	17	Traction
CGJ7_up-back	Class 93 Electric	BR TR 56 t	56	10	30	17	Traction
CGJ7_up-back	Class 99 Diesel	BR TR 56 t	56	10	30	22	Traction
CGJ7_up-back	Class 99 Electric	BR TR 56 t	56	10	30	22	Traction

Table 33 R Tool Results for Reading West

Route	Locomotive	Coupler	Max Coupler Rating (t)	Min Wagons	Max Wagons	Optimum Wagons	Limiting Factor
readingw_central-curve_down	Class 60	BR TR 34.5 t (Original Rating)	34.55	25	60	44	Coupler
readingw_central-curve_down	Class 66 (65 mph geared)	BR TR 34.5 t (Original Rating)	34.55	25	60	44	Coupler
readingw_central-curve_down	Class 66 (75 mph geared)	BR TR 34.5 t (Original Rating)	34.55	25	60	44	Coupler
readingw_central-curve_down	Class 70	BR TR 34.5 t (Original Rating)	34.55	25	60	44	Coupler
readingw_central-curve_down	Class 93 Diesel	BR TR 34.5 t (Original Rating)	34.55	25	60	33	Traction
readingw_central-curve_down	Class 93 Electric	BR TR 34.5 t (Original Rating)	34.55	25	60	33	Traction
readingw_central-curve_down	Class 99 Diesel	BR TR 34.5 t (Original Rating)	34.55	25	60	44	Coupler
readingw_central-curve_down	Class 99 Electric	BR TR 34.5 t (Original Rating)	34.55	25	60	44	Coupler
readingw_central-curve_down	Class 60	BR TR 56 t	56	25	60	53	Traction
readingw_central-curve_down	Class 66 (65 mph geared)	BR TR 56 t	56	25	60	53	Traction
readingw_central-curve_down	Class 66 (75 mph geared)	BR TR 56 t	56	25	60	53	Traction
readingw_central-curve_down	Class 70	BR TR 56 t	56	25	60	54	Traction
readingw_central-curve_down	Class 93 Diesel	BR TR 56 t	56	25	60	33	Traction
readingw_central-curve_down	Class 93 Electric	BR TR 56 t	56	25	60	33	Traction
readingw_central-curve_down	Class 99 Diesel	BR TR 56 t	56	25	60	46	Traction
readingw_central-curve_down	Class 99 Electric	BR TR 56 t	56	25	60	46	Traction
readingw_central-curve_up	Class 60	BR TR 34.5 t (Original Rating)	34.55	25	60	44	Coupler
readingw_central-curve_up	Class 66 (65 mph geared)	BR TR 34.5 t (Original Rating)	34.55	25	60	44	Coupler
readingw_central-curve_up	Class 66 (75 mph geared)	BR TR 34.5 t (Original Rating)	34.55	25	60	44	Coupler
readingw_central-curve_up	Class 70	BR TR 34.5 t (Original Rating)	34.55	25	60	44	Coupler
readingw_central-curve_up	Class 93 Diesel	BR TR 34.5 t (Original Rating)	34.55	25	60	34	Traction
readingw_central-curve_up	Class 93 Electric	BR TR 34.5 t (Original Rating)	34.55	25	60	34	Traction
readingw_central-curve_up	Class 99 Diesel	BR TR 34.5 t (Original Rating)	34.55	25	60	44	Coupler

Route	Locomotive	Coupler	Max Coupler Rating (t)	Min Wagons	Max Wagons	Optimum Wagons	Limiting Factor
readingw_central-curve_down	Class 60	BR TR 34.5 t (Original Rating)	34.55	25	60	44	Coupler
readingw_central-curve_up	Class 99 Electric	BR TR 34.5 t (Original Rating)	34.55	25	60	44	Coupler
readingw_central-curve_up	Class 60	BR TR 56 t	56	25	60	51	Traction
readingw_central-curve_up	Class 66 (65 mph geared)	BR TR 56 t	56	25	60	51	Traction
readingw_central-curve_up	Class 66 (75 mph geared)	BR TR 56 t	56	25	60	51	Traction
readingw_central-curve_up	Class 70	BR TR 56 t	56	25	60	52	Traction
readingw_central-curve_up	Class 93 Diesel	BR TR 56 t	56	25	60	34	Traction
readingw_central-curve_up	Class 93 Electric	BR TR 56 t	56	25	60	34	Traction
readingw_central-curve_up	Class 99 Diesel	BR TR 56 t	56	25	60	45	Traction
readingw_central-curve_up	Class 99 Electric	BR TR 56 t	56	25	60	45	Traction
readingw_east-curve_down	Class 60	BR TR 34.5 t (Original Rating)	34.55	25	60	40	Coupler
readingw_east-curve_down	Class 66 (65 mph geared)	BR TR 34.5 t (Original Rating)	34.55	25	60	40	Coupler
readingw_east-curve_down	Class 66 (75 mph geared)	BR TR 34.5 t (Original Rating)	34.55	25	60	40	Coupler
readingw_east-curve_down	Class 70	BR TR 34.5 t (Original Rating)	34.55	25	60	40	Coupler
readingw_east-curve_down	Class 93 Diesel	BR TR 34.5 t (Original Rating)	34.55	25	60	31	Traction
readingw_east-curve_down	Class 93 Electric	BR TR 34.5 t (Original Rating)	34.55	25	60	31	Traction
readingw_east-curve_down	Class 99 Diesel	BR TR 34.5 t (Original Rating)	34.55	25	60	40	Coupler
readingw_east-curve_down	Class 99 Electric	BR TR 34.5 t (Original Rating)	34.55	25	60	40	Coupler
readingw_east-curve_down	Class 60	BR TR 56 t	56	25	60	46	Traction
readingw_east-curve_down	Class 66 (65 mph geared)	BR TR 56 t	56	25	60	46	Traction
readingw_east-curve_down	Class 66 (75 mph geared)	BR TR 56 t	56	25	60	46	Traction
readingw_east-curve_down	Class 70	BR TR 56 t	56	25	60	47	Traction
readingw_east-curve_down	Class 93 Diesel	BR TR 56 t	56	25	60	31	Traction
readingw_east-curve_down	Class 93 Electric	BR TR 56 t	56	25	60	31	Traction

Route	Locomotive	Coupler	Max Coupler Rating (t)	Min Wagons	Max Wagons	Optimum Wagons	Limiting Factor
readingw_central-curve_down	Class 60	BR TR 34.5 t (Original Rating)	34.55	25	60	44	Coupler
readingw_east-curve_down	Class 99 Diesel	BR TR 56 t	56	25	60	41	Traction
readingw_east-curve_down	Class 99 Electric	BR TR 56 t	56	25	60	41	Traction
readingw_east-curve_up	Class 60	BR TR 34.5 t (Original Rating)	34.55	25	60	44	Coupler
readingw_east-curve_up	Class 66 (65 mph geared)	BR TR 34.5 t (Original Rating)	34.55	25	60	44	Coupler
readingw_east-curve_up	Class 66 (75 mph geared)	BR TR 34.5 t (Original Rating)	34.55	25	60	44	Coupler
readingw_east-curve_up	Class 70	BR TR 34.5 t (Original Rating)	34.55	25	60	44	Coupler
readingw_east-curve_up	Class 93 Diesel	BR TR 34.5 t (Original Rating)	34.55	25	60	34	Traction
readingw_east-curve_up	Class 93 Electric	BR TR 34.5 t (Original Rating)	34.55	25	60	34	Traction
readingw_east-curve_up	Class 99 Diesel	BR TR 34.5 t (Original Rating)	34.55	25	60	44	Coupler
readingw_east-curve_up	Class 99 Electric	BR TR 34.5 t (Original Rating)	34.55	25	60	44	Coupler
readingw_east-curve_up	Class 60	BR TR 56 t	56	25	60	51	Traction
readingw_east-curve_up	Class 66 (65 mph geared)	BR TR 56 t	56	25	60	51	Traction
readingw_east-curve_up	Class 66 (75 mph geared)	BR TR 56 t	56	25	60	51	Traction
readingw_east-curve_up	Class 70	BR TR 56 t	56	25	60	52	Traction
readingw_east-curve_up	Class 93 Diesel	BR TR 56 t	56	25	60	34	Traction

6.5 SRTcalc: modelling the impact of trailing loads on meeting Sectional Running Times

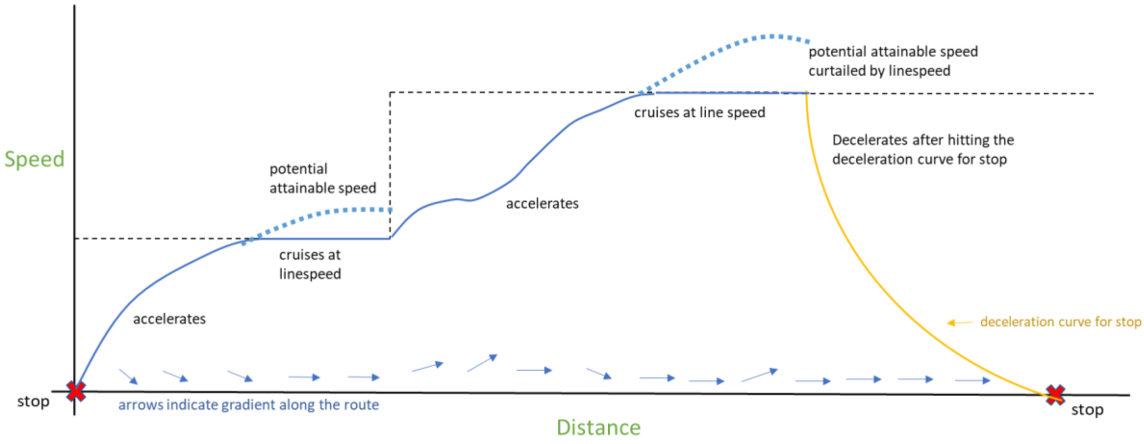
While coupler strength and available tractive effort will dictate whether a freight train can move at all on the network, the ability to keep to Sectional Running Times between TIPLOCs is a key determinant on whether a train can be permitted to run on the network. Learnings from this project were included in a force-balance model to enable the determination of running times for various locomotive and wagon combinations along routes with different geographical characteristics. This model (called 'SRTcalc') was coded in R. It is a development of the model used in the RSSB T1186 project and is similar to that developed for the RSSB T1229 project.

6.5.1 Approach

A simplistic approach to train performance was taken, whereby the train is assumed to accelerate at the highest possible rate to reach line speed (accounting for the route geography), remaining at the line speed if there is sufficient tractive effort, and then braking following a standard braking curve for changes in line speed or to come to a planned stop. Variations in acceleration rates and driver decisions to accelerate or decelerate at different rates are not considered. This approach mirrors that used in timetabling applications such as the British Rail TRATIM software where curvature was not explicitly included. Future work could address this.

The train experiences a force balance considering the tractive effort, resistive forces, body forces, and braking forces as defined in Section 5. A positive force balance will result in acceleration, a negative force balance will result in deceleration. The train starts its journey by accelerating in Notch 8 until it reaches the designated line speed. Once the line speed is attained, the train switches to a cruise mode, maintaining a constant speed equal to the line speed, provided the tractive effort in Notch 8 is greater than the resistances. However, in this situation the train is not allowed to reach a higher speed than the line speed. However, if the tractive effort in Notch 8 is less than the resistances (say on a steep gradient) then the train will start to decelerate. In an extreme case the train will come to a stand. The train must be compliant with either any upcoming reductions in line speed on the need to come to a planned stop at a particular TIPLOC. Hence the model looks backward from the location of an upcoming reduction in line speed or specified stop and calculates where a conservative service braking curve will intersect the current speed and starts decelerating at that point, following the service braking curve. The duration of modelled journey can then be compared against the SRTs between each TIPLOC along the route.

Figure 52 Modelled speeds for different operational modes



SRTcalc uses a set of modules to model the forces and dynamics of a train moving along a track. The primary focus is on calculating the force balance for each 10 m segment of track, utilising the Davis equation to calculate the net force acting on the train and the resulting acceleration, speed, and the time taken to traverse each 10 m segment of track.

6.5.2 R script inputs

A Shiny for R interface enables the user to enter the following information:

- Leading and trailing loco class
- Wagon type
- Wagon mass
- Total trailing load range to be considered
- Coupler type
- Velocity at initial TIPLOC (zero represents a start)
- Maximum train speed
- Route characteristics (including line speed and gradient)
- Pass or stop at final TIPLOC.

6.5.3 R script key components

6.5.3.1 'tractive_force' module

- Utilises the minimum value of tractive effort from either:

    - Lookup the tables discussed in Section 5.2.1 to obtain the tractive force for different speeds for the leading locomotive (and the trailing locomotive if present); or
    - The maximum tractive effort that can be exerted by the locomotive at any particular speed when accounting for adhesion (μ) based on the adapted Curtius-Kniffler equation from Section 5.2.2).
- Returns the actual tractive force applied.

6.5.3.2 'resistive_force_loco' and 'resistive_force_wagon' modules

- Calculates resistive forces acting on locomotives (for leading/trailing and 4-axle/6-axle locomotives) based on the train's speed (see Section 5.3.2).
- Calculates resistive forces acting on wagons (4-axle only) based on the train's speed (see Section 5.4.2).
- Takes into account parameters such as locomotive/wagon mass and various Davis equation coefficients appropriate to each vehicle.
- Returns the resistive forces for wagons and locomotives.

6.5.3.3 'body_forces' module

- Returns the force due to gravity acting on a gradient if present (see Section 5.1.1).

6.5.3.4 'braking_force' module

- Returns the braking force based on the train's mass and *g* multiplied by a constant (0.065).

6.5.3.5 'force_balance' module

- Determines the net force acting on the train based on the mode of operation (accelerate, coast, or decelerate).
- Calls the aforementioned modules to determine the tractive effort, resistive forces, body force and braking force.
- Returns the force balance.

This module first checks the current operating mode which can be one of 'accelerate,' 'cruise,' or 'deceleration.' If the mode is 'accelerate' or 'cruise,' it calculates the balance of forces based on the given acceleration period and notch level. The module calls the tractive_force, resistive_force and body_forces modules to calculate the forces acting on the train. If the mode is 'deceleration,' it calculates the force balance for deceleration based on the resistive forces, body forces, and braking force.

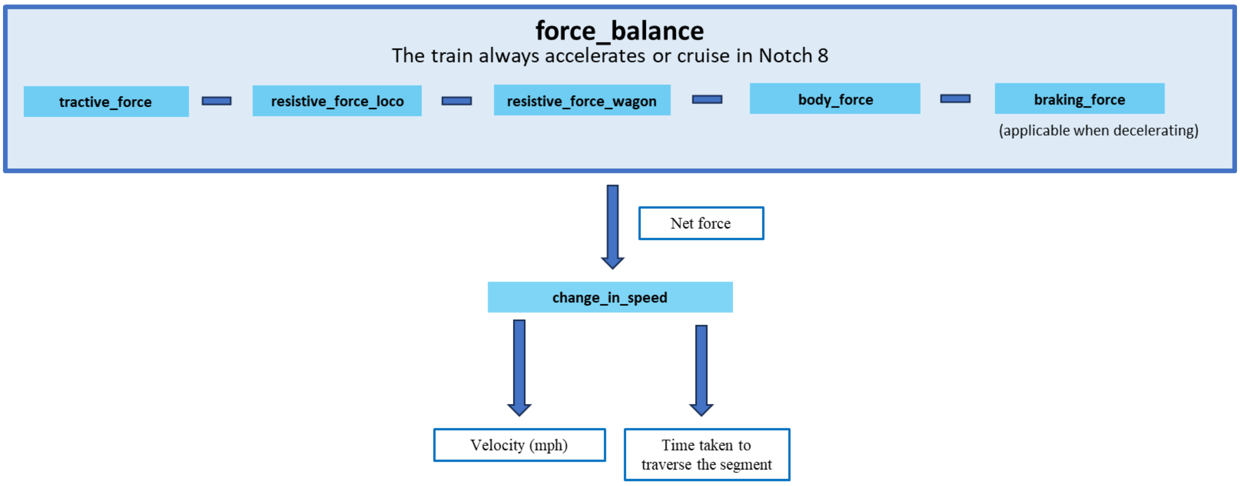
6.5.3.6 'change_in_speed' module:

- Computes the change in speed for a given operating mode and net force.
- Returns the updated velocity at the end of the 10 m segment and the time taken for the train to traverse that segment.

6.5.4 Calculation

At the start of each 10 m segment the force_balance module is called calculate the force balance based on the train's current operating mode. The change_in_speed module is then used to calculate the change in speed across the 10 m segment for a given force, mode, and initial velocity at the start of the segment.

Figure 53 Schematic showing interaction of the R modules for each 10 m route segment



As well as tracking the movement and timings of the modelled train through the prescribed route, the model also conducts four checks:

- ***Minimum acceleration check***: (Net Force / Total Train Mass) <0.025 N/tonne when starting is flagged as a STE Fail (see Section 5.1.2)
- ***Coupler check***: The first coupling between the locomotive(s) and wagons will fail if coupler strength [kN] is less than R_G(Section 5.1.1) and R_{AS} (total train mass) (Section 5.1.2) and R_{WCR} (total wagon mass) (Section 5.4.2.3) and the total resistive force of all wagons (Section 5.4.2.1).
- ***Starting fail check***: the maximum tractive effort that can be exerted by the locomotive is less than the sum of resistive force of all wagons (Section 5.4.2.1) and R_{LCR} (Section 5.3.2.3) and R_{WMS} (section 5.4.1.2) and R_{WCR} (total wagon mass) (Section 5.4.2.3) and R_{AS} (total train mass) (Section 5.1.2) and R_G (Section 5.1.1). A default curvature resistance of 1,000 m is assumed for this check.

- ***Momentum fail check*** (train does not have sufficient TE to maintain it current speed and is utilising momentum to help carry it through the section), ability to maintain speed utilising just TE is key assumption in MT19: the maximum tractive force is less than sum of resistive force of locomotive (Section 5.3.2) and R_{LCR} (total locomotive mass) (Section 5.3.2.3) and R_{WMS} (Section 5.4.1.2) and R_{WCR} (total wagon mass) (Section 5.4.2.3) and of the total resistive force of all wagons (Section 5.4.2.1) and R_{AR}(Section 5.1.2) and R_G (Section 5.1.1), and velocity is <5 mph.

7 Impact of the new methodology

7.1 Introduction

To test the impact of the new methodology (both the new empirical formula and the geographic model) the model (including the new formula) has been run for five different traction types and in seven different locations to enable a comparison with the current FTLB values to be made.

The five different traction types are:

- Class 70
- Class 60
- 'Standard' 75 mph Class 66
- 'Low geared' 60 mph Class 66
- Double-headed Class 90s.

The seven different locations chosen are:

- Desborough summit on the Midland Main Line
- West London Line rising northwards from Kensington Olympia to Mitre Bridge Junction
- Shap summit on the West Coast Main Line
- Travelling from Eastleigh up to Winchester
- The Lickey incline
- Miles Platting outside Manchester Victoria station
- The route out of Liverpool Docks to Bootle Junction.

These were chosen as a representative sample of some of the most demanding topography on the network.

7.2 Results

Table 34 below shows the results of the model runs compared against the stated loads in the FTLB. No loads are given within the FTLB for Class 70 or double-headed Class 90s so we have used the Class 60 values as a comparator.

Table 34 Results of model runs

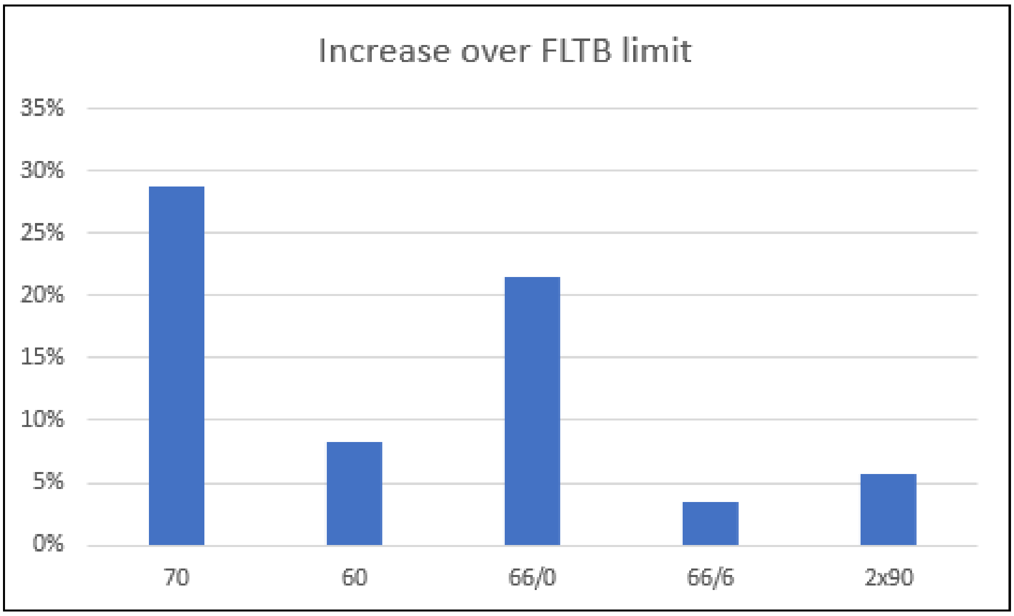
Location		Class 70			60			66 75mph			66 65mph			Double headed Class 90		
		Calc	FTLB*	Increase	Calc	FLTB	Increase	Calc	FTLB	Increase	Calc	FLTB	Increase	Calc	FLTB*	Increase
MML Desborough	No of wagons	39	30	30%	33	30	10%	25	22	14%	29	28	4%	30	28	7%
	Failure mode	STE			RTE			RTE			RTE			RTE		
West London Line	No of wagons	18	15	20%	14	15	-7%	10	11	-9%	12	14	-14%	12	14	-14%
	Failure mode															
Shap	No of wagons	26	20	30%	21	20	5%	16	15	7%	18	19	-5%	20	20	0%
	Failure mode	STE			RTE			RTE			RTE			RTE		
Eastleigh	No of wagons	65	51	27%	61	51	20%	48	38	26%	56	49	14%	55	49	12%
	Failure mode	STE			STE			RTE			RTE			RTE		
Lickey	No of wagons	13	10	30%	10	10	0%	8	7	14%	9	10	-10%	15	10	50%
	Failure mode	S&RTE			RTE			RTE			RTE			RTE		
Miles Platting	No of wagons	20	15	33%	20	15	33%	20	11	82%	20	14	43%	12	14	-14%
	Failure mode	Coupler (56t)			Coupler (56t)			Coupler (56t)			Coupler (56t)			RTE		
Liverpool	No of wagons	20	19	5%	16	19	-16%	12	19	-37%	14	20	-30%	14	20	-30%
	Failure mode	S&RTE			RTE			RTE			RTE			RTE		
Increase over FTLB limit, exc Liverpool & Eastleigh				29%			8%			21%			3%			6%

There are several conclusions to be drawn from this:

7.2.1 Significant increase in FLTB values

The Class 70s achieve a 29% increase over the Class 60 numbers and there is also a 21% increase for the Class 66s. The double headed 90s perform at above current Class 60 levels and the Class 60s themselves have an 8% increase, as shown in the figure below.

Figure 54 Locomotive increase over current FTLB limits



This approach sets new values where none existed for Class 70 and double headed Class 90 locomotives. The percentage increase above is over the current Class 60 limits.

This data is shown in the line below Table 34 which shows the average increase in train length, excluding Liverpool and Eastleigh. Liverpool was excluded as it is a sharply curved freight only line and we believe the FLTB loads have been significantly increased through Service Plan reviews based on a significant reduction in line speed up the gradient. Eastleigh is excluded as it is a relatively shallow gradient and the length of the train exceeds signalling section and terminal limits.

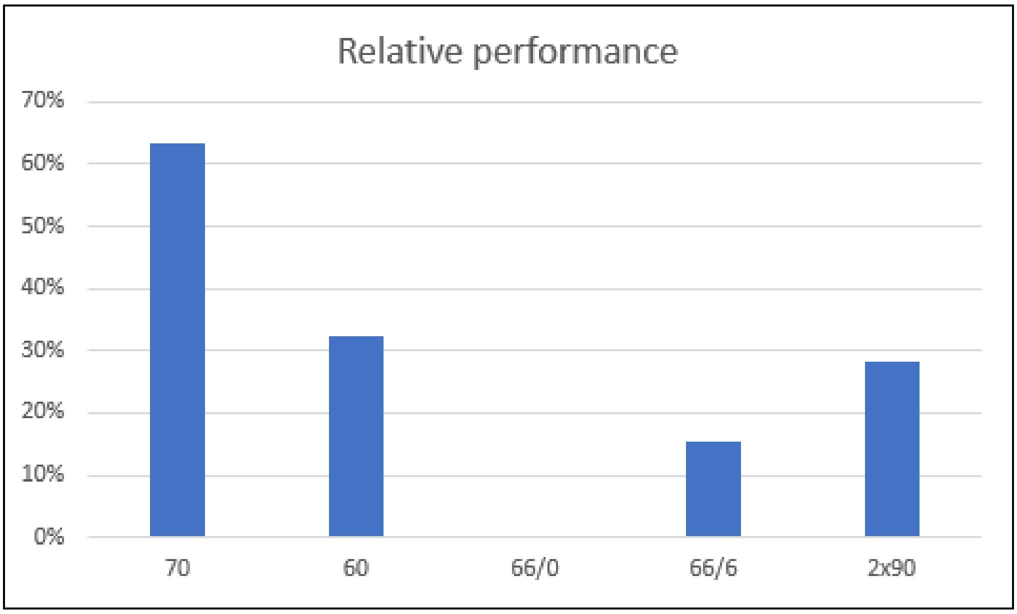
7.2.2 Further opportunity for improvement

Excepting Miles Platting (coupler failure mode) the more powerful Class 70's failure mode is starting tractive effort (STE) whereas other vehicles fail on rolling tractive effort (RTE). Where vehicles fail on RTE there is opportunity for improvement as the model does not make an allowance for deceleration up a gradient. However, in reality, some deceleration is acceptable provided the vehicle can start on the gradient (that is, STE is not a constraint) and that the vehicle can move through the section within the allotted Sectional Running Time (SRT). This opportunity is addressed later in the report.

7.2.3 Relative locomotive performance

The relative performance of the different traction types can be compared by looking at the number of wagons they can pull in the various scenarios defined above. The figure below shows the performance of the locomotives baselined against the performance of a standard 75 mph '66/0' locomotive.

Figure 55 Relative locomotive performance



These figures should be treated with some care due to the small sample size, but the figure does show the performance advantages of all the chosen locomotive types relative to the Class 66/0s. Whilst this will be of no surprise to experienced professionals, this is the first analysis providing some empirical support to define their relative performance in real world use.

The date from Miles Platting (coupler failure case) and Eastleigh (unrealistic scenario) were not included in this analysis.

7.2.4 How the benefit has been achieved

Two changes have been made in re-evaluating the FLTB values in this analysis:

- development of an MT19 compliant empirical TE model and then improving it using more current data
- application of the updated TE model within a geographical model enabling greater granularity of assessment.

Table 35, below, shows the number of track sections within the model which the train spans when on the most severe topography. Each 'track section' is a section of track in where both the horizontal and vertical alignment are unchanged. In most of the scenarios, the most severe track section is over a train length.

Table 35 Geographical complexity of ruling gradient sections

Location	Relevant track sections
Desborough	2 sections
WLL	6 sections
Shap	2 sections
Eastleigh	2 sections
Lickey	2 sections
Miles Platting	2 sections
Liverpool	1 section

In all but the West London Line, the track sections are quite long, with the train spanning no more than two track sections. Therefore, most of the improvement is due to the development of the model rather than the application of the model with greater geographic granularity, although that does benefit in some situations.

8 Enabling improved calculation of SRTs

8.1 Introduction

Sectional Running Times (SRTs) define the time a certain locomotive with a certain load requires to run between two timing point locations (known as TIPLOCs). They are the ‘building blocks’ of timetabling new freight services, when they are used to ensure that new services can move through the network without affecting other services. The table below shows the SRTs for a 2,000 tonne train hauled northwards on the West London Line by a Class 66 locomotive between 6 TIPLOCs, from Latchmere Junction to Mitre Bridge Junction.

Table 36 West London Line SRTs

Section	SRT
1 - Latchmere Junction - West Brompton	4min 0sec
2 - West Brompton - Kensington Olympia	3min 0sec
3 - Kensington Olympia - Shepherds Bush	1min 30sec
4 - Shepherds Bush - North Pole Junction	1min 30sec
5 - North Pole Junction - Mitre Bridge Junction	2min 0sec
Total	**12min 0sec**

The SRTs represent the ‘third leg’ of a supporting ‘stool’ for freight train performance, as shown below.

Figure 56 The three legs of the freight train performance stool

The train needs to have sufficient TE, to have an acceptable coupler strength, and to be able to progress through the network within the SRT time envelope available.

Coupler strength and available TE constraints have been the subject of earlier analysis in this report, and in the RSSB T1256 project. This section of the report looks at the opportunity for freight train length extension through the review of SRT allowances.

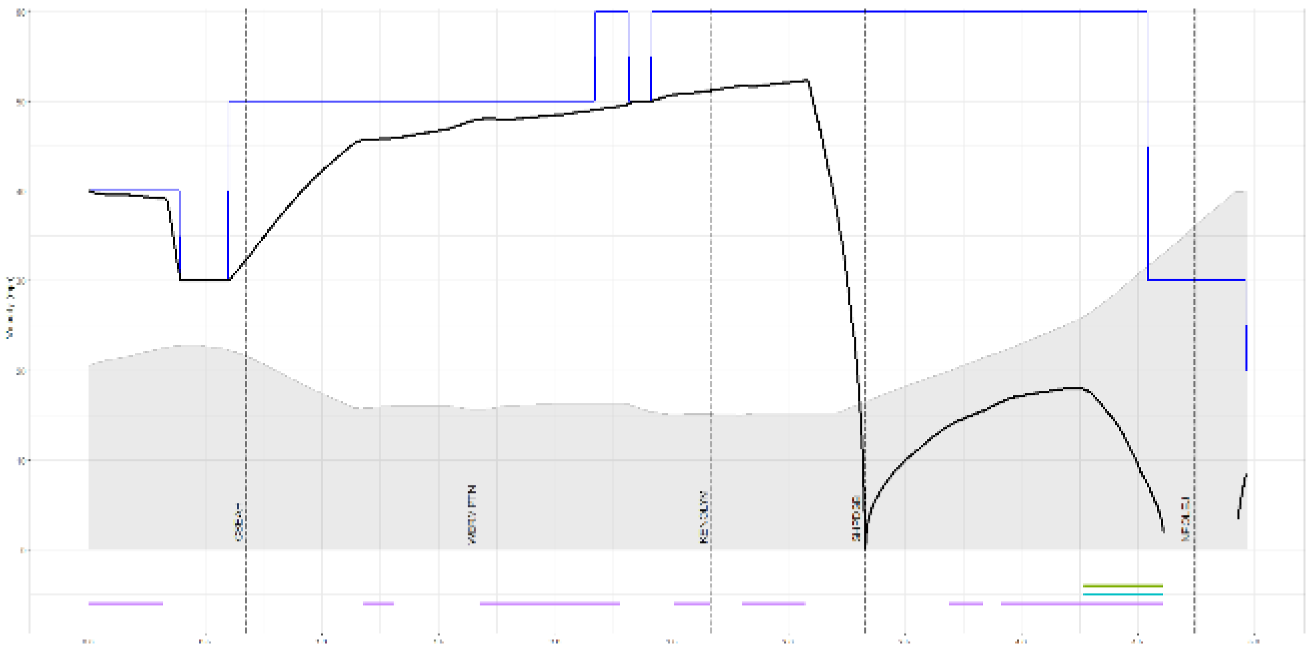
There are two areas of potential improvement:

- enabling longer trains to run within the existing SRT allowance (for example, recognising that a 2,200 tonne train could run in the existing 2,000 tonne allowance), and
- enabling longer 'off-peak' or 'interpeak' timing allowances, that is variable or 'dynamic' timing allowances within the day—at its most basic this recognises that more time is available for freight trains when running overnight when there are no passenger services.

8.2 Approach

The 'SRTcalc' tool, described in Section 6.5, was used to determine the travel times between junction-to-junction sequences of TIPLOCs. In some cases, a train is able to successfully pass through a section provided it does not stop. But if the train is stopped at an intermediate point, it fails to complete the full route. For example, if the train is stopped at Shepherds Bush, it loses its momentum and is not able to reach Mitre Bridge. The train performance is then as shown in the figure below (in poor adhesion circumstances).

Figure 57 WLL train performance when train stopped at Shepherds Bush



The lack of available power and momentum means that whilst the train accelerates in the initial part of the gradient but as it steepens the train comes to a halt and is then unable to restart. Note: in 'usual' rail head conditions the train can start, but a longer time allowance is required.

Operational constraints

This case study illustrates that, in places, 'external' operational constraints need to be considered when optimising train length within an SRT envelope. Two key ones found here are:

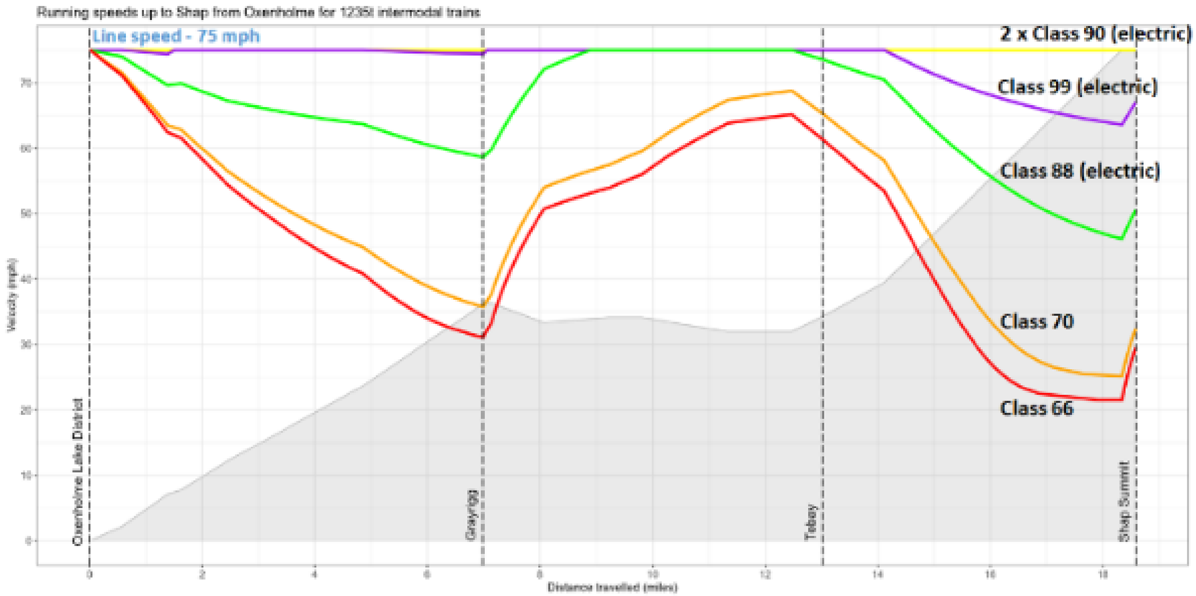
- need to work within passenger timings which are 'slow' in locations where stations are close together
- need to not stop freight trains at the bottom of a hill so momentum can be carried forward.

8.2.1 West coast main line

Comparative diesel and electric traction performance

The train performance graph below shows the performance of various locomotives taking a 1,235 tonne intermodal train up Grayrigg and Shap.

Figure 58 Various locomotive performance on WCML



This graph clearly illustrates the benefits of electric traction which have much more TE at higher speeds than diesel locomotives. Neither the Class 66 nor Class 70 is doing 25 mph at the top of Shap on this relative light train, yet a pair of Class 90s modelled at 75 mph and the new Class 99 is modelled at around 60 mph.

The diesel locomotives more than halve their speed going up to Grayrigg and are unable to recover to line speed before the more significant gradient to Shap. With the exception of the 4-axle Class 88, the electric locomotive combinations with more power or axles are barely affected by the gradient to Grayrigg, only losing speed (for the Class 99) on the gradient to Shap.

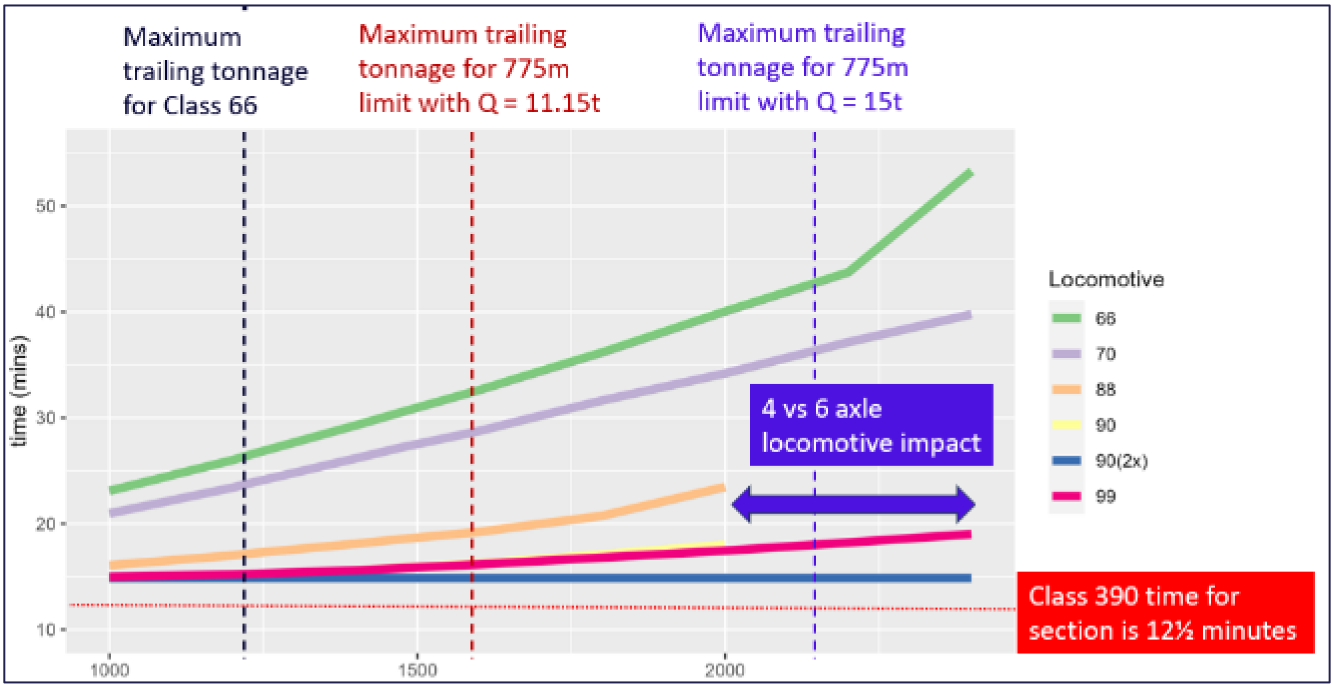
We have extended this analysis for the different traction types, which confirms the advantage of electric traction:

Table 37 WCML locomotive timing comparison

Locomotive	Model time	Diff. w.r.t. Class 90
Class 66	26min 37sec	+ 11min 45 sec
Class 70	23min 55sec	+ 9min 3 sec
Class 88	17min 13sec	+ 2min 21 sec
Class 90	**14min 52sec**	**-**
Class 99	15min 16sec	+24 sec

The overall effect of this is shown below.

Figure 59 WCML Overall locomotive performance



This chart shows electric locomotives are able to take significantly higher loads. As the ~25-minute SRT allowance for a Class 66 the electric locomotives can take over 2,500 tonnes, with the exception of the 4-axle Class 88 which is limited to 2,000 tonnes by its TE capability. The passenger train does not notice the gradient but is only 2.5 minutes faster than a pair of Class 90s, due to its higher maximum speed.

SRT performance

The timing comparison of the official SRTs against a modelled a Class 66 with 2,000 tonnes TLL is shown below.

Table 38 WCML SRT timing comparison

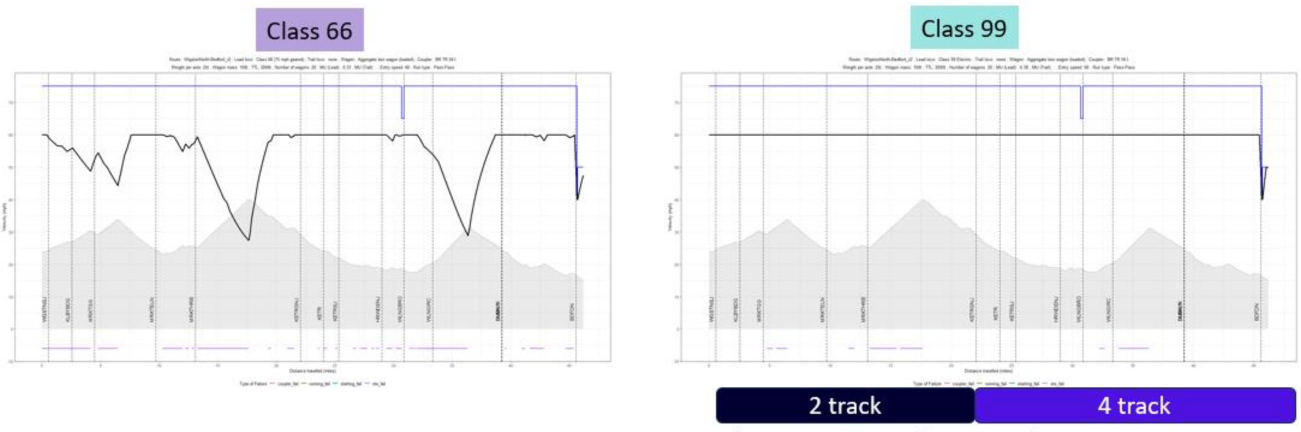
Section	SRT	Model Time
1- Oxenholme Lake District – Grayrigg	12min30sec	9min3sec
2 - Grayrigg – Tebay	6min30sec	6min40sec
3 - Tebay - Shap Summit	11min0sec	10min54sec
Total	**30min0sec**	**26min37sec**

The modelled performance of the Class 66 is 11% better than the SRT allowance, indicating a Class 66 could run with an extra wagon and a Class 70 could run with an extra 3 wagons.

8.2.2 Midland main line

The performance of a Classes 66 and 99 hauling 2,000 tonnes is shown below.

Figure 60 MML train performance



The 'three peaks' along this route slow down the Class 66 to over half on the line speed in places but the locomotive fairly quickly recovers on the downhill sections. The Class 99 is not slowed by the gradients at all.

The overall comparison of a 2,400 tonne Class 66 hauled train against SRTs is shown below.

Table 39 Performance against SRTs

Section	SRT	Model Time
Wigston North Junction - Kilby Bridge Junction	3min 30sec	3min 14sec
Kilby Bridge Junction - Market Harborough	15min 0sec	12min 2sec
Market Harborough - Kettering North Junction	13min 30sec	13min 11sec
Kettering North Junction - Kettering	3min 0sec	1min 58sec
Kettering - Kettering South Junction	2min 0sec	1min 19sec
Kettering South Junction - Harrowden Junction	3min 0sec	3min 40sec
Harrowden Junction - Wellingborough	2min 30sec	1min 55sec
Wellingborough - Sharnbrook Junction	11min30sec	11min 26sec
Total	**61min 0sec**	**56min 1sec**

The train runs 5 minutes faster than the SRT and a significant part of this may be due to the Network Rail's SRTs being rounded up from base data. Over the 'junction to junction' network through these 7 timing sections 5 minutes can be saved. At Kettering North Junction, the network becomes 4-track and the saving identified above may enable the train to get through the 2-track section, without being looped at Kettering or Knighton Junction.

8.3 SRT related conclusions

The key conclusions from this analysis are below.

- There are opportunities to run longer trains within the current SRTs allowance with our improved knowledge of traction performance.
- Alternatively, there is the opportunity to timetable 'same length' trains faster, which will bring operational benefits such as clearing two track sections quicker.
- The development of 'dynamic' (time variable) timetable allowances for heavier trains off peak would enable heavier trains and increase the efficiency of network operation. It is important to distinguish between:
  - SRT timing: the timetabling time allowance for a given locomotive and loading
  - the available 'white space' timing opportunity.
- Operational constraints can affect freight trains' SRTs such as the performance of the passenger service on the same lines. When the passenger service is not running but the same SRTs are applied, this reduces the timetabling opportunity for freight and leads to inefficient train running, wasting fuel, and time.
- Electric trains have much greater carrying capacity at speed due to their higher TE at line speed.

9 Cost benefit analysis

9.1 Introduction

Enabling longer trains by reviewing tractive effort, wagon and locomotive resistances, and SRTs allowances produces economic and environmental benefits. Consideration of the fixed and variable costs of freight train operation demonstrates this value.

The fixed costs of operating a train are:

- provision and maintenance of the locomotive
- locomotive track access costs
- provision of labour (driver and ground staff)
- payment of any third-party access fees (charged on 'per train' basis)
- corporate overhead.

The variable costs associated with the length of that train are:

- provision and maintenance of wagons (longer trains, more wagons)
- track access cost for wagons
- fuel, although this is a very partial increase with train length and is almost a fixed cost.
  - This is because the primary locomotive aerodynamic and internal resistances are largely unchanged and there is a small percentage increase in both wagon aerodynamic and internal resistances linked to the additional vehicles providing the train length extension. There is also a non-linear increase in fuel for starting and climbing power requirements and no difference for consumption when braking, coasting, or idling.

This commentary demonstrates that a, say, 20% increase in train length will not lead to a 20% increase in train cost, thereby generating a saving. The reduced fuel loading also leads to environmental benefits.

The benefits are assessed via case studies of two geographical locations. The increases in trailing load were calculated and 'before and after' calculations of cost and environmental impact were conducted, using a model held by the Network Rail freight team.

The two case studies are:

- movement of aggregate down the Midland Main Line: train length increased from 22 to 25 wagons using Class 66 haulage
- movement of lime from Shap: train length increased from 20 wagons to 26 wagons using Class 70 haulage.

9.2 Analysis

Table 40 below shows the calculated beneficial effects that the above changes will make to the two chosen case studies.

Table 40 Economic savings

		Payload (t)	Train cost	Cost/T	Saving/t	% saving	Saving/train
Shap	Current	1420	£11,095.00	7.81	1.28	16%	£2,366.50
	Future	1846	£12,057.00	6.53			
MML	Current	1540	£6,362.00	4.13	0.34	8%	£601.55
	Future	1750	£6,628.00	3.79			

The 'train cost' shown in the above table is based on a train costing spreadsheet developed by Network Rail. It uses current pricing for locomotive and wagon leasing and maintenance charges and assumptions for driver and groundstaff time for each flow. The model has recently been validated against several recently retendered flows to ensure it provides a realistic assessment of current haulage costing.

The savings are significant. In the Shap case study a 30% train length extension leads to 15% cost savings, whereas on the Midland Main Line a 14% train length extension leads to an 8% cost saving. These savings are also 'free'; no locomotive or infrastructure modifications are required, just the provision of additional wagons.

The level of adoption across the industry is not possible to assess as some trains will already be operating at their maximum train length due to terminal or network looping restrictions. However, there are around 1,000 freight trains running a day and if only 20% of them are lengthened, at an indicative saving of £1K per train, that is a daily industry saving of £200,000, or £52m/year (5-day week).

10 Implementation plan

10.1 Ownership and management of the timetabling process

Implementation of the changes identified in this report will require changes to the Freight Trailing Loads Book (FTLB) and SRTs across the network.

The FTLB is the intellectual property of Network Rail in their role as the Infrastructure Manager of the British rail network. In recent years, the Excel sheets defining the FTLB have been managed within the Freight and National Passenger Operators (FNPO) team within the System Operator function in Network Rail. Changes have only been made through the undertaking of site specific 'Service Plan Reviews' (SPRs) where a Freight Operating Company has asked for a trial of a longer train outside the current FTLB limit to be undertaken. Where successful after running trial trains, FNPO have updated the relevant Excel sheet to record the agreed increase.

The SRTs are held within the various software solutions used by Network Rail and the FOCs to manage train timings (principally ATTUne, RailSys® and TPS).

10.2 Required changes to standards and regulations

Updating the FTLB does not need any changes to any standards or regulations. It is currently irregularly updated following completion of successful SPRs as required. In future, when the digital platform is complete, change management will be even easier; the new data will just have to updated into the model.

10.3 Transition plan

Ideally the FTLB will transition away from the Excel based approach, to use the empirical model developed by this research project. This will ensure the optimum loads are available using the greater granularity within the model, as shown in Table 41 below.

Table 41 Comparison of the current and future FTLB input parameters

Current FTLB	Future FTLB
Pre-2000 locomotives	All locomotives, with the ability to differentiate between powertrain options for hybrid vehicles
Coupler strength (only 56 & 34.5 tonne)	Coupler strength (all, with the ability to add more)
	Track vertical and horizontal geometry
	2 or 4-axle wagon types
	Specific wagon types (for example hopper, intermodal)

	Multiple working (double heading)
	Variable wagon loading, for example 20 tonne car, 60 tonne intermodal, 75 tonne bulk

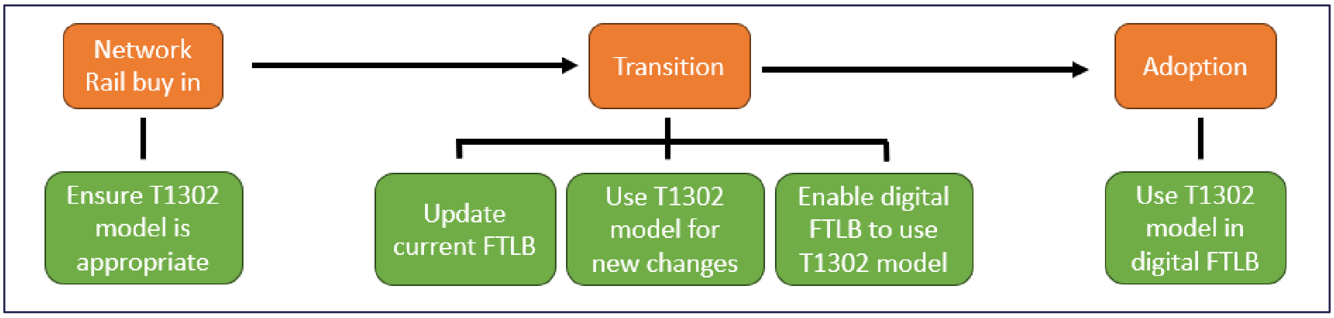
The model enables a geographically specific and consist specific train length to be easily established.

We suggest the following implementation plan is adopted.

1. Network Rail agree that the model produced by this report is appropriate to become the basis of the FTLB moving forward.
2. In a transition period:
   a. The T1302 model is used to update the FTLB for traction and couplers introduced this century since the last formal update of the FTLB.
   b. The T1302 model is used to generate new FTLB values for any new locomotive types or infrastructure changes.
   c. Network Rail's digital model is modified to be able to incorporate the empirical model.
3. Network Rail's digital model incorporates the empirical model within its programme to be able to auto-generate new FTLB limits for new locomotive and wagon types, and infrastructure changes.

This plan is shown schematically below.

Figure 61 Implementation Plan schematic



11 Areas for future development

Sufficiently accurate calculation of coupling loads, maximum trailing loads, and sectional running times requires an appropriate level of detail and confidence in input data and assumptions to accurately capture resistances and TE under a range of conditions and circumstances. As part of this project, several areas have been identified where future work could be carried out to improve some input assumptions, and these have been grouped below by locomotive, wagon, or track assumptions.

11.1 Locomotive data and assumptions

11.1.1 Locomotive TE and adhesion data and assumptions

Collect TE data across the entire range of operating speeds for the following locomotive classes where this is currently unavailable:

- Class 20
- Class 57
- Class 67
- Class 68
- Class 73/1 (on electric power)
- Class 73/1 (on diesel power, as built)
- Class 73/9 (on diesel power, post refurbishment and upgrade)
- Class 92 (on 3rd Rail).

Investigate the effectiveness of the railhead cleaning provided by the leading wheelset of the leading locomotive on the adhesion levels of the leading and subsequent wheelsets under a range of different rail head conditions, and the potential impact this has on design choices around the number of axles per locomotive and locomotives on achievable adhesion levels. For example, the comparative degradation in TE that can be delivered with reduced TE available from the leading wheelset has a smaller impact on a 6-axle locomotive than on a 4-axle locomotive. This will lead to improved confidence in μ values.

With newer locomotive types (with three phase traction electrical systems) assess the effectiveness on achievable adhesion with less-than-ideal railhead conditions from WSP, sanding, or other potential new adhesion improving methods.

Apply this knowledge across the range of operating speeds to identify the systematic conditions (or more likely combination of conditions) which prevent the highest adhesion levels being achieved with different permutations of track geometries:

- curvature

- cant (and cant deficiency)
- check rails

and track construction:

- continuous welded vs jointed rail
- different rail section
- sleeper type (concrete /wooden).

Improvements in the above items and understanding the impact of combinations of certain factors, improve confidence in µ values. Assumptions on many of these were hidden behind the mainline and secondary route adhesion differences (with secondary routes typically 0.02 lower) in MT19 but no definitions remain for the allocation of routes to mainline or secondary categories.

11.1.2 Locomotive resistance data and assumptions

Conduct research into the typical resistances of (new) modern locomotives with modern bogie designs which have been designed to have lower track forces, both though improved mechanical design as well as the utilising lighter three phase traction motors (which are typically at least a third lighter than older DC traction motors). The existing locomotive resistance equations values are likely to be significantly conservative for modern locomotive types.

11.2 Wagon data and assumptions

Develop or improve wagon resistance data and assumptions for the following cases where resistances are likely to be noticeably different to the cases discussed in section 4.4:

- Currently utilised designs of 2-axle wagons under current typical conditions (current data assumptions will be conservative as they assume mixed 2-axle wagon types and a mixture of bearing types).
- Wagons with smaller diameter wheels which are typically used in recent designs of 'low floor' intermodal wagons to enable the deck height to be reduced, so 9'6" high containers can be carried on route sections with more restrictive loading gauges.
- 40' container wagons. The default container wagons values are for 60' wagons, and 40' or 45' wagons will have lower resistances. The 'A' resistance values ($K_{WMR1}$and K_{WMR2}) will adjust automatically to the lower axle loads but the 'B' (K_{WMR3}) and 'C' values (K_{WMR5}) for 40' or 45' wagons will be lower than those for 60' wagons, but significantly less than proportionately lower.
- Automotive wagons. Currently utilised designs of automotive wagons come in four configurations, all of which have high aerodynamic drag compared to other wagon types.

- Low sided ballast wagons. These wagons are longer and will have higher 'B' (K_{WMR3}) and 'C' values (K_{WMR5}) than for high sided aggregate wagons.

11.3 Track assumptions

Conduct research into the variation in typical wagon resistances due to variation in track construction/quality and develop a suitable adjustment track construction factor if appropriate:

- continuous welded vs jointed rail
- different rail sections
- sleeper type (concrete /wooden).

11.4 Summary of recommendations

The areas for future development are summarised in the table below.

Table 42 Areas for potential research to improve TLL calculations

1	Improve available locomotive TE data.	Update available data and apply into the model for various traction types.
2	Evaluate the cleaning effect of first wheelset on the rail head.	Consider how the first wheelset improves rail head adhesion for the following wheelsets and take this forward into consideration of the effective frictional allowances for 4 and 6-axle locomotives.
3	Update understanding around rail head adhesion on modern traction.	• Assess the effectiveness of modern WSP, sanding and other methods on railhead adhesion. • Consider how track construction and orientation affects railhead adhesion.
4	Update locomotive internal resistance data.	Current resistance data is quite old and does not reflect developments such as low track force bogies or lighter traction motors.
5	Update wagon internal resistance data.	• 2 axle assumption overly conservative • use of smaller wheels not considered
6	Track characteristics	Evaluate how wagon coefficients vary with track construction.

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12 Conclusions

The key conclusions from this report are as follows:

1. Train length extension, through the adoption of the recommendations within this report, will significantly reduce the unit cost of running freight trains. Based on 20% of the daily freight services being extended, the industry will benefit through a cost saving of over £50m pa.
2. It has been possible to 'back-calculate' the historic FTLB values derived from MT19 using four components: gravity, curving, acceleration, and internal resistances
3. Through the analysis with the report, we have updated some of the force coefficients within the above model as they have not been reviewed for roughly 30 years. More work needs to be done in this area and detailed recommendations are included in Section 11. Some of these recommendations were initially identified over 40 years ago by BR.
4. Two load cases have been defined:
    - Starting Tractive Effort (STE): maximum acceleration, minimum internal resistances
    - Rolling Tractive Effort (RTE): no acceleration (hold line speed), maximum internal resistances.

    Previously, a 'continuous' load case has been considered, often expressed as a maximum load based on a 'continuous loading' and this significantly reduced calculation complexity. Now, due to the ability to accurately and easily model performance based on actual geography and locomotive performance, we do not consider this load case is now relevant as it is superseded by the more accurate definition of RTE, now possible. Secondly, the thermal degradation of modern locomotive traction equipment performance is much lower so this state (or even close to it) is very unlikely to be relevant for new locomotive types on the GB network.
5. By placing this model into Excel and allowing specific route geography to be input, it is possible to more accurately restate TLLs. This is particularly of value where the steepest gradient is less than the whole train length.
6. Within MT19, maximum locomotive tractive effort is capped by a locomotive (sub-)class specific rail head friction co-efficient (μ) of up to 0.33, and in certain situations for older locomotive types is reduced to below 0.25. For more modern locomotive classes this previous maximum figure is overly conservative and can be increased, up to 0.38.
7. Electric locomotives have significantly more power at higher line speed than diesel locomotives. Consequently, their usual failure mode is STE, as only a smaller proportion of their much higher maximum power can be delivered at low speeds where adhesion is the limiting factor. However, these consists may not be able to start if they are stopped, so, if this benefit is to be realised, a 'let it run' policy is required which, at times, will be operationally difficult.

8. From the four case studies undertaken within the study, historic SRTs for various locomotives and consists appear conservative, with generally at least a 10% improvement in trailing weight possible. For the modern electric locomotive (Classes 88, 93 and 99), SRTs should be established which take account of their significantly improved RTE which will lead to the ability to either run longer trains or run existing length trains at reduced SRT allowances.
9. In places, SRT allowances appear to reflect operational constraints of working around the passenger timetable in mixed use applications, with the freight trains given a longer than required SRT to avoid conflict. However, when the passenger trains are not running these SRT allowances are unchanged, unnecessarily slowing the freight trains and increasing their fuel usage. This should be amended and where this is an issue 'peak', 'off-peak', and 'no passenger service' SRTs developed and used.
10. As custodians of both the Loads Book and the Timetable management process Network Rail are key to the implementation of the opportunities identified within this report. Immediately positive change can be made through the development of new SRTs, adoption of revised (and variable within the year) coefficients of friction values, and increased train length enabled through the Service Plan review process. In the medium term, for these changes to be efficiently changes to some of the systems used by Network Rail will require updating, which will lead to a requirement for capital spending and staff training.

13 References

Allenbach, J.-M. 2012. Railway Technology. Available at: https://documents.epfl.ch/users/a/al/allenbac/www/documents/SummarET.pdf

AREMA, 2022. Vol 4 Systems Management, Railway engineering and operations. *Manual for Railway Engineering* Chapter 16

British Rail, 1978. Curve Resistance in Marshalling Yards. Report No. E308

British Rail, 1983. Starting & Curve Resistance. BR Technical Note SSP83N027, 2/9/83

British Railways Board, 1967. 'Manual of maximum freight train loads on gradients for various types of locomotive' (document referred to as 'MT19')

British Transport Commission, 1954. TN-EMMA-54, 261-63-54

Canadian National, 1980. Transportation Design Standards. 'Standard Method of Calculating Tonnage Ratings'. CN Transportation Planning Montreal

Canadian National, 1986. Transportation Design Standards

Canadian National, 1987. Train Performance Calculator Manual

Canadian National, 1990. Transportation Design Standards

Carus-Wilson, C. A., 1907. The predetermination of train resistance. Inst. Civil Engrs. 1907. Vol. 171, Pt. 1, Paper No. 3686

Corus, 2009. MT19 Tables review and analysis (Appendix B)

Curtius E. W., and Kniffler A., 1944. 'Neue Erkentnisse uber die Haftung zwischen Treibrad und Schiene,' Elektrische Bahnen, No. 1/2, pp. 25–29, No. 3/4, pp. 51–57

Davis, W. J., 1904. Train resistance. *The Street Railway Journal*. Vol. 24. No. 23, p. 1000-1003

Davis W. J., 1926. The Tractive Resistance of Electric Locomotives and Cars. Gen. Electr. Rev. p. 29

Dunn H. H., 1914. The Tractive Resistance of a 28-ton Electric Car. Bulletin of the Engineering Experiment Station of the University of Illinois No 74. p. 45

Marta, H.A., Mels, K.D., and Itami, G.S., 1972. Design Features and Performance Characteristics of the High Traction, Three-Axle Truck. ASME-Paper No 72-RT-3, Railroad Conference 1972, USA

EMD, 1994. SD70M-AC technical sales literature

Erie-Lackawanna Railroad, 1966. 'Erie-Lackawanna Test Piggyback, Rack Car Resistance,' *Railway Locomotives and Cars*, pages 23-54

FRA (Federal Railroad Administration), 2009. 'Final Report Comparative Evaluation of Rail and Truck Fuel Efficiency on Competitive Corridors'

Grebenyuk, P.T., Dolganov, A.N., et al. 1985. Правила тяговых расчетов для поездной работы (Rules of traction calculations for train working), Moscow: Transport. p287

Hammitt, A. G., 1976. 'Aerodynamic Forces on Freight Trains, Volume 1, Wind Tunnel Tests of Containers and Trailers on Flatcars,' U.S. Department of Transportation, Federal Rail Administration, Report No. FRA/OR&D-76-295.1, pages 47-48

Harada, M., 1967. 'Experimental Study on the Running Resistance of JNR Freight Cars, General Equation of Resistance and Its Variance,' Railway Technical Research Institute, Japanese National Railways, Vol. 8, No. 2

Hargraves, J.E., 1974. A Computer System for Train Performance Calculations. Technical Memorandum TMAM 6, British Railways Board, Research and Development Division, Train Control Group, Mathematics Applications Section

Headech, A. L., 1982. Train Resistance - A Comprehensive Review. British Rail M. & E. E. Department, Railway Technical Centre, Report No. SSP/R/82/002

Hoerner, S. F., 1965. 'Fluid Dynamic Drag', Second Edition

Johansen, F.C., 1936. 'The air resistance of passenger trains', Procs. Inst. Mech. Engrs. Vol. 134

Lomonosov, Y., 1898. 'Traction Calculations and Appendixes with Graphical Methods' Traction Department of the Kharkiv-Mykolaiv Railway

Muhlenberg, J.D. 1977. Resistance of a Freight Train to Forward Motion. MITRE Technical Report 7664, produced for US Department of Transportation/Federal Railroad Administration, Project No. 274A

Petrov, N., 1898. 'Train Resistance on Railways'. Saint-Peterburg

Rangelov, V. N., 2012. Gradient modelling with calibrated train performance models. Computers in Railways XIII, WIT Transactions on The Built Environment, Vol 127, p. 123-134

Rochard B., and Schmid, F., 2000. A Review of Methods to Measure and Calculate Train Resistances. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit. Vol. 214. No 4. p.p. 185-199

Sapronova, S.Yu., Tkachenko, V.P, Fomin, O.V., Kulbovskiy, I.I., and Zub., E.P., 2017. Rail Vehicles: The Resistance to the Movement and the Controllability: Monograph. Dnipro: Ukrmetallurginform STA

Schmidt, E.C., 1910. 'Freight Train Resistance; Its Relation to Car Weight.' Bulletin of the Engineering Experiment Station of the University of Illinois No. 43, p.144.

Schmidt, E.C., 1927. Freight Train Curve Resistance on a One-Degree Curve and on a Three-Degree Curve. University of Illinois Bulletin. Vol. XXIV. July p. 12

Schmidt E.C., and Dunn H.H., 1916. The Tractive Resistance on Curves of a 28-ton Electric Car. Bulletin of the Engineering Experiment Station of the University of Illinois No 92. p. 54

Schmidt W.J., and Dunn H.H., 1918. Passenger Train Resistance. Bulletin of the Engineering Experiment Station of the University of Illinois No 110, p. 4

Schmidt E.C., and Marquis F.W., 1912. The Effects of Cold Weather upon Train Resistance and Tonnage Rating. Bulletin of the Engineering Experiment Station of the University of Illinois No 59, p. 25

Spiryagin, M., Wolfs, P., et al. 2016. *Design and Simulation of Heavy Haul Locomotives and Trains* (1st ed.). CRC Press

Stehly, M. 2008. Train Resistance and Railroad Emissions and Efficiency. BNSF Presentation, October 24, 2008

Strahl, G., 1913. The calculation of times and speeds from the maximum loads of locomotives. Glasers Annalen, Vol. 37, p. 124 (German)

Szanto, F., 2016. 'Rolling resistance revisited', Railway Technical Society of Australasia, Maintaining the momentum: CORE 2016: conference on railway excellence, 16-18 May 2016, Melbourne, Victoria, Australia

Totten, A.I., 1937 'Resistance of Lightweight Passenger Trains', Trans. ASME, Vol. 59, pp. 329-334

Tuthill, J.K., 1948. 'High-Speed Freight Train Resistance: Its Relation to Average Car Weight', University of Illinois Engineering Bulletin, 376

14 Appendix: factors affecting adhesion

14.1 Introduction to adhesion

The friction coefficient (μ_{max}) between wheel and rail is usually in the range of 0.40 to 0.45 for relatively clean, dry rail in reasonable condition and is essentially the same for all locomotives. Locomotive adhesion variability (η) represents the ability of the locomotive to convert the available friction into usable friction at the wheel rail interface with $\mu_{achievable}$ being lower than µmax.

$$\mu_{achieveable} < \mu_{max}$$

$$\mu_{achieveable} = \eta \times \mu_{max}$$

Locomotive adhesion variability (η) varies dramatically from about 45% for the oldest DC traction electrical equipment locomotives (for example, first-generation BR locomotives) to about 90% for modern AC traction locomotives with three-phase variable voltage and frequency drives (for example, Classes 68, 70, 88, 93 and 99). This variable incorporates many factors related to the locomotive or track, including electrical design, control systems, bogie type, wheel conditions, locomotive speed, track condition, track curvature, weather, and other factors.

Chosen values of $\mu_{achievable}$ used for adhesion calculation have different assumptions based on probability of the µ value being at or above this value under a wide range of conditions and these assumptions and conditions can vary by country, region, and operator.

It is important to note that in the case of the traction wheel, the tractive effort is transferred to the rail due to sliding friction by very small levels of slip between the wheel and rail. Initially as tractive effort is increased, slip increases in proportion, with maximum tractive effort attained when slip is around 1.0 to 1.5%, and this is the maximum value of sliding friction which can be converted into adhesion to maximise transfer of tractive effort. If slip increases beyond that level the efficiency of transferring TE reduces as the level of slip increases, hence slip needs to be optimised at ~1.0 to 1.5% where possible (for example, it is difficult to reduce and maintain slip below 1.8% on wet rail heads).

Wheel slip starts when the tractive effort exceeds the product of adhesive weight and adhesion factor at that point in time.

The following factors, affecting the variability in adhesion, are included in tractive effort and trailing load calculation methodologies internationally, and in GB to varying extents:

- track construction, condition and quality
- train speed
- weather conditions
- track curvature

- steerable bogies and traction control
- traction control
- wheel slip protection and sanding systems.

14.2 Track construction, condition and quality

Track quality, both in terms of construction and current condition, affects the both the mechanical resistance (starting and rolling) and adhesion. Several countries have documented approaches to adapt mechanical resistance and adhesion due to differences in track construction and condition with each being different:

- Great Britain (MT19): adjusts adhesion values but not mechanical resistances
- Soviet Union and successor states: adjusts mechanical resistance equation coefficients (and hence values) but does not adjust adhesion values
- US and Canada (AAR/AREMA rules, for example, AREMA (2022)): adjusts both mechanical resistance and adhesion values, but is very flexible based on best available industry data and operator guidance in place.

Both North American and Soviet traction calculation methodologies assume a reduction in μ values with increasing train / locomotive speed, which complicates international comparisons.

14.3 Train speed

Maximum obtainable adhesion is higher at very low speeds (when it is most useful to be high) and declines gradually with increasing speed. This is covered in detail in Section 4.3.1.

14.4 Weather conditions and rail head contamination

While μ_{max} values can theoretically be as high as 0.7, this requires clean dry wheels and very low relative humidity. For relative humidity (RH) above 45%, achievable μ_{max} values are limited to ~0.45 due to a thin film of water on the surface acting as a lubricant even in 'dry' conditions. RH in Britain is virtually always above 45% apart from on some hot summer days, hence maximum achievable μ values are effectively limited to 0.45.

14.5 Even weight distribution across axles

Weight transfer occurs between both bogies and between axles within each bogie when power is applied, especially during starting. This redistributes the locomotive weight on each axle depending on the reactions and couples acting. The weight on the leading bogie gets lighter and that on the trailing bogie gets heavier; similarly the weight on the leading axle of the bogie gets lighter and that on the trailing axle gets heavier. Hence it is important to have the weight evenly distributed between axles when no power is applied as imbalances will be accentuated in real world use.

For a modern well-designed locomotive at full power, the steady-state weight transfer between each bogie is typically around 5% resulting in the weight distributions of 95% on the leading bogie and 105% on the trailing bogie. Similarly, for the axles within each bogie the steady-state weight transfer between leading and trailing axles is typically around 3% resulting in the weight distributions of 97% on the leading axle and 103% on the trailing axle within each bogie. Overall, this can lead to a range of axle loading between ~92% and ~108% for the leading and trailing axles on the locomotive. Two methods are typically used to address weight redistribution issues:

- Mechanical design of the bogie, bogie mounting on to the locomotive and traction motor mounting on to the bogie.
- With modern traction electronics with advanced microprocessor control, it is possible to identify the transient conditions of weight transfer on each axle and reduce or increase the TE as required, which requires individual axle control.

Better weight distribution can be achieved with good mechanical design including:

- traction motor mounting – creating a couple that counteracts the 'weight transfer' movement between bogie and locomotive for example, for 3-axle bogies mounting traction motors behind of wheelsets on the leading bogie and in front of the wheelsets on the trailing bogie
- relatively stiff secondary suspension pads that are as widely spaced as practicable between the bogie and locomotive bodies to reduce bogie movement (a compromise with minimising track forces geometry)
- king pin geometry with the mounting as low (as close to the rail head) as possible, which reduces both rotational forces and movement.

14.6 Early traction electrical systems and traction control systems

Diesel electric locomotives traditionally have had traction electrical systems with DC traction motors because of the ability to control the power and speed of the motor, unlike other technologies at the time. Early diesel electric locomotives had generators attached to the diesel engines providing a DC power supply without the need for rectification. Later DC diesel electric locomotives have alternators attached to the diesel engines providing a more powerful and uniform AC power supply which then needs rectification to convert the current to DC for use in the traction motors. Older AC electric locomotives had complex electro-mechanical systems that control the outputs from multiple secondary transformer windings to attempt to control the power supplied to single-phase AC traction motors. While these systems are simple and relatively effective (and were sensible design choices at the time), they do not produce a constant motor torque since motor power is the product of motor torque and speed. Therefore, the relative tractive effort delivery varies significantly for each throttle setting depending on speed, making it impossible to obtain maximum adhesion. Two strategies have been deployed to improve the performance of these simple traction systems:

- changing the way in which the traction motors are connected depending on speed
- changing from a fixed linkage between motor stator and rotor voltage to some degree and allowing variation between the two.

The first is applicable to diesel electric locomotives and the second to both diesel electric and older single-phase AC electric locomotives.

The first strategy involves enabling the traction motors to be connected in different combinations to maximise performance across the locomotive speed range so that the generator/alternator can better match the current the traction motors can take at a given speed:

- series (all traction motors connected in series to the alternator)
- parallel (all traction motors connected in parallel to the alternator)
- series-parallel (where a group of 2 or 3 traction motors are connected in series, with these 2 or 3 groups of motors then connected in parallel to the alternator).

Series-parallel is typically used at low speeds, up to circa 20 mph, then a transition to all motors being fully parallel. Reconnection of the traction motors transitions from pairs in series, with each pair in parallel, to all in parallel. On older current locomotives (for example, Class 59) the transition is managed by large contactors in the traction electronics and on slightly newer DC locomotives the transition is achieved using contactors in the traction alternator that change the connections between the alternator windings (for example, Class 66) which is more efficient (especially in lower power notches) and results in smoother transitions.

The second strategy involves breaking the direct linkage between the traction motor stator and field voltages. In older motors the current flows sequentially through both stator and rotor. This works well enough at low and mid motor speeds, but as the motor speeds increase, the back EMF produced in the stator winding increases, consequently reducing locomotive performance. A frequently utilised approach to ameliorate this effect is to reduce the stator or field voltage at higher motor speeds (equivalent to above 70-75% of the maximum locomotive speed) and is often referred to as field weakening or weak field mode. This is used on both older DC diesel electric locomotives used for freight (for example, Class 20 to Class 58) and single-phase AC traction motors (for example, Class 86 and 90). An alternative approach is only to use the motor at speeds up to the critical threshold, that is, below ~75% of the maximum motor speed by selecting the gearing ratio between the motor and wheelset so that the maximum locomotive speed is ~75% of the maximum motor speed. This approach has been used on Class 43, 59, 66, and 67 locomotives but reduces the mid-speed range tractive effort (and train acceleration) compared to what it could be if a weak field mode was available. A further step involves completely breaking the link between rotor and stator voltages and current by controlling them independently of each other, which is usually called separate excitation (SepEx). This requires relatively modern microprocessors and power electronics (thyristors or newer) as a prerequisite. With SepEx each motor stator and rotor are individually controlled with no series, parallel or series parallel motor connection changes which no longer limits the traction performance of the locomotive or bogie to the performance of the worst wheelset and traction motor, substantially increasing achievable adhesion levels and tractive effort. In India, SepEx DC motors with slip-slide control can enable adhesion of 0.38 to be regularly attained in real use, which is higher than the 0.33 for mainline and 0.30 for secondary route values used in MT19.

14.7 AC traction electrical systems and traction control systems

AC drives, also known as Variable Voltage and Frequency Drives (VVFDs by electrical engineers), Variable Voltage and Speed Drives (VVSDs in applications sales literature) or three-phase drives, have been the standard for new equipment designs both inside and outside the rail industry for over two decades. Starting first in Europe and Japan, these were then adopted later elsewhere for both diesel electric and electric locomotives. The AC drive works by converting the traction alternator output (in diesel locomotives where the AC frequency is a function of engine rpm) or transformer output (in AC OHLE locomotives with single-phase mains frequency AC) to DC and then reconverting this to three-phase AC with variable voltage and frequency which powers the three-phase AC traction motors.

Most rail traction motors used with three-phase VVFDs are asynchronous induction motors. With induction motors the electric current in the rotor needed to produce torque is obtained by electromagnetic induction from the magnetic field of the stator winding without the need for electrical connections to the rotor (for example, no commutator). As AC motors operate at approximately the frequency of the current, the drives must adjust the frequency so that the motors can have a speed range of zero to maximum rpm and suitably match the motor speed to the train speed as appropriate. In asynchronous induction motors the number of rotor elements is greater than the number of stator windings; for example, for a 4-pole three-phase motor there are 12 stator windings but typically 14 rotor elements, or for 6-pole three-phase motors there are 18 stator windings but typically 20 rotor elements (for example, Figure 62). This mismatch in the number of rotor and stator elements combined with skew setting of the rotor elements enables a more continuous even torque to be provided by the motor which helps with achieving higher adhesion in practice. However, due to the mismatch in the number of rotor and stator elements with asynchronous motors, the AC frequency supplied by the VVFD to the motor needs to be either slightly higher when increasing or maintaining the motor speed or slightly lower when actively reducing the motor speed (braking) with the precise amount depending on the motor characteristics and geometry. Typically, the ideal frequency mismatch between the supplied frequency and rotor frequency / rotational speed is 7-9% for 4-pole motors and 5-7% for 6-pole motors.

The rotating magnetic field spins faster than the motor is turning, which means the rotor cannot exceed the stator field speed for more than a very short period as the torque quickly reduces (the torque can fall by circa 10% if the rotor speed increases by just 1% above the maximum torque speed), thus inherently limiting the potential for wheel slip compared to DC traction systems. This means that accurate and fast wheel and ground speed (radar) measurement is required for VVFD operation to set the stator field rotation speed. This is illustrated in Figure 6362 by a typical motor torque versus relative stator field rotation speed curve where the peak motor torque occurs at ~96% of the stator field rotation speed and the torque rapidly reduces as the rotor speed diverges from the optimum. This also enables target running speeds to be easily set making ETCS implementation easier and potentially more beneficial.

Figure 62 Illustration of 6-pole 3-phase asynchronous motor, with 18 rotor elements and 20 rotor elements, a common arrangement for larger freight locomotive AC traction motors.

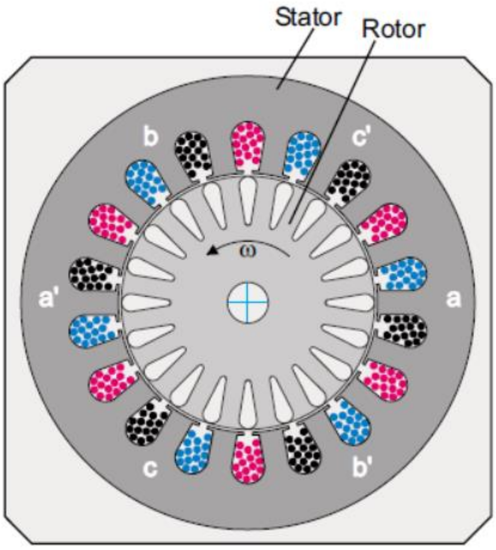
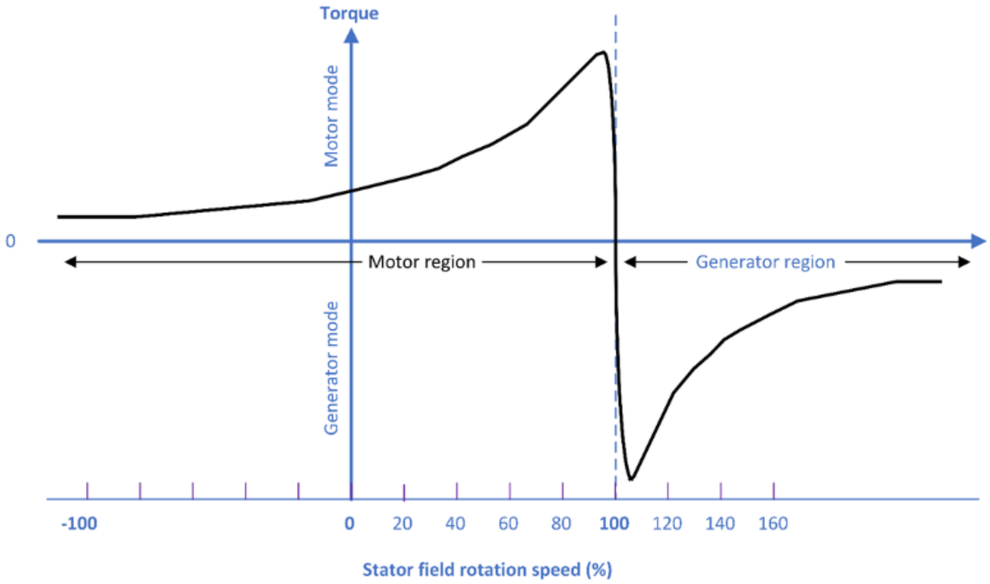


Figure 63 Illustration of the shape of the torque vs relative stator field rotation speed curve for a 6-pole 3-phase asynchronous motor illustrated in Figure 62 above.



RAIL SAFETY AND STANDARDS BOARD

Summary of why asynchronous 3-phase motors can have higher µ:

- Very precise control of motor torque and motor rpm (with the desired rpm includes assumptions about controlled slip rates at the wheel for different train speeds and rail head conditions) at high power levels.
- An automatic natural rapid reduction in motor torque if the motor rpm moves away from the set rpm providing good innate first order wheel slip and slide protection (for both power application and rheostatic or regenerative braking).
- The maximum torque variation with rpm is much smaller than for other motor types leading to a more uniform performance, with better torque performance where other motor types often have reduced performance.

14.8 Individual axle control

To reduce cost and complexity, some early VVFD systems utilised one drive unit per bogie rather than the current practice of one drive unit per traction motor (individual axle control), with the penalty of no compensation for weight transfer. All recent designs (or design iterations) in the last 10-15 years globally have utilised individual axle control due to the increased adhesion and tractive effort and maintenance reduction benefits.

There are three primary reasons that AC traction offers much more adhesion than DC traction systems.

First, in a standard DC drive, if wheel slip occurs, there is a tendency for the traction motor to speed up and run away if the load is not quickly reduced. As the wheel slippage increases, the coefficient of friction also drops rapidly to a level of 0.10 or less, and because all the motors are connected together (either in parallel or series-parallel), the load to all the locomotive's traction motors must be reduced. Therefore, maximum adhesion in practice is obtained by operating at a level with a comfortable margin below the theoretical maximum. More modern DC systems incorporate a wheel slip control which senses the beginning of a slip and automatically modulates the power in order to retain control. This allows the locomotive to operate safely at a point closer to its theoretical maximum (although not as close as with VVFD and individual axle control). The AC system, however, operates in a very different fashion. The VVFD creates a rotating magnetic field which in traction mode spins a few percent faster than the motor is turning. Since the rotor cannot exceed the stator field speed for any substantive period, any wheel slip is inherently minimal and as the motor torque automatically reduces. Hence wheel slip protection systems and traction control systems on locomotives with VVFD and individual axle control are of a more secondary nature to prevent recurrence of the slip. Slippage is prevented in the first place by monitoring wheel creep virtually instantaneously, thus accurately allowing the creep to be optimised to maximise adhesion in practice. Repeat slippage can be prevented by reducing the rate of increase of motor torque as it is increases again post slippage.

Second, the DC locomotive typically has a number of throttle settings with a set power level for each one. While this system is simple and effective, it does not produce a constant motor torque since motor power is the product of torque and speed. Therefore, the tractive effort varies significantly due to torque variation for each throttle setting depending on speed, making it impossible to obtain maximum adhesion under most conditions. AC traction locomotives with VVFD and individual axle control, however, can control to a specific motor torque level, allowing the tractive effort to be essentially constant at the higher range of available adhesion. This fast-acting inherent wheel slip control can counteract any wheel slip that occurs so that the torque level can be set close to the upper limits.

The third way that AC traction provides improved adhesion is through weight transfer compensation. When a locomotive is applying power and pulling a load, weight tends to transfer from the front axle to the rear axle of each bogie. At maximum tractive effort, the weight on the lead axle may be reduced by about 20%. Since overall locomotive tractive effort is proportional to the weight on the driven wheels, than in a DC system where the motors are fed from a common source, the tractive effort will be determined by the lightest axle fed by that source. Thus, in effect, the equivalent locomotive adhesion weight is reduced by circa 20%. With an AC system with individual axle control, however, the drive is able to almost directly compensate for the weight transfer. When the lead axle goes light, the AC drive system will reduce power to that axle and apply more power to the rear axle on the bogie without incurring wheelspin.

14.9 Braking

With AC traction, it is also important to consider braking. As with traction, braking is a function of weight on the wheels. Therefore, when using standard locomotive friction braking (tread or disc brakes) the braking capability of the locomotive (excluding train braking) is proportional to the locomotive weight. With AC traction, however, the regenerative or rheostatic braking can be much higher because the drive system during braking acts in a very similar way to traction use, thus eliminating wheel slip. The drive converts the motors to generating mode with the electricity produced dissipated in the braking resistors (rheostatic braking) or else transferred to batteries or back to the OHLE supply (regenerative braking). Thus, the motors can slow the locomotive without using the air brakes.

14.10 AC/DC traction motor comparison

With AC traction systems, the adhesion levels are much higher than DC, so the locomotive can again be significantly lighter for the same amount of braking. The dynamic braking in AC traction locomotives also allows braking down to almost zero speed, unlike DC rheostatic or regenerative braking.

AC traction for locomotives is a major improvement over the old DC systems. The primary advantages of AC traction are adhesion levels up to 100% greater than DC and much higher reliability and reduced maintenance requirements as there are no commutators and carbon brushes and wheel wear can be lower.

14.11 Gearing

Three-phase AC traction motors typically rotate at higher speeds (typically up to 50% higher) than their DC equivalents, which results in the selection of higher gearing ratios than for DC traction motors for the same maximum locomotive speed. The increase in gearing ratio effectively requires a smaller number of teeth on the pinion (motor) gear and a larger number of teeth on the wheel set gear. Straight-cut gears have traditionally been used due to their theoretically high efficiency and ease of manufacture. The transfer of torque through gears varies slightly with time as the contact points and geometry between the teeth changes with rotation. When $\mu_{achieveable} \ll \mu_{max}$ this torque variation is not a factor in overall locomotive adhesion; however, with modern traction systems when the difference is much smaller, minimising this variation in torque due to gearing factors can become important, so manufacturers have tended to use helically cut gears, either single or double (herring bone), on newer locomotive designs to improve adhesion and reduce gear wear.

14.12 Steerable bogies

Steerable bogies significantly reduce the level of wheel slip, since the radial position the wheelsets adopt relative to track curvature minimises the creep forces arising from curving at the contact patch, and thus increases the amount of creep attributable to traction that can be achieved before the contact patch is saturated. A much lower coefficient of friction is thus required on these locomotives to achieve the same trip reliability.

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