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VTISM Analysis to Inform the Allocation of Variable Usage Costs to Individual Vehicles

Prepared for	Network Rail
Prepared by	Serco
Your Reference	2013 Periodic Review (PR13) of Variable Usage Charge (VUC) Model
Our Reference	SERCO/RAIL/E.006488/001 Issue 1
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Executive Summary

Serco Technical Services – Rail have undertaken a study on behalf of Network Rail, using the Vehicle Track Interaction Strategic Model (VTISM) to inform the allocation of total variable usage costs between passenger and freight vehicle types on a national average basis.

The work was focused on the track impact costs associated with vertical forces only (which account for approximately 70% of total track variable costs). Network Rail have carried out a separate internal study of the horizontal (rail RCF and wear-related) costs. This work will inform the variable usage charges (VUCs) payable by passenger and freight train operators in Control Period 5 (CP5), commencing 1 April 2014.

The remit for this work was developed in consultation with an industry working group (ATOC, freight operators and ORR). The Vehicle Track Interaction Strategic Model (VTISM) was used in the study given its capability to assess how changes to vehicle characteristics can affect track renewal, maintenance and inspection costs. VTISM was developed on behalf of the Vehicle/Track Systems Interface Committee (V/T SIC) by RSSB and Network Rail to support the rail industry in managing changes around the interface more effectively and to realise savings through optimised track and vehicle maintenance and renewal. It links inputs such as track and vehicle characteristics to outputs such as whole life costs, asset life, future condition and performance.

VTISM's track damage models simulate the deterioration of rail, sleepers and ballast on plain-line and switches and crossings given the contribution of vertical and lateral forces from each axle that passes over the track. The original models were based on BR Research in the late 1980s and developed further as part of a European collaborative research project known as EUROBALT (European Research Project for Optimised Ballasted Tracks) up to 2001. The early models formed the basis of the original 'Mini-Marpas' model that was used in a parametric study to derive the track damage formula used in CP4 and earlier control periods. The latest version of VTISM (2.7) used in the study contains validated track deterioration and cost model relationships (for vertical and horizontal damage) accounting for the majority of Network Rail's track renewals, maintenance and inspection activities and costs. It was also updated for the study, to include a snapshot of the latest track asset, condition and traffic data obtained early in 2012.

The VTISM-derived track impact (vertical damage) cost is the bottom-up cost associated with track renewals, maintenance and inspection, which serves to show the relative vertical damage impact between vehicles with different characteristics. It is not a track access charge; this will be determined by ORR following a separate exercise by apportioning the pre-determined total variable usage costs using the revised formula derived in this study based on the VTISM results. It should be noted that that the total track variable usage costs to be apportioned were also estimated using VTISM.

VTISM was used to re-calibrate the previous CP4 track VUC equation, shown below:

Equivalent Track Damage = $Ct.A^{0.49}.S^{0.64}.U^{0.19}$ *(per tonne.mile).GTM where,*

Ct is 0.89 for loco-hauled passenger stock and multiple units, and 1 for all other vehicles, A is the axle load (tonnes), S is the vehicle operating speed (miles/hour), U is the un-sprung mass (kg/axle) and GTM is the Gross Tonne Miles.

Using VTISM, a hybrid formula (with 77% degree of fit) based on axle load, operating speed and un-sprung mass was defined, as follows:

Proposed VTISM-derived track damage formula based on a hybrid fit:

Relative damage (per axle.mile) $= 0.473.e^{0.133A} + 0.015.S.U - 0.009.S - 0.284.U - 0.442$

where:
A = Axle load (tonnes), within the range: 5 to 25 tonnes
S = Operating speed (mph), within the range: 25 to 100 mph
U = Un-sprung mass (tonnes / axle), within the range: 1 to 3 tonnes

Note that the number of significant figures of the parameters ensures precision in the use of the formula and avoids rounding errors but does not reflect the accuracy of the formula. An alternative VTISM power formula was also derived to enable a comparison of the exponents with the previous CP4 power formula as shown in Table 1, however, it must be noted that it has a slightly lower degree of fit of 75%, compared with the hybrid formula:

Parameter	Exponents (per axle.mile)	
	CP4 power formula	VTISM power formula
Axle load	1.49*	1.71
Operating speed	0.64	0.27
Un-sprung mass	0.19	0.31

*Note *: The axle load exponent of 0.49 is used when the formula is expressed in terms of per tonne.mile and 1.49 when expressed in terms of per axle.mile, given that there is an additional axle load multiplier in GTM.*

Table 1. Comparison of power fit exponents from the VTISM-derived formula and CP4 formula

The hybrid formula is considered to be more appropriate than the power formula because of its higher degree of fit and stronger correlation to the VTISM results. The power formula has a weaker correlation to VTISM data, particularly at higher relative damage values. Therefore, it is recommended that the hybrid formula is used in the CP5 VUC apportionment process.

The VTISM results and associated formulae show that damage is more sensitive to axle load and un-sprung mass and less sensitive to vehicle speed, compared with the previous CP4 formula. Therefore, the impact of the proposed hybrid formula on a range of passenger and freight generic vehicles was assessed. The main change is that vehicles with a high axle load or un-sprung mass would attract a greater share of the variable usage costs than in CP4 and vehicles with a high operating speed would attract a smaller share, all other things being equal. In general, it is most probable that heavy freight traffic will attract more cost and high speed trains will attract less cost. This can be confirmed after the relative damage indices for all vehicles and their traffic contribution have been determined.

A secondary aspect of the study was to briefly review whether the existing approach to apportioning non-track variable usage costs (relating to wear and tear of civils engineering and signalling assets) continues to be broadly fit for purpose and, if not, propose a revised approach. The review was based on discussions held with Network Rail's civils and signalling representatives and takes into account the views expressed during 1-2-1 meetings with RFOA, ATOC and ORR:

i. For civils assets, the existing civils equation should only be applied to metallic underbridges, using a modified axle load exponent of 4 (rather than the existing higher value of 4.83, noting this includes the axle load component of Gross Tonne Miles (GTM)), which is more consistent with Euronorm standards. Therefore, the exponent to use in the VUC equation (per tonne.mile) would be 3. The axle load and speed exponents cannot be justified for application to other civil asset groups: brick and masonry underbridges, embankments and culverts and therefore it would more applicable to use the revised track VUC hybrid equation based on VTISM analysis as its provenance is known. Further research and development of a vehicle-structures model is recommended in time for the next review in CP6, with priority for the highest cost brick and masonry underbridge renewals.

ii. For signalling assets, it would be suitable to apply the revised track VUC hybrid equation for a proportion (50%) of the variable costs that are load-related with the remaining costs apportioned by train movements (vehicle mileage). Further research and development of signalling asset models is recommended, in time for CP6.

iii. It is recommended that a consistent approach is used to determine freight and passenger vehicle respective operating speeds (i.e. all passenger vehicle operating speeds should be determined on the same basis and all freight vehicles should be determined on the same basis). Also, if the relevant operational data is available, then there would be merit in reviewing whether the existing vehicle operating speeds used in the charging model continue to be broadly appropriate.

Contents

Acronyms and Abbreviations

AREMA	American Railway Engineering and Maintenance-of-Way Association
ATOC	Association of Train Operating Companies
BR	British Rail
CP	Control Period
EUROBALT	European Research Project for Optimised Ballasted Tracks
GTM	Gross Tonne Miles
MGTPA	Million Gross Tonnes Per Annum
ORR	Office of Rail Regulation
RCF	Rolling Contact Fatigue
RFOA	Rail Freight Operators Association
ROSCO	Rolling Stock Operating Company
RSSB	Rail Safety and Standards Board
S&C	Switches and Crossings
TOC	Train Operating Company
T-SPA	Track Strategic Planning Application
VTISM	Vehicle / Track Interaction Strategic Model
V/T SIC	Vehicle / Track System Interface Committee
VUC	Variable usage charge
WLRM	Whole Life Rail Model

1 Introduction

Serco Technical Services – Rail have undertaken a study on behalf of Network Rail, using the Vehicle Track Interaction Strategic Model (VTISM) to inform the allocation of total variable usage costs between passenger and freight vehicle types on a national average basis.

The work is focused on the track impact costs associated with vertical forces only (which account for approximately 70% of total track variable costs). Network Rail have carried out a separate internal study of the horizontal (rail RCF and wear-related) costs. This work will inform the variable usage charges (VUCs) payable by passenger and freight train operators in Control Period 5 (CP5), commencing 1 April 2014.

The remit for this work was developed in consultation with an industry working group (ATOC, freight operators and ORR), who agreed that the Vehicle Track Interaction Strategic Model (VTISM) was the best tool available for this type of assessment. VTISM was selected for the study given its capability to assess how changes to vehicle characteristics can affect track renewal, maintenance and inspection costs. VTISM was developed on behalf of the Vehicle/Track Systems Interface Committee (V/T SIC) by RSSB and Network Rail to support the rail industry in managing changes around the interface more effectively and to realise savings through optimised track and vehicle maintenance and renewal. It links inputs such as track and vehicle characteristics to outputs such as whole life costs, asset life, future condition and performance.

A secondary aspect of the study was to briefly review whether the existing approaches to apportioning non-track variable usage costs (relating to wear and tear of civils engineering and signalling assets) and estimating vehicle operating speed continue to be broadly fit for purpose and, if not, propose a revised approach. The review is based on discussions held with Network Rail civils and signalling representatives and takes into account the views expressed during 1-2-1 meetings with industry stakeholders, RFOA, ATOC and ORR.

The report contains:

- An overview of the VTISM model, its capability and key stages involved in performing a scenario projection (Section 2).
- The methodology adopted in setting up VTISM for this particular study, the results and subsequent development of a revised algebraic function for track damage (Section 3).
- A review of the existing approach to apportioning non-track variable usage costs and estimating vehicle operating speed (Section 4).
- Conclusions and recommendations (Section 5).

1.1 Project aims and objectives

The aim of this work is to inform the allocation of total variable usage costs (excluding horizontal track costs) between passenger and freight vehicle types on a national average basis. A breakdown of total variable usage costs, based on end CP4 traffic levels is set out in Table 1 below.

Asset type	Costs (£M per year)
Track:	**242.4**
Track maintenance and renewals	242.4
Civils:	**25.5**
Embankments renewals	1.9
Metallic underbridge renewals	9.7
Brick and Masonry underbridge renewals	13.3
Culverts renewals	0.5
Signalling:	**13.6**
Maintenance	8.2
Minor works points renewals	5.4
Total	**281.5**

Table 1. Breakdown of variable usage costs

The study was driven by the following objectives:

1. To use VTISM to establish and validate an algebraic function describing the relationship between vertical track damage cost and the following key vehicle parameters that are the dominant drivers of track deterioration and associated renewal, maintenance and inspection cost:

    a. Axle load
    b. Operating speed
    c. Un-sprung mass

    Previous control periods included the above parameters within a track damage formula that was based on a parametric study using earlier BR-research track damage models. Therefore, the objective is to effectively re-calibrate the relationship between these parameters and cost using the current models and track asset data within VTISM.

2. To review the approaches and formulae used for apportioning the variable usage costs of civils and signalling assets, covering:

    a. The historical basis of the equation used for apportioning civils costs between individual vehicles and the method of apportioning signalling costs according to track costs.
    b. Advantages and disadvantages of the current methods.
    c. Recent research workstreams undertaken that link vehicle impact to civils and signalling asset deterioration.
    d. Further research needed and / or aspirations for future methods of apportionment.

3. To review the approach to determining ‘vehicle operating speed’, which in CP4 was the distance-based average speed of a vehicle that is input to the formulae used for track, civils and signalling cost apportionment.

2 Overview of VTISM Model

This section provides an overview of the VTISM vision and capability and a brief insight into the track damage models and operation of the software.

2.1 Vision and capability

The development of the Vehicle Track Interaction Strategic Model (VTISM) is a significant research programme, led by the Vehicle/Track Systems Interface Committee (V/T SIC) and managed by RSSB. VTISM aims to support the rail industry in managing changes around the interface more effectively and to realise savings through optimised track and vehicle maintenance and renewal. It has been developed and validated in stages involving stakeholder input, review and acceptance from across the rail industry (ref. VTISM Stage 1 Research Brief[1], VTISM Stage 2 Summary Report[2] and VTISM Stage 2 Research Brief[3]) and the software has been developed to ISO9001 / TickIT quality assurance standards. It links inputs such as track and vehicle characteristics to outputs such as whole life costs, asset life, future condition and performance. Since its release to the rail industry in 2006, VTISM has been used in numerous applications by different organisations as summarised in Table 2.

VTISM was specifically designed for the assessment of the impact of trains (train configuration, vehicle and bogie designs) on track damage cost and was used by DfT, Network Rail and train manufacturers as part of the Intercity Express Programme (IEP) and Thameslink rolling stock procurement programmes.

VTISM users	Example applications
Network Rail	• Setting route strategies for track • Estimating total VUC costs based on marginal traffic increases (+5%,+10% and +20%) • Optimising grinding and lubrication
Department for Transport	• Evaluating new rolling stock bids • Calculating indicative maintenance costs • Evaluating routes for cascading trains and potential vehicle modifications
Office of Rail Regulation	• Evaluating network and route strategies • Developing track access charges
Vehicle manufacturers	• Evaluating different train configurations - e.g. axle load distribution, traction arrangement, bogie parameters, etc.
Vehicle maintainers, TOC's and ROSCO's	• Optimising maintenance decisions - e.g. mileage between re-profiling • Balancing corrective and preventive maintenance • Optimising overhaul periods • Determining the size of wheelset float
RSSB, universities and other rail research organisations	• Train mass sensitivity study • Analysis of whole life costs associated with different track quality improvement techniques • Specific route / vehicle studies

Table 2. VTISM users and applications

Figure 1 shows the vision for VTISM. At the centre of the vision is the basic science that describes vehicle / track dynamics. VTISM is about assessing consequences of scenarios based around renewal and maintenance policies or changing vehicle characteristics and train service patterns. The vision is to capture the consequences of these scenarios in economic terms for both the trains and the track to provide a whole-life, whole-system cost modelling tool. By understanding the impact of changes to subsystems on the wheel-rail system it will enable substantial savings to be made.

The vision has been realised to the extent that the latest version of VTISM (2.7) incorporates:

- Validated track deterioration and cost model relationships (for vertical and horizontal damage) accounting for the majority of Network Rail's track renewals, maintenance and inspection activities and costs. The vertical damage modelling capability has been applied in this study.

- A new wheelset management model developed during 2011/12, which extends VTISM capability on the fleet maintenance side, to enable modelling of wheelset deterioration, maintenance and renewal based on track characteristics. Conversely, it enables modelling of the impact of different wheelset management strategies (e.g. time-based vs condition-based wheel turning) on wheel profile distribution and its impact on track deterioration and (rail wear and RCF) costs.

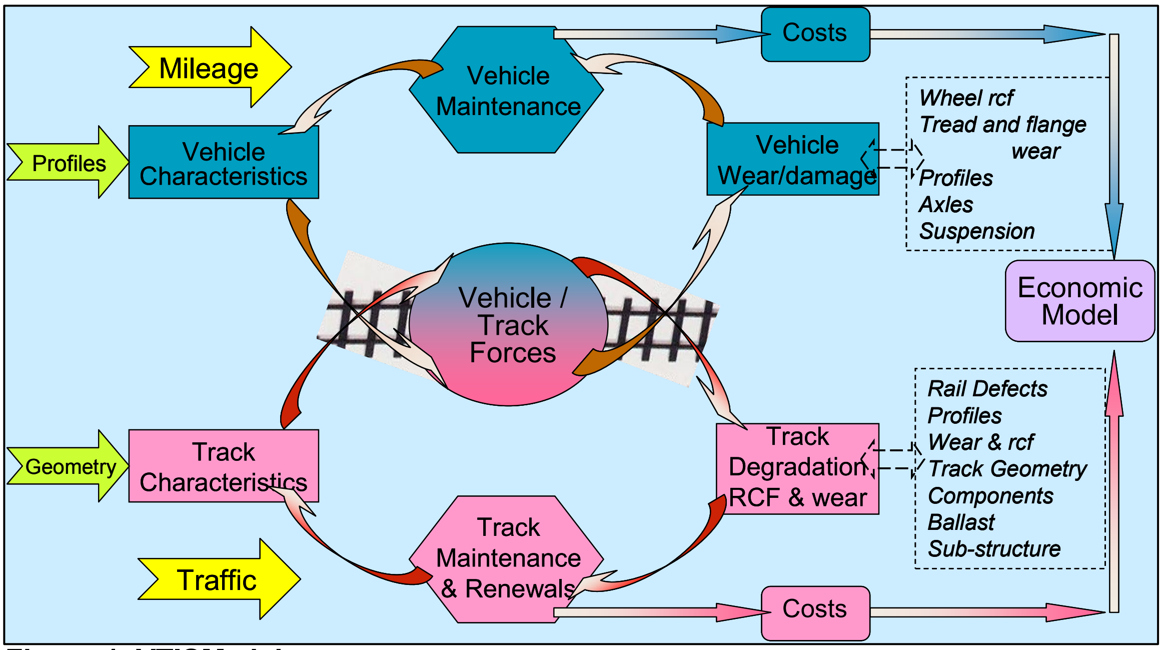

Figure 1. VTISM vision

2.2 VTISM track damage and cost models

VTISM's track damage models simulate the deterioration of rail, sleepers and ballast on plain-line and switches and crossings given the contribution of vertical and lateral forces from each axle that passes over the track. The original models were based on BR Research in the late 1980s and developed further as part of a European collaborative research project known as EUROBALT (European Research Project for Optimised Ballasted Tracks) up to 2001. The early models formed the basis of the original 'Mini-Marpas' model that was used in a parametric study to derive the track damage formula used in CP4 and earlier control periods, as follows:

*Equivalent Track Damage = Ct * $A^{0.49}$ * $S^{0.64}$ * $U^{0.19}$ (per tonne.mile) * GTM where,*

Ct is 0.89 for loco-hauled passenger stock and multiple units, and 1 for all other vehicles, A is the axle load (tonnes), S is the vehicle operating speed (miles/hour), U is the un-sprung mass (kg/axle) and GTM is Gross Tonne Miles.

Further track damage model research, development and validation studies have been undertaken by Network Rail and RSSB as part of VTISM-related developments since 2002. The vertical track damage and cost models (applied in this study) contain complex relationships and the main elements are briefly summarised as follows:

- Vertical track geometry model – this models the deterioration of the vertical geometry due to settlement of the ballast from traffic load (measured as the standard deviation over 1/8th mile) and its restoration by maintenance (tamping and stoneblowing) or renewal. The model takes into account the gradual build up of fines in the ballast (from traffic, the environment or from tamping restoration) which prevents the geometry from being fully restored to its original state. The general form of geometry deterioration is highly non-linear with contributions from static load and dynamic (ride) forces associated with the vehicle and its axles. The main components of the forces are axle load, speed and un-sprung mass.
- Rail defect model – this models the accumulation of defects (cracks) and breaks in the rails and their removal by maintenance (weld repair or rail changing) or rail renewal. The model contains an exponential relationship with cumulative tonnage and a linear relationship with vertical geometry.
- Track damage and other parameters drive the maintenance, renewal and inspection work activities according to engineering standards (e.g. track quality standards) and asset policies (e.g. rail grinding frequency) and there are complex interactions between the maintenance and renewals requirements.
- VTISM operates as a bottom-up tool as it can simulate the life (deterioration of condition parameters and the maintenance and renewal actions) of each track section individually from a base year up to, for example, a 60 year projection period in monthly increments. A network wide track asset database is regularly updated to provide a current snapshot of track characteristics (rail, sleeper, ballast, switches and crossings type and age, curvature, condition, traffic levels, etc.). The database holds some 600,000 track sections of varying length covering ~19,300 miles of operational GB railway track, which includes ~800 miles of switches and crossings. Predicted work volumes (e.g. mileage of complete track renewal, tamping, rail renewal, etc.) are converted to costs via standard Network Rail unit costs.

In addition to the VTISM Stage 1 Research Brief[1], VTISM Stage 2 Summary Report[2] and VTISM Stage 2 Research Brief[3] provided by RSSB, VTISM's user documentation and training course material provides further information on the nature of the models and more in-depth technical basis documentation is also available from RSSB and Network Rail.

2.3 VTISM software

VTISM itself is a collection of integrated software modules, including databases, calculation software and user defined renewal and maintenance policy criteria, as shown in Figure 2. These are all held on a single PC, and can be accessed using a single software application and user interface. VTISM is distributed on a software installation DVD.

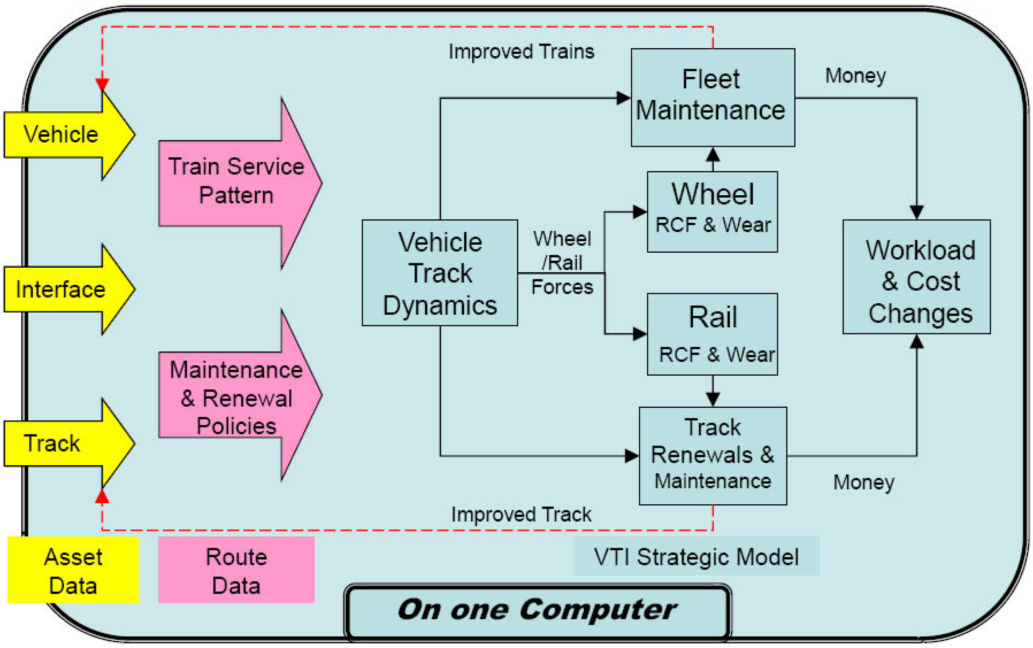

Figure 2. VTISM components

The key stages in performing a VTISM simulation are shown in Table 3.. The process essentially allows the VTISM user to define an investment scenario in terms of a specific route section, traffic / vehicle conditions and track renewals and maintenance strategy, over a defined future investment period, e.g. 30 years. The model then simulates deterioration of individual track sections and renewal and maintenance according to the defined strategy. The total discounted renewal and maintenance costs can then be compared with alternative scenarios, for example:

- Revised traffic levels, modified vehicle / axle / suspension characteristics or rolling stock replacement
- Track replacement with alternative rail, sleeper or ballast design / performance characteristics
- Alternative renewal, maintenance and inspection strategies
- Alternative unit cost assumptions and discount rates

Stage	Description
1. Create / select project file	Create a VTISM project file – e.g. create a new project, open an existing project.
2. Define route	Define route – e.g. East Coast Mainline up line or network sample.
3. Define vehicle characteristics and traffic	Define vehicles and traffic on selected route / track sections, e.g. current or revised future traffic levels and / or replacement rolling stock.
4. Analyse lateral track forces	Run vehicle dynamics software (e.g. VAMPIRE® Pro) to create lateral track forces (Tgamma) data for specified track conditions and vehicles / bogies. This stage can be done outside VTISM, but VAMPIRE® results must be registered within VTISM.
5. Simulate rail RCF and wear on the route	Run the Whole Life Rail Model (WLRM) software to calculate rail RCF and wear rates using the selected traffic / track data and lateral track forces outputs, ensuring track features are correlated with forces data via route curvature matching.
6. Analyse vertical track forces	Run the Track Strategic Planning Application (T-SPA) vertical geometry pre-processor to calculate the vertical geometry forces and geometry progression parameters based on traffic and track data.

Stage	Description
7. Simulate track deterioration, work volumes and costs over time	Run T-SPA – Define renewal, maintenance and inspection activities and required budget / volume constraints and run a simulation over a defined future investment period, e.g. 30 years, to calculate track deterioration parameters and future work volumes and costs.
8. Summarise results	Analyse results (aggregated work volumes and costs, per track mile, per train mile, discounted, etc. over specific periods) and compare alternative investment scenarios.

Table 3. Key stages in performing a VTISM simulation

3 VTISM Analysis of Track Variable Usage Costs

3.1 Methodology

VTISM was setup to run several variant cases for axle load, operating speed and un-sprung mass to enable a robust relationship between these input parameters and cost to be determined. A total of 48 variant cases were needed to support curve-fitting, based on the following combinations:

a. 4 axle load variants (5, 10, 17.5 and 25 tonnes)
b. 4 operating speed variants (25, 50, 75 and 100 mph)
c. 3 un-sprung mass variants (1,000, 2,000 and 3,000 kg)

The following steps were required in setting up the track, traffic and vehicle inputs and running the simulations.

Step 1. Selection of representative track

A representative sample of the GB rail network (from the total ~19,287 track miles, comprising 18,467 miles of plain-line track and 820 miles of S&C) was randomly selected from the VTISM track database, ensuring that:

1. It was based on a representative, average-based sample of the network in terms of route, track construction, condition and traffic (i.e. vehicle type mix and associated annual tonnage levels). It is important to sample average traffic and establish an average tonnage in order for the analysis to be based on normal parameter ranges within the track damage relationships, producing a representative cost impact for each variant case.

2. It was not biased towards higher speed or higher tonnage track, such as that represented by the VTISM standard routes: MML and SWML respectively.

3. It was a sufficiently large enough sample to represent the total network, whilst giving acceptable processing run times. Several test cases were carried out which concluded that a 5% sample provided acceptable accuracy (within 1.5% accuracy of analysing the full network) and run times.

4. It took into account the need to exclude track sections with a line speed that is lower than the vehicle speed to be analysed, otherwise lower forces and costs would be generated (given the minimum of the line speed and vehicle speed is used in calculating forces). Therefore, four track databases were created to filter the line speeds, one each for the four vehicle speed steps (25, 50, 75 and 100 mph) to be assessed. Given that the available mileage for sampling varies across the speed range (i.e. clearly there is less track with 100 mph or greater line speed compared with 25 mph or greater), the sampling frequency was adjusted in order to produce the necessary overall minimum 5% of mileage in each line speed sample (approximately 923 miles (5%) of plain-line and 50 miles (6%) was selected for each line speed sample). Note that VTISM models whole S&C units comprising one or more sections (e.g. through line and turnout), therefore, this mileage is the total S&C unit mileage where the through line speed has been filtered. Table 4 shows the sampling frequencies used and Table 5 shows the distribution of route type mileage (primary, secondary, rural and freight) across the network and in each line speed sample. This confirms that the line speed samples closely reflect the network distribution of route types.

Line speed sample	Plain line		S&C	
	Available network mileage	Sampling frequency (1 every x sections)	Available network mileage	Sampling frequency (1 every x sections)
>=25 mph	17,555	19.0	694	13.9
>=50 mph	15,369	16.6	502	10.0
>=75 mph	8,675	9.4	280	5.6
>=100 mph	3,267	3.5	105	2.1

Table 4. Plain-line and S&C track section sampling frequencies

Line speed sample	Route type	Network				Sample			
		Plain line mileage	S&C mileage	Plain line % of network total	S&C % of network total	Plain line mileage	S&C mileage	Plain line % of sample	S&C % of sample
>=25 mph	Primary	5,925	320	34%	55%	313	26	34%	52%
	Secondary	8,624	215	49%	37%	455	19	49%	38%
	Rural	2,333	22	13%	4%	124	2	13%	5%
	Freight	673	23	4%	4%	35	3	4%	5%
>=50 mph	Primary	5,557	186	36%	58%	335	28	36%	57%
	Secondary	7,778	118	51%	37%	466	18	50%	37%
	Rural	1,825	11	12%	4%	109	2	12%	4%
	Freight	209	5	1%	1%	13	1	1%	2%
>=75 mph	Primary	4,875	120	56%	76%	519	37	56%	73%
	Secondary	3,486	36	40%	23%	375	12	41%	24%
	Rural	277	1	3%	1%	28	0	3%	1%
	Freight	36	1	0%	1%	4	1	0%	1%
>=100 mph	Primary	3,019	56	92%	96%	855	47	92%	94%
	Secondary	248	2	8%	4%	69	2	8%	5%
	Rural	0	0	0%	0%	0	0	0%	0%
	Freight	0	0	0%	0%	0	0.3	0%	1%

Table 5. Distribution of route type mileage across the network and in each line speed sample

The latest version of VTISM (2.7) was used for the study, which contains a snapshot of the latest track asset, condition and traffic data obtained early in 2012.

Step 2. Creation of VTISM traffic files

The overall approach was to introduce an artificial vehicle (with varying axle load, speed and un-sprung mass parameters) as incremental traffic on existing base traffic levels so that the incremental cost could be derived. Traffic files were setup as follows:

1. Initialisation traffic files - VTISM needs to know the current 2012 traffic levels and cumulative tonnage (accounting for historical traffic growth) that has led to the current state of the track in 2012, in order to calibrate the models at the start of the projection.

2. Base case traffic files – Base traffic levels were defined in order to obtain a representative base cost from which the relative costs of introducing the artificial vehicle could be derived. It was important to normalise the tonnage across the four sample track databases (i.e. 25, 50, 75 and 100 mph or greater line speed) because different levels of traffic / tonnage exist at different line speeds (generally high speed track has higher tonnage levels than lower speed track) and the higher the tonnage, the lower the cost / tonne. This effect is captured in VTISM's models which account for the non-linear nature of the track geometry deterioration rate, i.e. track settlement is greatest when traffic is first introduced so geometry deterioration rate reduces with cumulative tonnage. Normalising the traffic was achieved by scaling the traffic on individual sections so that the overall average tonnage was equal between samples. This was set equal to the '25 mph or greater' line speed sample overall average tonnage of 6 MGTPA (Million Gross Tonnes Per Annum), which approximately represents the network average tonnage, given 94% of the network has a line speed of 25 mph or greater.

3. Variant traffic files – Variant traffic files were setup comprising:

    a. The base, normalised traffic on each traffic segment.
    b. An additional 20% of the base tonnage attributed to the artificial vehicle with traffic levels adjusted to maintain constant tonnage whilst axle load is varied.

Step 3. Creation of VTISM vehicle files

Vehicle files (definition of vehicle and axle parameters, assuming a 4-axle vehicle) were created for each artificial vehicle variant case (change in axle load, speed and un-sprung mass). These parameters contribute to the static load forces imposed on the track. Another, smaller component of the total track forces is the ride force which requires suspension-related ride force parameters to be defined. These parameters are derived using vehicle dynamics software and within VTISM there is a range of generic ride force parameters for different vehicle models. An appropriate generic ride force model was chosen using the closest matching reference axle load and ride speed, from which VTISM extrapolates to obtain the estimated ride forces for the given artificial vehicle axle load and speed.

Independent verification of all setup files was undertaken to assure quality of all parameters and integrity of database files.

Step 4. Setup of the T-SPA projection criteria

T-SPA is used to simulate track deterioration, work volumes and costs over time and the standard Network Rail renewal, maintenance and inspection policy criteria and unit costs were used. This policy criteria is suitable for establishing the relative damage impact of different vehicles. An important consideration was the selection of a suitable projection period, which should ideally be up to 60 years to represent a renewal cycle for all track sections, whilst not requiring excessive processing time. Shorter projection periods would have results skewed by the variation in annual renewal volumes. Several test cases were carried out with varying timeframes (from 20 to 60 years in 5 year steps). It was found that a 37 years projection period was suitable as it was within 1% accuracy of the 60 year projection and takes the projection to the end of CP11, which is consistent with ORR's sustainability requirement.

Step 5. Setup and running of the VTISM batch scenario processing function

The VTISM batch processing function was used to execute the variant cases automatically over several hours. This feature was particularly useful for the study because of the numerous variant scenarios required and it provides an audit trail of the input and output files.

3.2 Results

Firstly, it must be noted that the VTISM-derived track impact (vertical damage) cost is the bottom-up cost associated with track renewals, maintenance and inspection, which serves to show the relative vertical damage impact between vehicles with different characteristics. It is not a track access charge; this will be determined by ORR following a separate exercise by apportioning the pre-determined total variable usage costs using the revised formula derived in this study using the VTISM results. It should be noted that that the total track variable usage costs to be apportioned were also estimated using VTISM.

Figure 3 shows the VTISM results (total plain-line and S&C track impact cost are expressed as a relative damage index per axle per mile) for the key variant cases. The costs were derived by taking the total annual costs associated with the artificial vehicle traffic over the 37 years projection period relative to the base case costs associated with other traffic on the route.

Key observations are as follows:

- There is a consistent pattern of increasing relative damage with increasing axle load and unsprung mass between the vehicle speeds 25 to 75 mph, which is sufficient to support curve fitting and development of a robust formula. No further intermediate variant cases in axle load and un-sprung mass need to be considered to improve the relationships.
- At 100 mph (and the high axle load cases at 75 mph), some cases have significantly less relative damage than the lower speed cases. This is due to:
    - The highest quality track construction is used on the high-speed lines, which has a longer service life despite the increased speed and therefore, lower renewal rates.
    - VTISM uses average unit costs for the network. In reality, the renewal cost is much higher on high speed lines due to the better track construction methods, improved track geometry quality techniques and higher cost of possessions.

    Therefore, it would only be appropriate to use the results from the 25 to 75 mph cases (excluding the 75 mph high axle load, 25 tonne cases) to develop a revised track formula. The trend in relative damage can then be extrapolated between 75 and 100 mph.

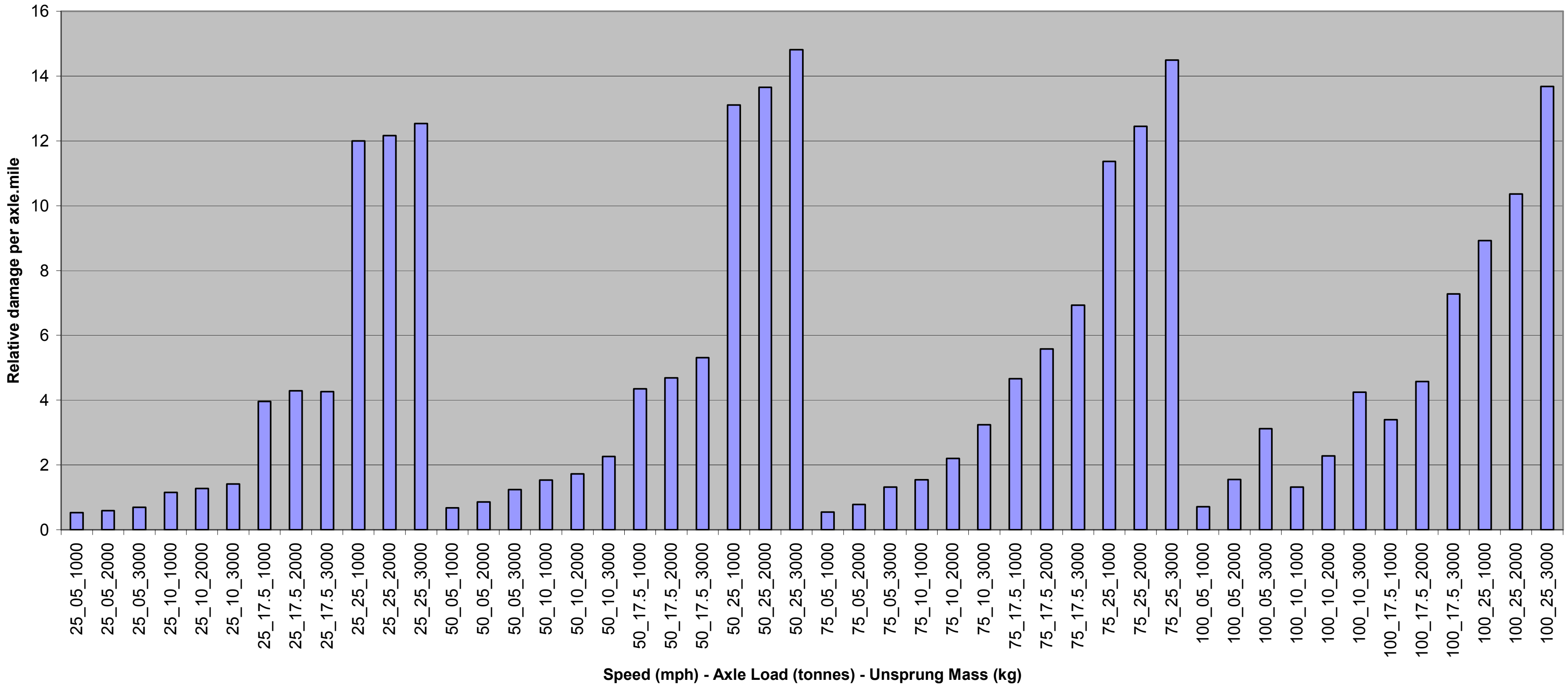

Figure 3. VTISM-derived relative damage indices for variant cases

3.3 Development of a revised track damage formula

Regression analysis (establishing a best fit to results and deriving a mathematical relationship for track damage impact as a function of speed, axle load and un-sprung mass) was undertaken. As stated in section 3.2, it was only appropriate to use the results from the 25 to 75 mph cases and to extrapolate the trend in damage between 75 and 100 mph. Several methods of fitting were trialled (including power, quadratic, exponential and cubic functions) and it was determined that the most appropriate, robust function is a hybrid because it had the highest degree of fit, 77% and the strongest correlation to the VTISM data (see goodness of fit measures in Appendix 1):

Proposed VTISM-derived track damage formula based on a hybrid fit:

Relative damage (per axle.mile) $= 0.473.e^{0.133A} + 0.015.S.U - 0.009.S - 0.284.U – 0.442$

where:
A = Axle load (tonnes), within the range: 5 to 25 tonnes
S = Operating speed (mph), within the range: 25 to 100 mph
U = Un-sprung mass (tonnes / axle), within the range: 1 to 3 tonnes

Note that the number of significant figures of the parameters ensures precision in the use of the formula and avoids rounding errors but does not reflect the accuracy of the formula. The formula is applied by calculating the relative damage per mile for each axle of a vehicle and then summing to derive the total relative damage for the vehicle per mile. Figure 4 to Figure 6 show the relative damage variation with speed, axle load and un-sprung mass using the hybrid function.

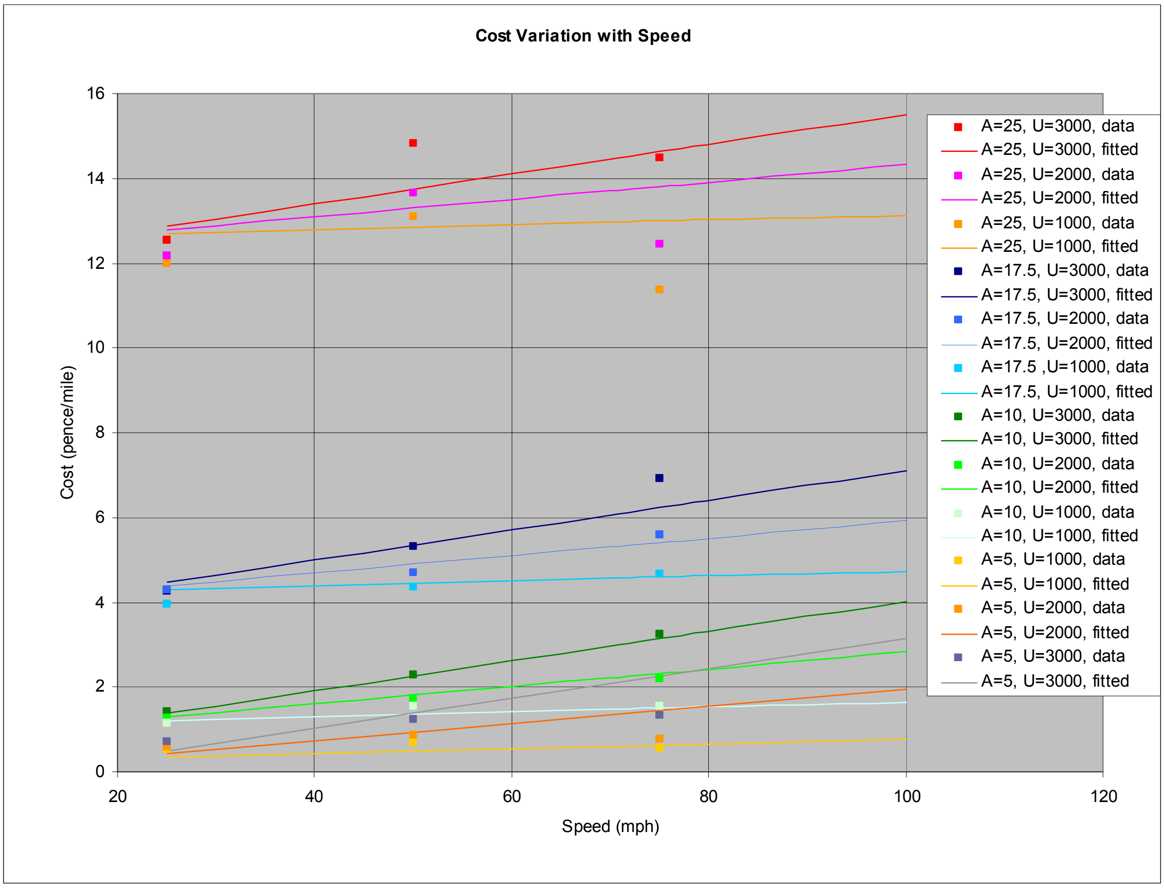

Figure 4. Relative damage variation with speed using fitted data (hybrid formula)

The fitted relationship between speed and relative damage is fairly linear between 25 and 75 mph (with relative damage extrapolated to 100 mph) and the profiles (gradients) are consistent for each axle load and unsprung mass combination. Note that relative damage would not be expected to extrapolate to zero for zero speed, given that there would still be a component of static load force and damage associated with the artificial vehicle traffic's tonnage and axle load.

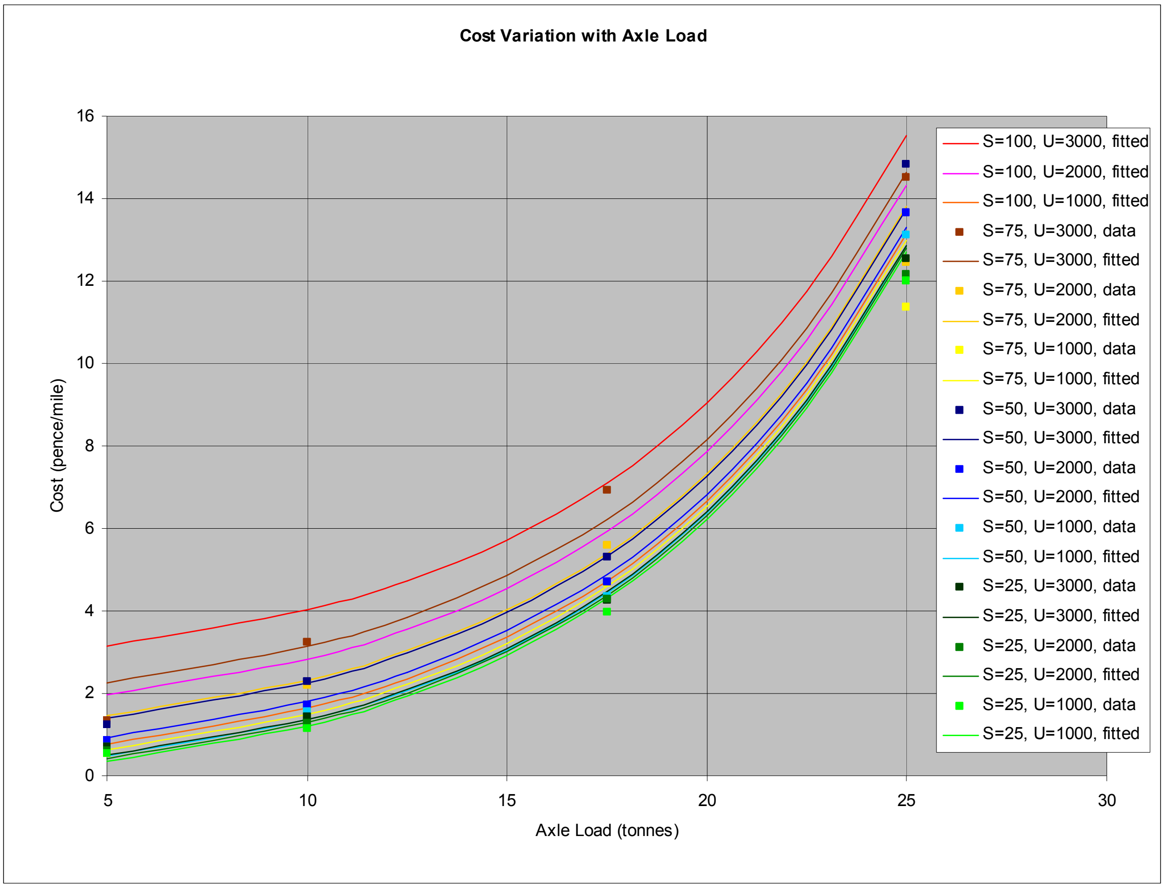

Figure 5. Relative damage variation with axle load using fitted data (hybrid formula)

The relationship between axle load and relative damage is non-linear (exponential) and all profiles (gradients) are similar. Note that at zero axle load there would still be a small component of static and dynamic forces and damage associated with the artificial vehicle traffic's un-sprung mass and speed.

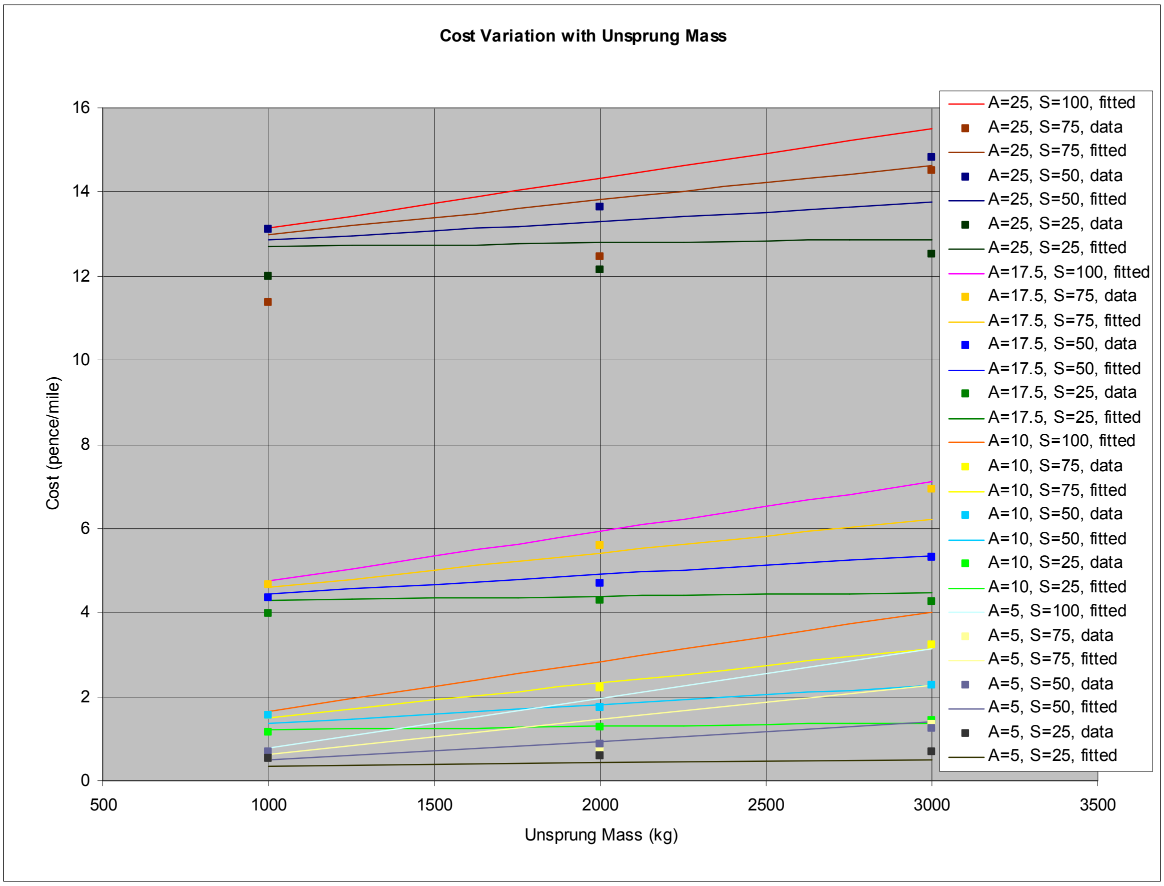

Figure 6. Relative damage variation with un-sprung mass using fitted data (hybrid formula)

The relationship between un-sprung mass and relative damage is fairly linear and the profiles (gradients) are consistent for each axle load and speed combination. Note that at zero un-sprung mass there would still be a component of static and dynamic forces and damage associated with the artificial vehicle traffic's tonnage, axle load and speed.

The benefits of the hybrid function compared with other methods are:

- The hybrid function more closely represents the different forms of relative damage variation that VTISM predicted for speed, axle load and un-sprung mass, hence the highest degree of fit of 77% compared with the power function's lower fit of 75% and weaker correlation to VTISM data, particularly at higher relative damage values (see Appendix 1, Figure A.1). The power fit exponents can be compared with those used in the previous CP4 track formula as shown in Table 6:

Parameter	Exponent (per axle.mile)	
	CP4 power formula	VTISM power formula
Axle load	1.49*	1.71
Speed	0.64	0.27
Un-sprung mass	0.19	0.31

*Note *: The axle load exponent of 0.49 is used when the formula is expressed in terms of per tonne.mile and 1.49 when expressed in terms of per axle.mile, given that there is an additional axle load multiplier in GTM.*

Table 6. Comparison of power fit exponents from the VTISM-derived formula and CP4 formula

- There is no additional worthwhile benefit in using a significantly more complex formula such as a cubic fit (which requires 20 terms).

Figure 7 shows how well the VTISM results can be predicted by the two VTISM-derived fits (the proposed hybrid formula and an alternative power formula) and how the original CP4 track damage formula compares with the VTISM results. For comparison purposes, the CP4 damage indices were scaled to match the VTISM hybrid formula result for an average reference vehicle (operating speed 50 mph, axle load 12.5 tonnes and un-sprung mass 2,000 kg).

- The VTISM hybrid formula shows a close match across all cases (accounting for the extrapolated fit in the 100 mph cases and 75 mph high axle load, 25 tonne cases).
- The VTISM power formula shows a close match in some cases but there are some significant differences, particularly for the higher axle loads at lower speed, which means that it would not provide an acceptable fit overall.
- The previous CP4 power fit is broadly in the range of the VTISM results, however, there are significant differences in that:
  - VTISM predicts much higher damage for high axle loads, particularly at the lower speeds 25 and 50 mph.
  - VTISM predicts much higher damage for high un-sprung mass, particularly at the higher speeds 75 and 100 mph.

    This is consistent with the higher axle load and un-sprung mass exponents and lower speed exponent in the VTISM power fit.

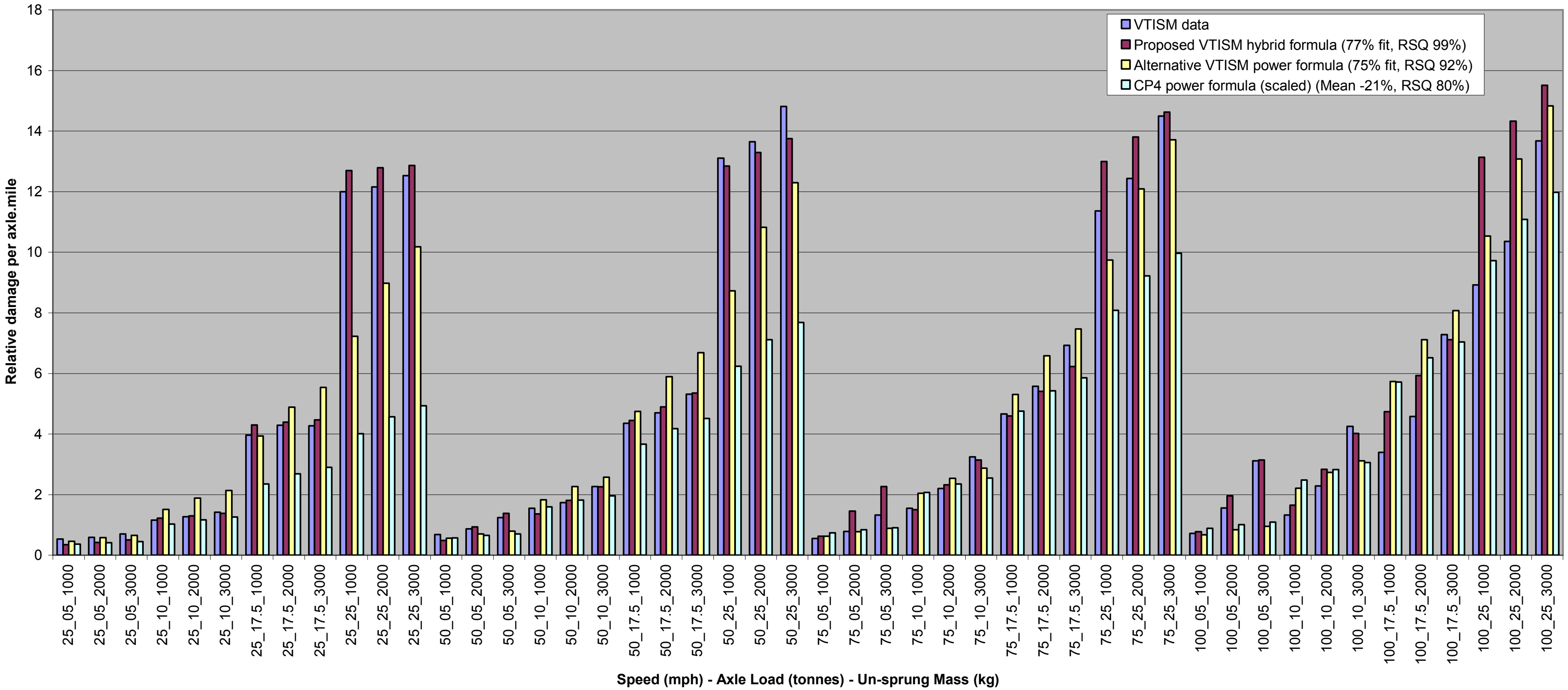

Figure 7. Comparison of relative damage indices between VTISM, fitted data (proposed hybrid fit and alternative power fit) and the original CP4 track damage formula

3.4 Impact of revised track damage formula on generic vehicles

The VTISM results and associated formulae show that damage is more sensitive to axle load and un-sprung mass and less sensitive to vehicle speed, compared with the previous CP4 formula. Therefore, the impact of the proposed hybrid formula on a range of passenger and freight generic vehicles was assessed (see Table 7). In comparing the damage indices (per tonne.mile and relative to the reference vehicle, Mark 3 coach) between the CP4 power formula and the proposed VTISM hybrid formula, the main changes (highlighted by the coloured cells) are that vehicles with a high axle load or un-sprung mass would attract a greater share of the variable usage costs than in CP4 and vehicles with a high operating speed would attract a smaller share, all other things being equal. In general, it is most probable that heavy freight traffic will attract more cost and high speed trains will attract less cost. This can be confirmed after the relative damage indices for all vehicles and their traffic contribution have been determined.

Generic vehicle	Axle load (tonnes)	Oper-ating speed (mph)	Un-sprung mass (kg)	Damage index (per tonne.mile)			Damage index (relative to Average Vehicle)		
				CP4 Power formula	VTISM Hybrid formula	VTISM Power formula	CP4 Power formula	VTISM Hybrid formula	VTISM Power formula
Average vehicle	12.5	50	2,000	0.203	0.203	0.258	1.00	1.00	1.00
Mark 3 coach	9.2	78	1,260	0.212	0.172	0.203	1.05	0.85	0.79
Freight wagon 4 axle - empty	5.5	41	1,380	0.111	0.114	0.122	0.55	0.56	0.47
Freight wagon 4 axle - laden	19	35	1,380	0.185	0.289	0.280	0.91	1.43	1.09
Freight wagon 2 axle - empty	9	41	1,820	0.149	0.151	0.188	0.74	0.74	0.73
Freight wagon 2 axle - laden	21	32	1,820	0.193	0.350	0.320	0.95	1.73	1.24
High speed multiple unit - motor	14.1	81	1,835	0.288	0.257	0.311	1.42	1.27	1.21
High speed multiple unit - trailer	13.6	81	1,699	0.279	0.242	0.296	1.38	1.20	1.15
Multiple unit - motor	12.9	55	1,931	0.217	0.212	0.267	1.07	1.05	1.04
Multiple unit - trailer	10.2	55	1,548	0.186	0.170	0.211	0.92	0.84	0.82
Locomotive	17.5	37	2,200	0.201	0.267	0.310	0.99	1.32	1.20

Table 7. Impact of revised track damage formula on generic vehicles

4 Review of Approaches to Non-Track Variable Usage Costs and Estimating Vehicle Operating Speed

This section contains a brief review of:

- The approaches and formulae used for apportioning the variable usage costs of civils and signalling assets which aimed to include:
  - The historical basis of the equation used for apportioning civils costs between individual vehicles and the method of apportioning signalling costs according to track costs.
  - Advantages and disadvantages of the current methods.
  - Recent research workstreams undertaken that link vehicle impact to civils and signalling asset deterioration.
  - Further research needed and / or aspirations for future methods of apportionment.
- The approach to determining 'vehicle operating speed'.

4.1 Civils variable usage costs

In CP4, civils variable usage costs were apportioned between individual vehicles based on the following equation:

Equivalent Structures Damage = $Ct.A^{3.83}.S^{1.52}$ (per tonne.mile).GTM where,

Ct is a constant: 1.20 for two-axle freight wagons, and 1 for all other vehicles
A is the axle load (tonnes)
S is the operating speed (miles/hour)
GTM is the Gross Tonne Miles

The civils equation was derived by fitting regression relationships to a large number of results produced by fundamental structures damage models, as part of earlier BR Research, hence the need to review the current approach in the light of new research and asset knowledge. The equation and its applicability to the civils assets groups below were reviewed with Network Rail civils representatives and industry stakeholders (RFOA, ATOC and ORR).

- Embankments renewals
- Metallic underbridge renewals
- Brick and Masonry underbridge renewals
- Culverts renewals

There is a concern with a single equation being applied to several different types of civil assets as there are different drivers for the deterioration of each asset. In general, stress and fatigue in structures is mainly related to the 'live load' of the train based on axle load and axle spacing. There is also a lesser important, dynamic component related to speed and the effect of the transition (change from plain track to bridge, which affects track stiffness and track geometry).

The civils VUC equation parameters and exponents were reviewed and the following issues noted:

i. The axle load exponent of the equation is 4.83, after including the axle load component of Gross Tonne Miles (GTM). Fatigue damage in steel bridges is typically dependent on stress raised to a power between the range of 3 to 5[7] so the value of 4.83 is at the high end and there is no evidence to suggest that Network Rail's structures have increased susceptibility to stress.

Note that axle spacing is an important component of stress and is not included in the formula, however, it is possible that the Ct multiplier is used to approximate the increased level of stress from 2 axle, heavier axle load freight wagons (Ct = 1.2), compared with load spread between lighter 2 axle passenger vehicles or 4 or more axle vehicles (Ct = 1). However, current research by Network Rail contradicts this basis when analysing stress on masonry bridges due to load spread across arches[5], which is further discussed below.

ii. The speed exponent of the equation is 1.52, which is consistent with AREMA guidelines[6] for speed limits on bridges, whereby 1.0 and 2.0 are used for concrete and steel bridges respectively. Research related to the dynamics effects of vibration and resonance on structures caused by high speed trains has been carried out in the past by RSSB[7] but the phenomena is related to very high speed trains (above the current maximum of 125 mph on the GB network) and there is currently insufficient research linking this effect to structures damage.

iii. The operating speed used in the equation is, for passenger vehicles, the distance-based average speed of the vehicle and for freight vehicles, a commodity-based speed. Network Rail have observed that modern freight trains with increased power and improved traction accelerate more quickly and this was causing structures in some locations to show new signs of deterioration due to being subjected to higher speeds than in the past. This is considered further in the review of the approach to vehicle operating speed (section 4.3).

The relevance and suitability of the civils VUC equation parameters and exponents to each asset group and the drivers of asset deterioration are summarised below, noting recent research that has been undertaken:

i. Metallic underbridge renewals (£9.7M / year) - driven by stress and fatigue life. *It can be concluded that the civils equation is relevant to this asset group, however, it would be more reasonable to assume the median axle load exponent of 4 based on the EN Eurocode standard[4], rather than continuing to use the current higher value of 4.83 which cannot be substantiated. Therefore, the exponent to use in the equation (per tonne.mile) would be 3.*

ii. Brick and masonry underbridge renewals (£13.3M / year) – cracking and unpredictable failure of spandrel walls on arch bridges at the vulnerable, quarter-point has become a common problem believed to be caused by the heavier (~25t) axle load freight vehicles. Network Rail have recently completed a study[5] into this problem. Stress modelling and analysis has shown that the HTA 4-axle 100t freight wagon is more aggressive than other freight wagons (e.g. HAA 2 axle) and there is a complex inter-relationship between the structural configuration (such as span length) and axle / bogie spacing. The problem can be further exacerbated by environmental factors (cold weather) affecting previously cracked walls. *It can be concluded that the civils equation is unsuitable given that an appropriate axle load exponent cannot yet be defined (given failure mechanisms are not yet fully understood) and axle spacing is not included. Inclusion of axle spacing would need further analysis of the distribution of span lengths. Therefore, the revised track VUC hybrid equation would be more applicable as its provenance is known.*

iii. Embankment renewals (£1.9M / year) – serviceability problems (e.g. excessive deformation of the embankment clay fill material, leading to the track geometry defects) are related to axle load, plasticity of the clay filling and track bed configuration. RSSB have recently completed a research project in this area[8] but deterioration relationships have not yet been defined. It is possible that embankment deterioration is more closely related to the drivers of track deterioration. *It can be concluded that the equation is unsuitable given that relevant axle load and speed exponents cannot yet be defined, therefore, the revised track VUC hybrid equation would be more applicable as its provenance is known.*

iv. Culvert renewals (£0.5M / year) – traffic load has less effect on culverts due to the depth of culverts and spread of stress within the soil. *It can be concluded that the equation is unsuitable given that relevant axle load and speed exponents are expected to be lower but cannot yet be defined, therefore, the revised track VUC hybrid equation would be more* *applicable as its provenance is known.*

The above conclusions are broadly consistent with industry stakeholder views in that:

- the basis for the civils formula can only be currently justified for metallic bridges;
- in the absence of any better deterioration models and given the low costs associated with vehicle damage to brick and masonry under-bridges, embankments and culverts, the revised track VUC hybrid equation offers some consistency and simplification in the overall calculation of VUCs.

It is recognised that Network Rail have recently undertaken further research into the drivers of masonry bridge and embankment deterioration and understand that further research should focus on linking traffic impact to renewal and maintenance costs of structures. ATOC expressed that it would have liked to have seen more robust models in place for CP5 and stakeholders in general have expressed the need for sound asset degradation model for civils assets, particularly for the higher cost brick and masonry underbridge renewals, to be established as a priority, in time for the next review, CP6.

4.2 Signalling variable usage costs

In CP4, due to their materiality, signalling variable usage costs were apportioned using the same basis as the track costs. This approach and its applicability to the signalling assets groups below were reviewed with Network Rail signalling representatives and industry stakeholders (RFOA, ATOC and ORR). Network Rail have determined that the following maintenance and renewals items are driven by traffic usage (frequency of train movements and load-related damage) and therefore contribute to the estimated total variable usage costs of £13.6M:

i. Train detection and points maintenance (£8.2M) - Train detection maintenance is associated with response to alerts / alarms raised caused by vibrations from trains and traction interference. Points maintenance involves response to alerts / alarms and maintenance of points components such as motor brushes which are caused by vibrations from trains. Level crossings maintenance is driven by frequency of train movements only (not load-related damage) and thus it would be more appropriate to apportion these costs using vehicle movements (vehicle mileage) than the track formula.

ii. Minor work points renewals (£5.4M) – Vibrations from trains cause wear and failure of clamplocks and point machines.

Load-related damage is considered to be linked to axle load and speed and in the absence of any specific signalling component deterioration models, then the revised track VUC hybrid equation would be a suitable approximation. It was estimated that 50% of the total costs (£6.8M) is attributed to load-related damage and therefore, it could be apportioned using the track equation. This is based on the assumption that two-thirds of the above signalling maintenance and renewals costs are classed as load-related damage, however, approximately 25% of the cost is related to non-mechanical systems (e.g. electronics) which is not relevant (hence approximation that 67% of 75% = 50% of total cost can be apportioned using the track VUC hybrid equation). The remaining 50% of cost can be apportioned by vehicle movements (vehicle mileage) only. *It can therefore be concluded that the revised track VUC hybrid equation is suitable for apportioning 50% of the signalling variable usage costs with the remaining 50% of costs apportioned by train movements (vehicle mileage) only.*

It was noted that signalling density is not a significant factor to distinguish between passenger and freight usage. Whilst signalling density may increase for passenger metro-services, additional signals are required to handle freight traffic on mainline and cross-country routes.

Industry stakeholders expressed that signalling costs were not significant (accounting for ~5% of total VUC costs) to warrant detailed analysis and that it should be included in the fixed costs or that any apportionment should be based on a simplified approach such as train movements. However, they were not averse to using the track VUC hybrid equation if it could be justified that there was load-related damage caused by trains. Network Rail has some evidence to support this so the above approach should be acceptable to stakeholders.

Further research to improve signalling variable usage cost apportionment may not be worthwhile or cost effective bearing in mind the very small proportion of total signalling costs that are considered to be variable with traffic. However, ATOC expressed that it would have liked to have seen more robust models in place for CP5 and have requested the development of signalling asset models to be undertaken as a priority, in time for CP6.

4.3 Approach to estimating vehicle operating speed

The track and civils VUC equations include the vehicle operating speed as an input. The 'operating speed' is used to reflect the fact that when operating on the network vehicles generally do not always operate at their maximum speed and thus it would be inappropriate to assume this for charging purposes. In CP4, this parameter was defined in different ways for passenger and freight vehicles, as follows:

i. For passenger vehicles, the distance-based average speed of the vehicle was provided either as a known value or defaulted to a value calculated using a formula based on the vehicle's maximum speed:

$$\text{Operating Speed} = 0.021.\text{Max. Speed}^{1.71}$$

There is a spread of manually-entered vehicle speeds compared with the formula. Figure 8 shows the plot of vehicle max. speed vs. manually-entered operating speed for each vehicle type (around 70% of vehicle types have manually-entered values). It can be concluded that the default formula was based on a fit of the manually-entered values as the trendline formula is very similar to the default formula. The relationship is not very strong however, and there is a large spread between the manual values and the formula (up to +/- 20 mph difference). Therefore, it appears that most vehicles were assessed on a case-by-case basis possibly because they have unique speed profiles (e.g. different stopping patterns for intercity and metro services).

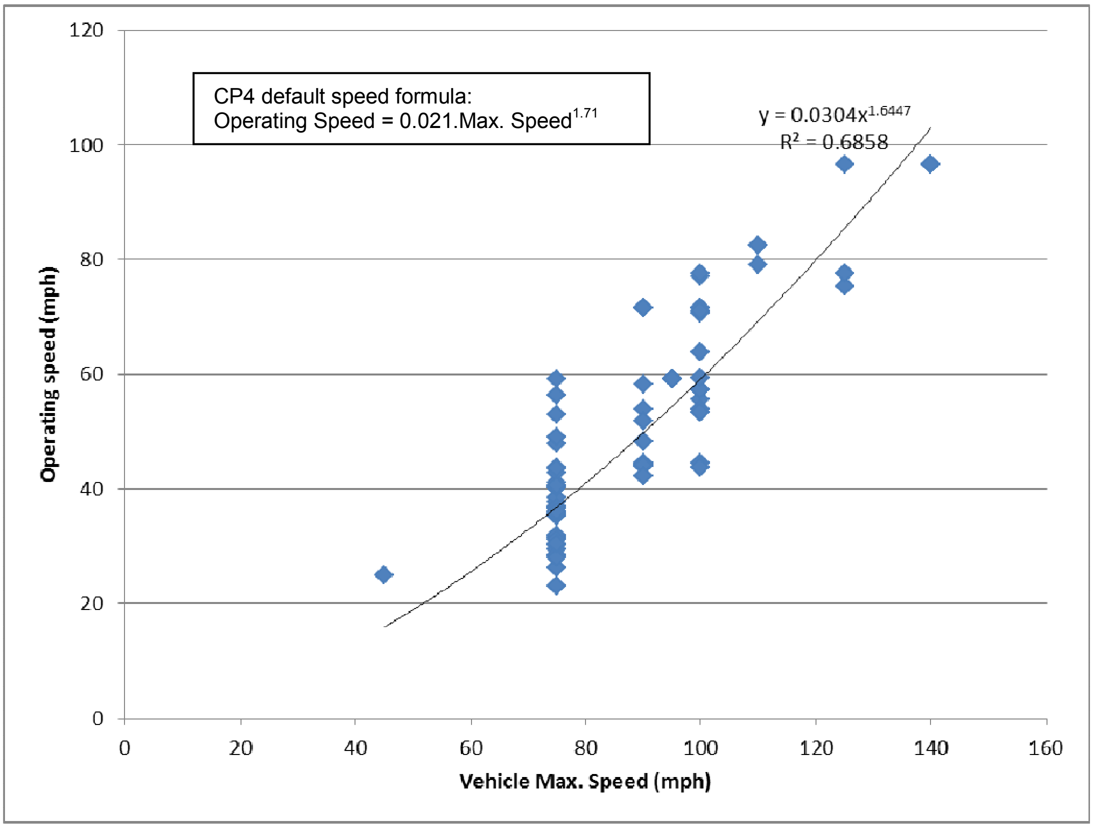

Figure 8. Relationship between Vehicle Max. Speed and Operating Speed for Passenger Vehicles in the CP4 VUC model

ii. For freight vehicles, the operating speed was selected from a lookup table of average speeds based on commodity type and whether the vehicle is laden, empty or a locomotive.

Stakeholders have expressed the importance of using a consistent approach in defining operating speed, i.e. passenger vehicles should be assessed on a consistent basis and all freight vehicles should be assessed on a consistent basis. They have undertaken to review the data using operational data, where available, as part of Network Rail's consultation, in particular:

i. ATOC would prefer that all passenger vehicle types have operating speed assigned using a formula for consistency and if a change is required then evidence should be provided for this.

ii. RFOA would like to review the basis for the commodity categories and associated average speeds.

iii. The existing default passenger vehicle speed formula and the freight commodity-based speeds may not accurately reflect that modern trains with increased power and improved traction accelerate more quickly, therefore, average speeds may have increased significantly.

5 Conclusions and Recommendations

1. The rail industry's VTISM tool was used to re-calibrate the track VUC equation and a hybrid formula based on vehicle speed, axle load and un-sprung mass was defined. An alternative power formula was also derived for comparison with the previous CP4 formula but the degree of fit to the VTISM results was not as good as the hybrid formula. Therefore, it is recommended that the hybrid formula is used in the CP5 VUC apportionment process.
2. The VTISM results and associated formulae show that damage is more sensitive to axle load and un-sprung mass and less sensitive to vehicle speed, compared with the previous CP4 formula. Therefore, the impact of the proposed VTISM hybrid formula on a range of passenger and freight generic vehicles was assessed. In comparing the damage indices between the CP4 power formula and the proposed VTISM hybrid formula, the main change is that vehicles with a high axle load or un-sprung mass would attract a greater share of the variable usage costs than in CP4 and vehicles with a high operating speed would attract a smaller share, all other things being equal. In general, it is most probable that heavy freight traffic will attract more cost and high speed trains will attract less cost. This can be confirmed after the relative damage indices for all vehicles and their traffic contribution have been determined.
3. The approach to non-track VUC's and estimating vehicle operating speed was reviewed:
   3.1. For civils assets, it is proposed that the existing civils equation should only be applied to metallic underbridges, using a modified axle load exponent of 4 (rather than the existing higher value of 4.83, noting this includes the axle load component of Gross Tonne Miles (GTM)), which is more consistent with Euronorm standards. Therefore, the exponent to use in the VUC equation (per tonne.mile) would be 3. The axle load and speed exponents cannot be justified for application to other civil asset groups: brick and masonry underbridges, embankments and culverts and therefore it would more applicable to use the revised track VUC hybrid equation based on VTISM analysis as its provenance is known. Further research and development of a vehicle-structures model is recommended in time for the next review in CP6, with priority for the highest cost brick and masonry underbridge renewals.
   3.2. For signalling assets, it would be suitable to apply the revised track VUC hybrid equation for a proportion (50%) of the variable costs that are load-related with the remaining costs apportioned by train movements (vehicle mileage). Further research and development of signalling asset models is recommended, in time for CP6.
   3.3. It is recommended that a consistent approach is used to determine freight and passenger vehicle respective operating speeds (i.e. all passenger vehicle operating speeds should be determined on the same basis and all freight vehicles should be determined on the same basis). Also, if the relevant operational data is available, then there would be merit in reviewing whether the existing vehicle operating speeds used in the charging model continue to be broadly appropriate.

6 References

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Appendix 1. Goodness of fit measures for VTISM track damage formulae

Table A.1 shows the goodness of fit measures for the two different methods of fitting the VTISM results to a formula using hybrid and power-based fits and how they compare with the previous CP4 power formula. The two methods provide a good correlation between VTISM results and the predicted values, however, the co-efficient of determination 'Adjusted R-Squared' (which accounts for using multiple input variables: axle load, operating speed and un-sprung mass) shows that the hybrid provides a better fit of 99%. The standard deviation of residuals also reveals the extent of errors and inversely, the overall degree of fit of 77% for the hybrid and 75% for the power fit. The CP4 power formula has a significant deviation in the average of the residuals, under-predicting the VTISM results by 21%.

Figure A.1 illustrates the degree of fit between the VTISM data and the three formulae, which confirms that the hybrid formula provides an acceptable fit, whereas both the VTISM and CP4 power fits significantly under-predict the high relative damage values.

In conclusion, it is better to use the hybrid formula which contains sufficient parameters to more accurately describe the relationship between VTISM results and the input variables, albeit requiring a more complex formula.

VTISM track damage formula	Correlation co-efficient	Adjusted R-squared	Standard deviation of residuals	Average of the residuals
VTISM Hybrid	100%	99%	23%	2%
VTISM Power	96%	92%	25%	3%
CP4 Power	89%	80%	25%	-21%

Table A.1. Goodness of fit measures

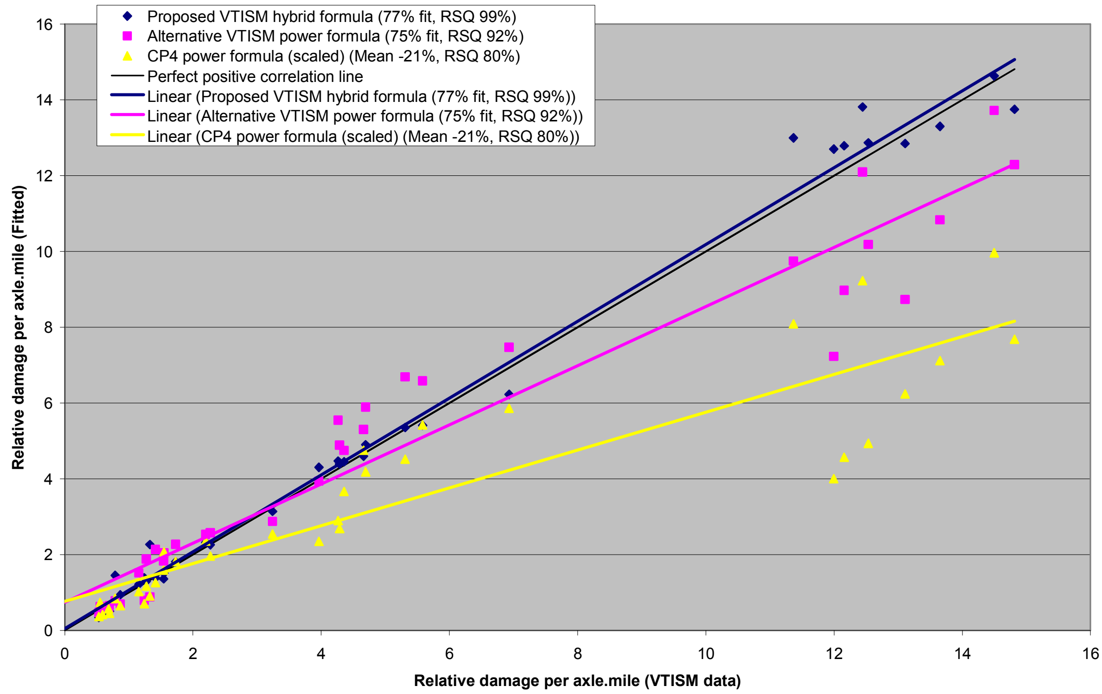

Figure A.1. Degree of fit between VTISM data and track damage formulae