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# Reducing the Diameter of Freight Vehicle Wheels – The Suitability of Q/D as a Control for Wheel-Rail Contact Stress

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## Introduction

High wheel-rail contact stress is related to rail damage mechanisms such as gross plastic flow. Such high contact stresses are often generated by freight vehicles which have comparatively high axleloads. On railways in Great Britain (GB) a limit is placed on the ratio of static wheel load (Q) to wheel diameter (D) as a proxy to control contact stress related damage. However, there is increasing interest in the use of smaller diameter wheels on freight vehicles, in order to prolong wheelset life (smaller scrap diameter) and increase capacity within the GB's constrained structure gauge.

GB Railway Group Standards [1] limit Q/D to 0.13 kN/mm. However it is known that a number of freight wagons already operate above this limit, either due to derogations granted against the standard, or as a result of being introduced prior to the standard's universal application ('Grandfather Rights'). At least one vehicle type is known to operate with a Q/D ratio of up to 0.165 kN/mm.

This paper presents the results of an investigation into the contact stress state of the GB network. This formed part of a larger study [2] undertaken with a view to allowing a reduction in wheel diameters for freight vehicles. The research was conducted as part of the industry's R&D programme managed by the Rail Safety and Standards Board (RSSB).

## Use of Hertzian Contact Stress

Hertzian theory is widely used to approximate rolling contacts for wheel and rail applications due to its computational efficiency. However, the speed of the calculations comes at a cost to accuracy, through a number of simplifying assumptions. Two of the most significant approximations are:

- The simplification of the contacting geometry as constant radius curves: one for each of the wheel and the rail in the longitudinal direction; and one for each in the lateral direction. As a consequence of the approximations the resulting contact patch will always be elliptical.
- The wheel and rail material will always deform elastically – irrespective of the stress (or strain) to which they are subjected.

Contact stress is not uniform across the contact patch, due to the geometry of the wheel and rail. Hertzian theory finds that the contact stress distribution is elliptical where the peak contact stress is 1.5 times the mean ( $\sigma_{max} = 1.5 \times \bar{\sigma}$ ).

The high loads and comparatively small contact areas of wheel rail contacts often lead to peak stresses beyond the yield stress of the material. Consequently plastic deformation occurs, which results in greater deformation of the bodies within the contact patch, a larger contact area and reduced peak contact stress. In these circumstances the Hertzian theory over predicts the peak contact stress and in some cases the difference has been shown to be in the order of 30% [3].

The calculation of the more accurate elastic-plastic contact stress is a computationally demanding task, and a finite element model may take a number of hours to solve a single contact case. Hertzian elastic stress is relied on in the work presented in this paper for a number of reasons:

- Speed of calculation – millions of wheel-rail contacts have been evaluated in this study.
- Many rail damage models have been developed using Hertzian contact parameters and peak or mean Hertzian contact stress.

- While the accuracy of Hertzian stress is limited under certain circumstances, it provides a consistent means for comparisons.

Other parts of the work considered elastic-plastic contact stress, but these are beyond the scope of this paper.

Results in this paper sometimes show unrealistically high Hertzian contact stress values ( $> 3$  GPa). These values have been included as they offer a means for comparison between data sets. It should be noted that plastic deformation is likely to prevent such high contact stresses occurring in reality.

### Q/D Distribution – GB Freight Fleet

A key premise of the argument for reducing wheel diameters was that as vehicles currently operate at  $Q/D > 0.13$  kN/mm without apparently causing excessive rail damage, evidence already exists to support a change to standards. An important element in testing this assertion was to understand the operating distribution of Q/D values in the freight vehicle fleet.

Initially Q/D ratios were calculated for new and scrap wheel diameters under each vehicle in the laden condition and the distribution calculated according to fleet size. This distribution was further weighted by annual wheelset mileage for each vehicle type. This initially suggested that, in theory, nearly 50% of the annual wheelset miles for freight wagons could occur at Q/D ratios in excess of the 0.13 kN/mm limit. In practice vehicles do not operate at maximum axle load all the time, indeed some vehicles may rarely be loaded to their maximum.

In order to provide a more realistic Q/D distribution, a further weighting was applied to represent the load condition of the various wagon types. It was assumed that bulk wagons operate 50% of their annual mileage laden and 50% tare. For container wagons, which can operate in many different load states, data was obtained for seven trains (a total of 175 vehicles carrying over 300 containers) and the resulting load distribution assumed to be typical for all container wagons in the fleet. The modified Q/D distribution is shown in Figure 1. In addition to the new and scrap diameter distributions, a 'Q/D Distributed' line is shown, which assumes that the wheels in service are evenly distributed between the new and scrap diameters. In reality the balance would be shifted slightly towards new diameters as some wheelsets are taken out of service for reasons other than reaching a minimum diameter, such as tread damage.

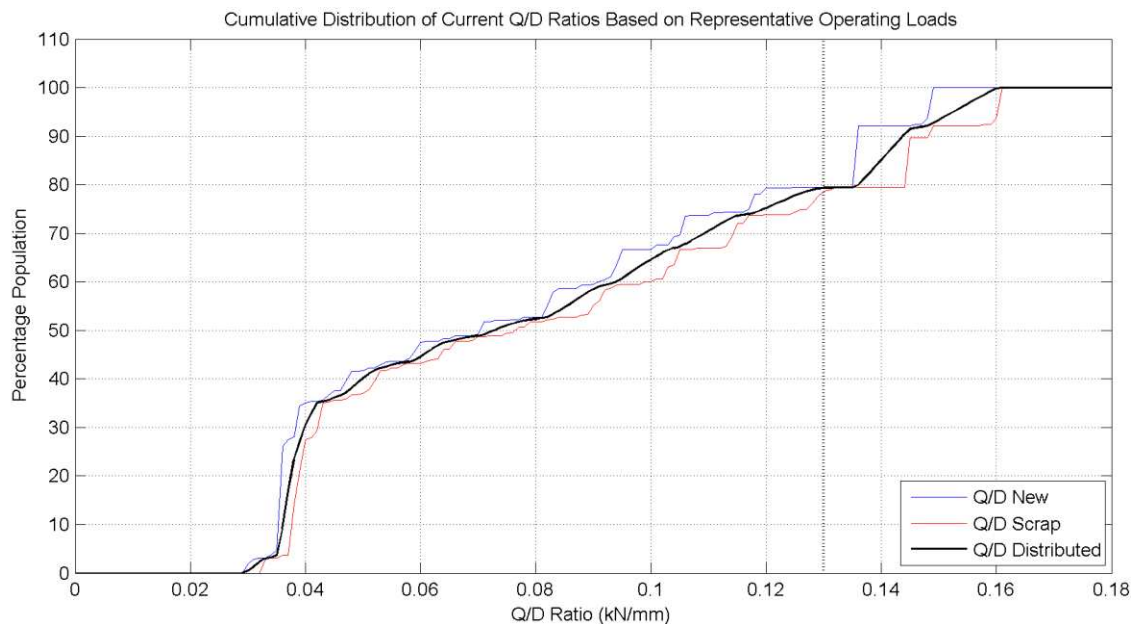


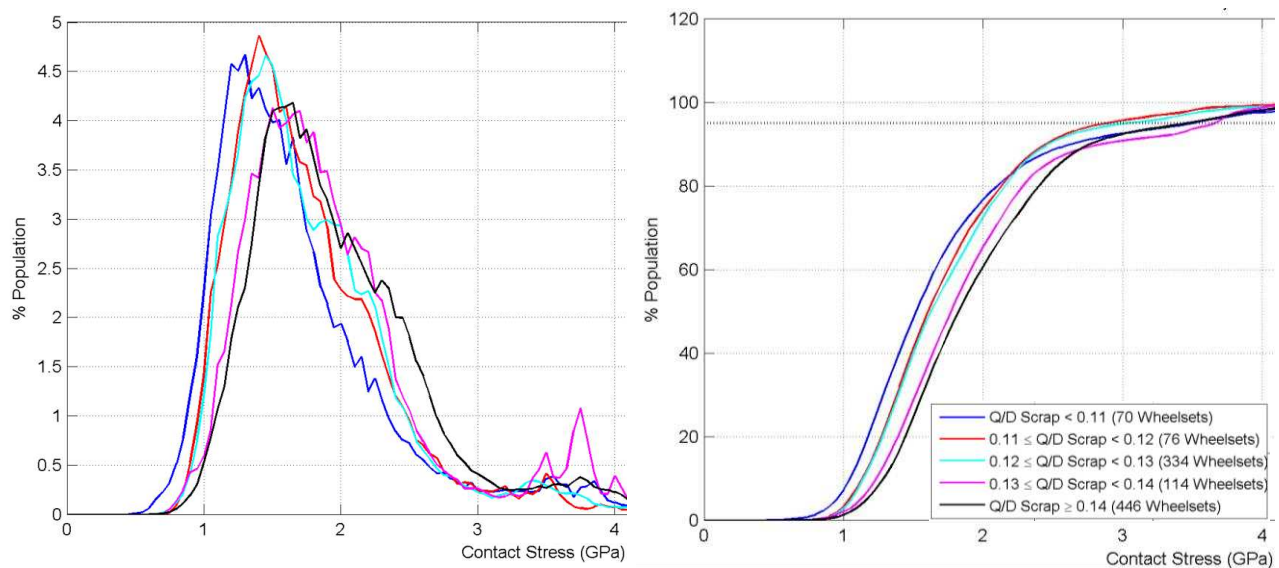
Figure 1: Current Q/D Distribution Weighted by Annual Wheelset Mileage and Operating Load Distribution

It can be seen that at the time the study was undertaken, 20% of GB freight vehicle wheelset miles were operated at a Q/D ratio greater than 0.13 kN/mm. Values above the limit were primarily attributable to bulk carriers (coal, aggregates etc). A small number of container vehicles have maximum Q/D ratios above 0.13 kN/mm, although the distribution of axle payloads for these vehicles indicates that these higher Q/D ratios occur infrequently.

### Contact Stress State – Freight Fleet on the GB Network

Understanding the current contact stress state of the network was considered essential in order to define representative input parameters for subsequent investigations of contact stress related damage and to ensure that observations made in the subsequent analyses are relevant to, and in the context of, the GB mixed traffic railway.

In order to determine how the contact stress distributions for worn wheel profiles differ from those for new profiles more than 2000 wheel profiles were measured. The profiles came from vehicles which represent around 80% of the total GB wagon fleet, on an annual mileage basis, including all major wagon types. Three representative worn rail profile pairs were selected and the VAMPIRE<sup>®</sup> contact data pre-processor was used to generate the Hertzian contact patch area for a range of lateral wheelset positions. This in turn allowed the Hertzian peak contact stress to be calculated for each contact. The analysis resulted in over 5 million individual contact patches. Flange contacts were excluded from the analysis.



**Figure 2: Hertzian Peak Contact Stress Distribution (Left) and Cumulative Distribution (Right) for Ranges of Q/D Ratio for Maximum Axleload and Minimum Wheel Diameter**

Figure 2 shows the results of this analysis, sorted into five Q/D ratio 'bins', in this case presenting the Hertzian elastic contact stresses for each vehicle type at its maximum laden axleload and minimum (scrap) wheel diameter. The majority of the Hertzian contact stress populations approximate a bell curve with a range from 1 to 3 GPa, and a secondary peak appears between 3 and 4 GPa. The secondary peak was found to be a consequence of the wheel and rail profiles analysed and could not be attributed to specific profiles or contact conditions. From these static cases it was observed that 95% of contact stresses were less than 3 GPa, and 85% of contact stresses were less than 2.25 GPa. Various limiting values of contact stress have been quoted historically in GB [4,5,6], all within the range 1 GPa – 1.5 GPa. It is clear from these results that many freight vehicle wheel-rail contacts occur at much higher values of contact stress than the quoted limits.

A trend was observed between the contact stress distribution and ranges of Q/D ratios, with the primary distribution peak shifting towards higher contact stresses with increasing Q/D.

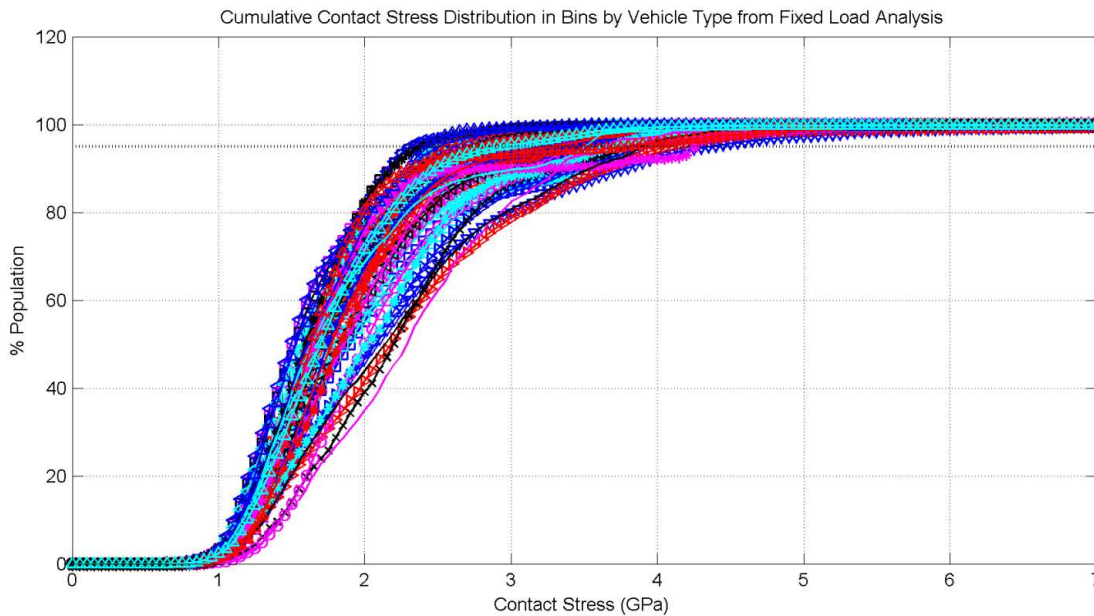
A number of dynamic simulation cases were carried out to investigate how the static contact stress distribution changes when weighted by the time spent at a given contact stress range. The analyses featured four real track cases which carry a significant volume of freight traffic.

The resulting contact stress distributions showed that the higher ranges of contact stresses calculated in the static analysis (between 3 GPa and 4 GPa) seldom occurred in the dynamic simulations. For a container flat wagon with Y33 bogies having a static Q/D = 0.131 kN/mm, the contact stress range was effectively reduced to between 0.8 GPa to 2.9 GPa, with the 95th percentile at approximately 2.4 GPa. The secondary high contact stress peak noted in the static analyses (between 3 and 4 GPa) was far less apparent.

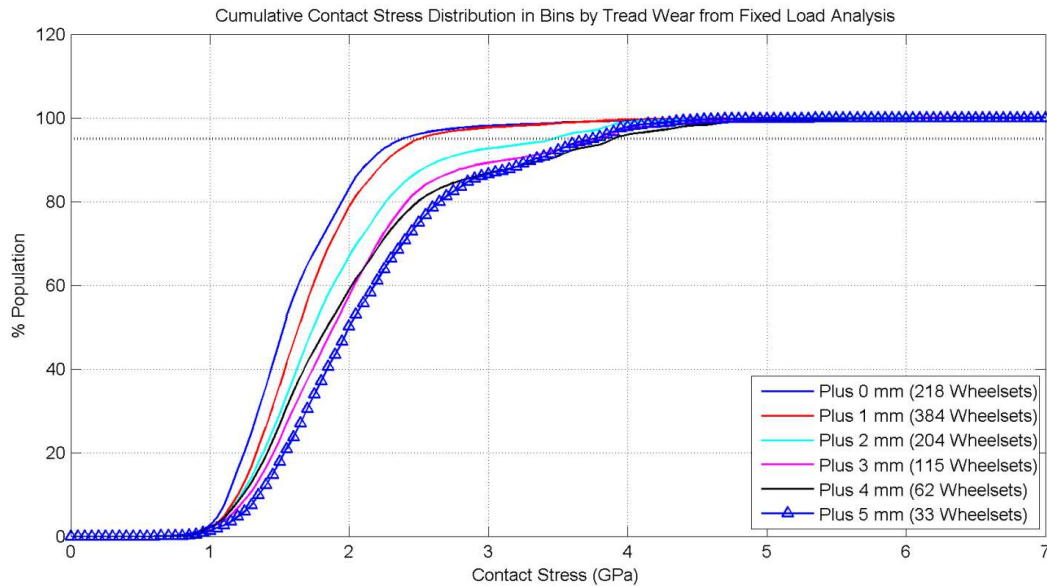
### Influence of Vehicle Type and Wheel Profile on Contact Stress

Having determined that many freight vehicle wheel-rail contacts occur at higher contact stress than the previously quoted limiting values, further analysis was carried out to determine which factors had the greatest influence on the contact stress distribution. It was found that two factors, the vehicle type and the amount of wheel wear had a much greater influence on the contact stress distribution than the Q/D ratio.

Figure 3 shows the cumulative distribution of contact stress by vehicle type (the actual vehicle types have been deliberately omitted from the plot). Figure 4 shows the same information for ranges of wheel tread wear calculated from the increase in flange height from the appropriate unworn wheel profile. Tread wear can also be considered a reasonable proxy for wheelset mileage since turning (which was not known for the measured wheels), although there are other influencing factors such as tread or disc braking. In both plots the contact data is based on a single fixed load and wheel diameter (the differences in stress are due solely to the wheel profile shape).



**Figure 3: Contact Stress Distribution by Vehicle Type – Fixed Load and Diameter Case**  
(Each Line Represents One Vehicle Type)



**Figure 4: Contact Stress Distribution by Profile Tread Wear – Fixed Load and Diameter Case**

The results in Figures 3 and 4 are not independent as the vehicle type (suspension characteristics, operating conditions, operating axle loads, braking type, etc.) influences the worn wheel profile shape. However, it appears that for some vehicle types, wheel profiles wear to a significantly less ‘contact friendly’ state than for others. Similarly, a clear trend can be seen between the distribution of contact stress and increasing wear, with more heavily worn profiles tending to be less contact stress friendly. The number of wheelsets included in each range is shown in brackets in the legend. Whilst these results appear to show clear trends, it should be noted that whilst the study was based on a large number of wheel profiles, it only utilised three rail profiles. Although these were chosen with care, it would be interesting to investigate the effect that a wider range of rail profiles would have on these results.

Overall, it was concluded that, whilst higher Q/D ratios lead to higher contact stresses, a much greater variation in contact stress arises from different vehicle/suspension types and from wheel profile wear. Although the wagons in this study used several different designs of new wheel profile, this was found to have comparatively no influence on the contact stress ‘friendliness’ of the worn wheel profiles,

### **Effect of Contact Stress on Damage Mechanisms**

Contact stresses are considered to be a significant factor in damage mechanisms such as squats, surface and subsurface crack initiation, Phase II crack growth, and plastic flow. However, the effect of incremental changes in contact stress, such as might be considered for GB national standards, are rarely dealt with explicitly by the available research which tends to concentrate on the fundamental damage mechanisms rather than the system level effects.

The influence of wheel diameter (as proxy for contact stress) on a number of rail damage mechanisms / models was investigated for a range of diameters from 1100 mm to 600 mm. It was found that

- The Whole Life Rail Model (a Ty based Rolling Contact Fatigue damage model [7]) and Archard wear model predicted no increase in RCF damage or wear as a consequence of reducing wheel diameter.
- A finite element based analysis of plastic work predicted that reducing wheel diameter will lead to increased plastic work and reduced rail life for sites currently experiencing high levels of plastic work. These typically include the low rail of small radius curves. The relationship between plastic work and rail life is not yet mature and requires further development.
- Shakedown analysis predicted an increase in subsurface fatigue initiation as a result of reducing wheel diameter. However there is limited confidence in relating shakedown predictions to observed track damage.

- The propensity for squat damage was found to increase marginally with reducing wheel diameter. However there is low confidence in the existing damage model.

There was not found to be a limiting Hertzian contact stress (or Q/D ratio), beyond which a step change in rail damage would occur. Current understanding of the engineering science alone does not therefore provide a clear limit to contact stress or Q/D ratio. It is likely that the effective limit is the point at which the contact stress driven damage becomes unsustainable from the point of view of track maintenance (costs of inspection, maintenance and renewals).

## Conclusions

Approximately 20% of freight vehicles on the GB network (on an annual wheelset mileage basis) operate with Q/D ratios in excess of the current limit of 0.13 kN/mm.

The shape of the worn wheel profile (a function of the vehicle type, bogie type, operating conditions etc.) has a greater influence on contact stress than Q/D ratio. A similar result was found when considering the influence of wheel wear (measured as tread loss). The best available evidence suggests modest increases in contact stress (as a result of increased Q/D from smaller wheels) would not lead to a step change in contact stress related damage.

The work reported in this paper formed part of a larger investigation into the potential for reducing the minimum wheel diameter of freight vehicles operating on GB railways. From the investigative work the research project concluded that, despite some shortcomings, Q/D ratio is the best available (most practical) proxy for Hertzian contact stress and contact stress driven damage, within the scope of a national standard. Including the effects of the lateral wheel profile shape would provide a more accurate estimation of Hertzian contact stress and potentially provide a closer control of contact stress. However the means to do so are considered too complex for practical implementation within the standards.

As current engineering science does not predict a step change in contact stress driven damage (within the range of conditions investigated), an access charge which includes a contact stress based weighting for freight vehicles could be envisaged in the long term. This would both incentivise reduced contact stress and provide an economic balance to the effects of increased contact stress. The control parameter could be Q/D ratio (accepting the limitations of this measure) or a more sophisticated, and therefore complex, approach based on wheel profile shape. However, a stronger evidence base, linking contact stress related damage to costs on a system-wide basis, would be required before such a regime could be implemented.

Based on the investigation, a proposal for change to the GB standard [1], increasing the permitted Q/D ratio and providing greater clarity on the assessment method, is now being progressed. This will improve the efficiency of freight operations by permitting smaller diameter wheels without compromising infrastructure performance or maintenance.

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