

Effects of Increased Axle Loadings on Local Roads

Dave Stevens, Graham Salt: GeoSolve Pavements Group

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Summary

While heavy vehicle loads will provide benefits once they reach their destination, some axle configurations applied to local roads will contribute disproportionately large adverse effects on the road pavements en-route. Unless the affected pavements have been designed to carry the extra loading, heavily loaded axles will inflict an exceptionally large proportion of additional wear on local pavements. The usual result is premature distress to a terminal condition which necessitates full structural rehabilitation or reconstruction rather than periodic resurfacing and maintenance.

A substantial increase in heavy vehicles on any road that is not designed to take the additional loads will involve multiple adverse effects in the form of:

- increased routine maintenance / resurfacing frequency
- reduction in level of service (as the pavement ages more rapidly) resulting in increased vehicle operating costs
- reduced structural life of the existing pavement resulting in bringing forward road reconstruction; thus requiring the necessary funds earlier than expected
- increased reconstruction costs due to the increase in required structural capacity
- added constraints and cost of control measures (eg. lower speed limits, signage, turning lanes, lane widening, islands, pedestrian or cycle-ways, removal of spillage to maintain safety and restore smooth traffic flow)
- environmental (ie. gaseous emissions and noise pollution)

This paper explains reasons for the increased road pavement wear and summarises state-of-the-art methodology for quantifying the adverse effects on the road pavement due to increased axle loadings, with an example provided in relation to a quarry truck loading.

Introduction

There is well developed precedence established in legislation and by other¹ road controlling authorities (RCAs) relating to the principles for assessing impacts of developments:

Under Section 17 of the Resource Management Act,

Every person has a duty to avoid, remedy, or mitigate any adverse effect on the environment arising from an activity carried on by or on behalf of the person, whether or not the activity is carried on in accordance with—

(a) any of sections 10, 10A, 10B, and 20A; or

(b) a national environmental standard, a rule, a resource consent, or a designation.

¹ Queensland Government, (2006). Department of Main Roads. *Guidelines for Assessment of Road Impacts of Developmental Proposals*. Brisbane.

As a result, a development's road impact is typically considered insignificant if traffic numbers and loadings in terms of Equivalent Single Axles (ESAs) increase by less than 5% from existing levels.

Developers are expected to provide or fund the provision of all roadworks that are required as a direct consequence of their development. An example is a road with an expected low volume of heavy vehicle use requires upgrading to accommodate a significant increase in heavy vehicles due to a development proposal.

The concept of "bring forward" costs is one means of assessing additional cost to an RCA.

"Bring forward" methodology determines the quantum of the difference between the discounted present value of the cost of construction of works as programmed or expected by the RCA and the discounted present value of the cost of construction of the same works, required to mitigate a development's impacts, at an earlier time. In order to quantify costs of a development's mitigation measure, it is necessary to determine when the roadworks are required by the development and when those roadworks would normally have been provided by the RCA.

This methodology has a limitation in that while it is simple in concept, in some cases it may not address all impacts, and may therefore may not be the sole mitigation measure.

The use of the "bring forward" methodology to mitigate impacts...may be unacceptable... due to funding contingents and competing priorities. In these instances, other assessment methods need to be considered by the proponents to mitigate their development impacts to an acceptable level.

For this reason the "bring forward" methodology should be regarded as only a tool to establish a lower bound contribution to road works. There will inevitably be several different standpoints for the issue. The drawback to the above methodology (and that in other Australian documentation²) is that it implicitly places zero value on the existing roading asset. As illustration, if the roads affected by a quarry development happen to have a 50 year life, and that gets halved to 25 years with additional traffic, there will be minimal payment required from the developer, compared to a parallel situation on a route where the structural capacity is less (existing 20 year life gets shortened to 10 years). Both imply the traffic loading would have doubled, but in the former case, using only the "bring forward" methodology would enable the developer to reap the benefits of the greater asset value established previously with ratepayers funding. Arguably, some circumstances may need to consider consumption of existing assets as well.

The option of upgrading the route prior to increased trafficking so that it will provide the same pavement life as before would compensate the existing users of the route, but would be inefficient, and still leave a shortfall for routine maintenance.

Several alternatives could be applied to meet the above principles for impact assessment:

A - Zero asset value option:

- (i) Determine the future life cycle costs for the route (ie. structural forward work programme) under the existing traffic using an appropriate mechanistic model, discussed further below.
- (ii) Repeat the above with the existing plus additional traffic.

² Martin, T. (2000). *Assessment of additional infrastructure costs due to increased axle mass limits*. Vermont South, Vic: ARRB Transport Research

- (iii) Using graphs of cost versus year from the two models above, calculate the difference in cost each year, and hence discount to obtain the net present value of imposing the additional traffic.

B - Equivalent pavement life option (similar to above, with changes italicised):

- (i) Determine the future life cycle costs for the route (ie. structural forward work programme) under the existing traffic using an appropriate mechanistic model, discussed further below.
- (ii) Repeat the above with the existing plus additional traffic *but in the first year of the FWP, determine the incremental cost to upgrade each treatment length of the road pavement to a standard so that each treatment length will have at least the same structural life and no greater maintenance requirements with the additional quarry truck loading as would normally be carried out on the route under existing traffic loading.*
- (iii) Using graphs of cost versus year from the two models above, calculate the difference in cost each year, and hence discount to obtain the net present value of imposing the additional traffic.

C - Full life cycle (25-year) pavement life option (similar to above, with changes italicised):

- (i) Determine the future life cycle costs for the route (ie. structural forward work programme) under the existing traffic using an appropriate mechanistic model, discussed further below.
- (ii) Repeat the above with the existing plus additional traffic but in the first year of the FWP, determine the incremental cost to upgrade each treatment length of the road pavement to a standard so that each treatment length will have at least the same structural life (*or not less than 25 years, whichever is greater*) and no greater maintenance requirements with the additional quarry truck loading as would normally be carried out on the route under existing traffic loading.
- (iii) Using graphs of cost versus year from the two models above, calculate the difference in cost each year, and hence discount to obtain the net present value of imposing the additional traffic.

Option C is likely to be the most appropriate in practice. In general, the key to equitable cost apportionment lies in accurate valuation of the asset using a soundly based procedure for quantifying pavement structural life under both existing traffic loadings and the proposed additional loadings. In the past, such procedures have been contentious, difficult and of low reliability. However, recent developments have transformed the state-of-the-art to the stage that dependable and sustainable quantification of pavement life can now be simply established for the majority of pavement types.

There are important financial implications attached to the net present value approach. The adopted discount rate will need to be negotiated, bearing in mind what current rates of return are available to the RCA, losses from taxation of interest on held funds, and an allowance for future proofing which may be required to reduce risk. An alternative is to transfer these risks to the developer by implementing payments progressively at the time expenditure is required instead of discounting to net present value. With this option, the quarry owner can progressively adjust an appropriate tariff per tonne of product.

Pavement Structural Life Evaluation

Impact of Increased Number of Vehicles

Where the number of vehicle passes per lane increases (assuming the spectrum of axle loads remains constant), the road pavement structural life calculation is straightforward as it is often assumed that structural wear will increase pro-rata with increasing passes. Accordingly, pavement life will decrease pro-rata. This tends to be the case for typical NZ road pavement construction, such as unbound granular pavements with chip-seal surfacing as well as those with thin asphaltic concrete surfacing, so long as regular maintenance and resurfacing is continued in order to offset environmental aging of binders. Maintenance costs are governed by both environmental factors and traffic loading, hence they will need to be accounted for separately in these pavement types and also for thick structural asphaltic concrete pavements.

Impact of Increased Axle Loads

It has long been recognised that small increases in individual axle loadings induce disproportionately large decreases in road pavement structural life; hence pro-rata calculation is inappropriate (and unconservative).

AASHO Road Test

The concept of exponential wear rates originated in the late 1950's with a major US study of test pavements subject to heavily loaded vehicles. Pavement wear was found to relate to the ratio of each axle load to an equivalent standard (8tonne) axle load (ESA) raised to the 4th power. In effect this means that for a pavement designed to last 25 years under 80 kN axles, if subject to the same number of axle loads but 20% heavier (ie $1.2 * 80 = 96$ kN), the wear will increase exponentially by 1.2 raised to the 4th power (ie 2.07). Hence the pavement structural life would then be expected to reduce to about 12 years rather than 25 years. The 4th power was used for many decades before researchers proposed a wider range of what were then termed load damage exponents.

Austroroads

The Austroroads Pavement Design Guide³ has picked up on various studies that found different pavement types could exhibit load damage exponents⁴:

- The pavement wear measure used was the number of standard axle repetitions (SAR) calculated for each vehicle type using the relevant wear relationship for each pavement type outlined in *Austroroads Pavement Design Guide (2004)*. Wear of sealed granular pavements is related to the 4th power law of the axle group load and its wear measure is referred to as SAR4 (i.e. ESA). For asphalt and cemented pavements, the wear is related to the 5th and 12th powers respectively and their wear measures are referred to as SAR5 and SAR12 respectively.

The SAR4 is intended to be used for "general" wear, but if subgrade rutting is identified as the sole distress mechanism, then Austroroads indicates a 7th power law should be used. Earlier Austroroads studies recommended a much higher exponent of 18, which was then reduced to 12 for cement bound basecourses.

³ Austroroads Guide to Pavement Technology <https://www.onlinepublications.austroroads.com.au/items/AGPT02-12>

⁴ Austroroads (2009) AP-T116/09, High Productivity Vehicles and Pavement Economic Impacts: Network Level Assessment Approach

To illustrate the consequences of different load damage exponents (LDE), the corresponding wear for a range of increases in axle loadings are given below.

		Load Damage Exponent (LDE)					
		1	2.7	4	8	12	18
% increase in axle load	0%	25.0	25.0	25.0	25.0	25.0	25.0
	10%	22.7	19.3	17.1	11.7	8.0	4.5
	20%	20.8	15.3	12.1	5.8	2.8	0.9
	30%	19.2	12.3	8.8	3.1	1.1	0.2

Table 1: Load Damage Exponent (LDE) - Pavement Life (Years) – Showing the Decreased Life for given % increase in standard axle load, for various Load damage exponents

From the above table, a 20 percent increase in axle load with a load damage exponent of 12 would be expected to reduce pavement life by almost an order of magnitude from 25 years to 2.8. The high sensitivity of the life prediction necessitates that the exponents are calculated reliably.

Until recently, a major limitation in the estimation of load damage exponents was that the only methods available were accelerated pavement testing on trial pavements using a series of different axle loadings (such as CAPTIF), or laboratory triaxial testing. Early New Zealand testing produced load damage exponents of typically 1.5-2.5 for general pavement wear, which is contrary to most other international research which invariably produced higher values. A reassessment of the same data, using more rigorous procedures, produced load damage exponents of 6-8 for subgrade rutting (similar to Austroads).

New Zealand Studies of in-service unbound granular pavements with thin surfacings.

Recently, a comprehensive study⁵ of all available pavement structural analyses from local unbound granular pavements was initiated to see what lessons could be learnt from the database of over a million Falling Weight Deflectometer (FWD) tests collected over the last 20 years. The Regional Precedent Performance (RPP) Project produced a number of unexpected outcomes, including particular insights into the pavement wear of unbound granular pavements.

Findings pertinent to wear in New Zealand pavements (ie. in situ data from in-service pavements rather than test pavements) are:

- Using newly developed data-analysis techniques⁶, load damage exponents can now be quantified for all treatment lengths in any region although a relatively large number of structural analyses from any one region is required (about 50,000 data points for good reliability).
- Load damage exponents can be determined for each distress mode and for the layer that will govern pavement life. Any method derived from an artificial test environment or based on the long outdated “structural number” approach is likely to produce inappropriate exponents (unless subgrade rutting is the terminal trigger for rehabilitation). Basecourse wear under heavy traffic or excessive maintenance costs will not be accounted for at all.

⁵GeoSolve (2015) Regional Precedent Performance Study of Pavements. Structural Life, Rehabilitation & Medium Term Forward Work Programme:

⁶ Reviewed (and commended) by Per Ullidtz, instigator of the ELMOD software and key contributor on CALME.

- Exponents vary markedly: 3 to 11 with medians of 6 for basecourses and 8 for subgrades are typical for wear of unbound structural layers in NZ pavements from studies of multiple regions. It is now a straightforward process to identify the distress mode and relevant critical layer, then determine the relevant load damage exponent.
- Exponents vary minimally for wear in thin seal surfacings: 2.5 to 3 with a median of 2.7, although these results are preliminary from studies currently in progress.

The Auckland region has a suitable database, and reliable determination of load damage exponents using the RPP procedures has been carried out for the majority of treatment lengths.

Maintenance Costs

Maintenance costs for roads that reach a terminal condition through roughness have been addressed by Martin (2000) for a selection of Australian pavements. Alternatively, for New Zealand pavements, the preliminary study of surfacings noted above has identified that the incremental load related damage to thin asphaltic or seal surfacings is given by a median exponent of 2.7. Hence if maintenance costs are known for the existing traffic, increased costs for additional ESAs can be approximated in advance if more detailed information is not available. Maintenance costs could also be adopted as provisional and subject to adjustment periodically as they are incurred.

Forward Work Programme

Along each route proposed for increased traffic, provided the relevant deflection test (FWD) data are available, the vital first step is to determine homogeneous structural treatment lengths methodically from structural analysis. The pavement life for each distress mode for treatment length can then be readily calculated using the loadings (derived with the correct load damage exponents) for both the existing traffic and the proposed increased traffic. Because distress mode can be identified, the most applicable treatment can also be determined so that multiple life cycles can be modelled with their associated costings.

Applying this procedure over all treatment lengths enables structural rehabilitation costs to be plotted against time for both the existing and proposed traffic scenarios. The difference in cost (ie the component relating to the increment in traffic) is then discounted to net present value to provide the lower bound cost of the proposed development excluding any valuation of the existing asset (Option A).

Because the remaining life of each treatment length under the existing traffic can readily be extracted from the above, each treatment length could then be modelled assuming immediate upgrade to carry the proposed traffic for the same life (Option B).

The same calculations could also be repeated using a minimum 25 year life rather maintaining the existing life if it is significantly greater (Option C).

The roads used by quarry trucks from an Auckland quarry, have been assessed using the above techniques and the impact of the increased quarry truck traffic on the road pavements is outlined below. The total length of road network analysed in this example is 14 km,

Example Quarry

- The full output for each Forward Work Programme is a spreadsheet which lists all structural treatment lengths in the route and gives the year in which each treatment length needs to be rehabilitated, the distress mode, and type of treatment required (normally running to at least 10 years but runs of 25 to 50 years are sometimes required before discounted costs

become negligible). Accuracy diminishes progressively with time, but when the same assumptions are applied to two comparative traffic loading scenarios, the net difference in cost still has reasonable reliability allowing informed decision making.

- The following example is for a roading network which was to be subjected to increased traffic from a new quarrying operation. The following figures are a summary of the full FWP and show just the year, type of rehabilitation, cost and number of lane kilometres experiencing a terminal condition from given distress modes.
- The increased traffic loading from the quarry is such that the total design traffic is excessive for an unbound granular pavement, and in this case, a higher quality (stiffer and more durable) structure such as a foamed bitumen pavement is recommended to meet the required structural capacity.

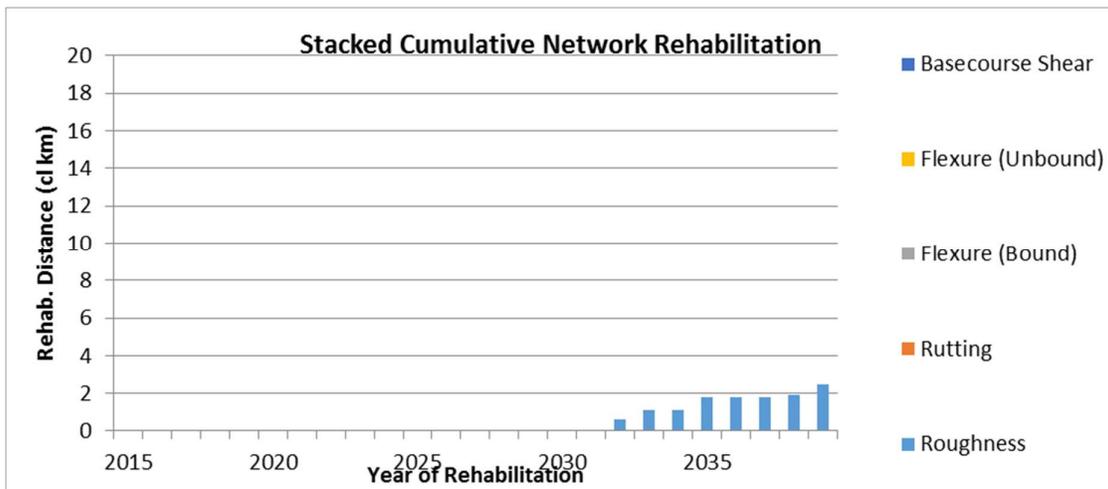


Figure 1a - Distress Modes and Annual Rehabilitation Treatments for the Existing Traffic (showing no rehabilitation would normally be required before 2032).

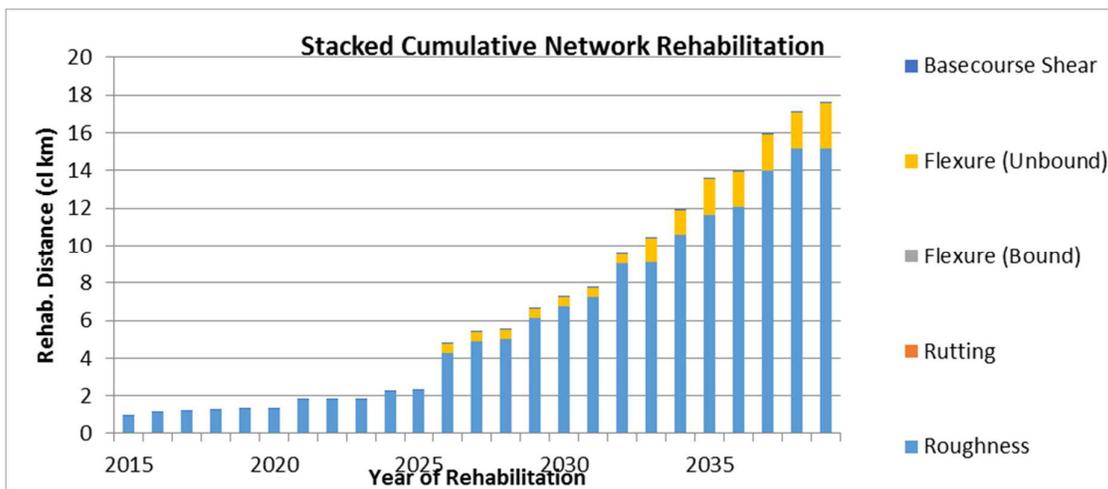


Figure 1b - Distress Modes and Annual Rehabilitation Treatments for the Proposed Quarry Trucks in combination with Existing Traffic (showing that some rehabilitation would be required from the outset in 2015 and after 2026 there would be a marked increase in the rehabilitation requirements).

This example illustrates the observation that the effect of increased loading does make a large difference to the amount of maintenance done in the long term, and that the date of rehabilitation is brought forward. It is the time cost of that earlier expenditure that affects the NPV calculation. Present value is calculated using present day construction costs and the discount rate established by the client. The discount rate used is based on NZTA and NZ Treasury advice and does not include inflation.

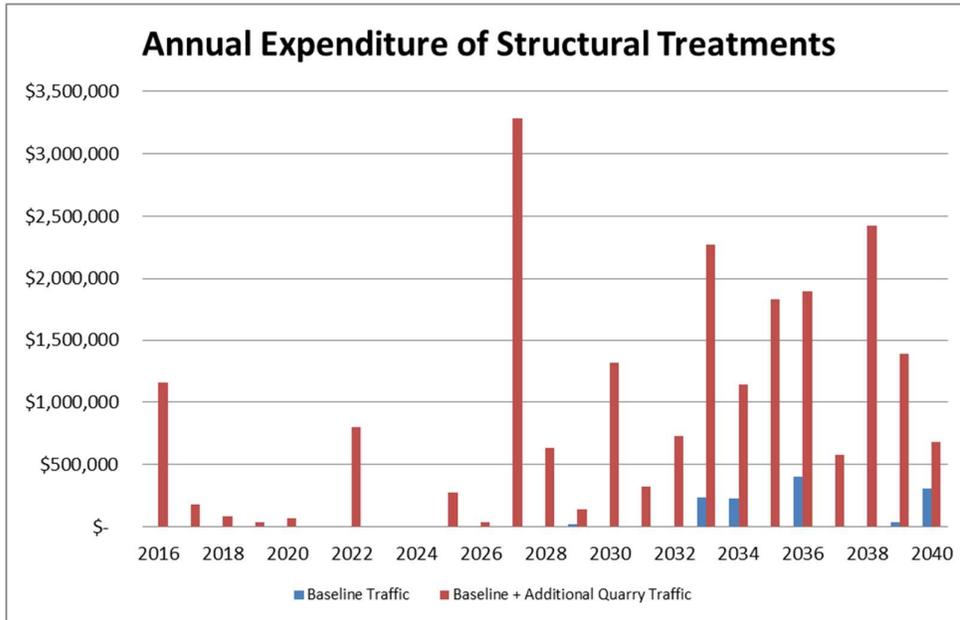


Figure 2a – Annual expenditure for pavement structural rehabilitation treatments.

The above bar graphs show that the expected costs of rehabilitation for the baseline case (blue bars) and additional quarry traffic (red bars). The same costs are shown as cumulative plots below.

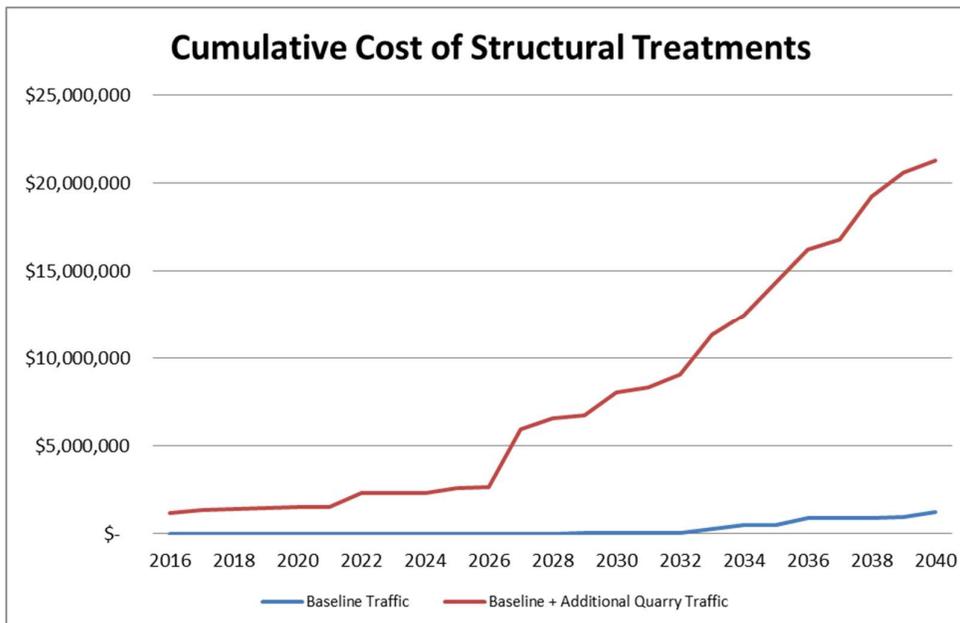


Figure 2b - Cumulative cost of pavement structural rehabilitation treatments.

The blue line shows the relatively minor cost of the existing (baseline) traffic while the red line shows the markedly higher cost of rehabilitation treatments for the existing traffic plus the additional quarry trucks. The difference between the two is used to calculate the net present value, which is the incremental cost incurred by the RCA and attributable to the quarry traffic specifically (not including existing traffic).

Other effects of increased quarry traffic

The impacts discussed so far are those for which there are well prescribed techniques to calculate the added costs of increased traffic, but there are other impacts that require site specific appraisals to establish optimum solutions. Rural roads usually have narrow traffic lanes and a surface water channel on each side of the road. This road pavement construction is adequate for low levels of heavy commercial traffic, however with increasing pavement loading due to quarry truck traffic, the additional loading often over-stresses the edge of the road pavement resulting in loss of edge support followed shortly thereafter by edge break and shear failure along the edge of the road, with associated substantial impacts on maintenance costs. Lane widening may be necessitated; as truck and trailer units tend to track along a wider traffic path on corners than normal traffic, thus requiring a wider traffic lane than normal traffic.

Other issues to evaluate are control measures, such as lower speed limits, signage, turning lanes, islands, lateral shoving on roundabouts, pedestrian or cycle-ways, or removal of spillage to maintain safety and restore smooth traffic flow. Environmental issues to consider are increased gaseous emissions and noise pollution.

Conclusions

From widespread testing of in-service pavements, using a new technique, it is now clear that the conventional fourth power law that has been used traditionally for estimation of pavement wear, applies primarily to high quality highways with thick structural asphaltic concrete (as were trafficked in the original 1959 study that led to the widespread use of this exponent). Substantially higher exponents apply to most local roads. As a result, there may well be a Goldilocks⁷ effect where heavy axle loads are used on roads for which they were not designed

Historically, quantification of such wear has been contentious and uncertain. Recent advances in pavement asset management technology, coupled with the comprehensive RAMM database available for many regions, now enable straightforward and more reliable quantification of pavement wear and the associated costs (if any) - once the existing and proposed future axle loadings (weights and numbers) are defined. The new technique provides a game changer in that the cost and uncertainty of determining load damage exponents from artificial test tracks is no longer necessary.

A load damage exponent applies not just to a particular material type with given compacted state and water content but is also governed by the stresses and strains (both compressive and shear) in that layer and its support. The principles are now established and specific damage exponents for any route or axle combination can now be well substantiated when assigning road user charges. It is important to consider both the “bring forward” costs of the added wear, as well as the consumption of existing assets for equitable apportioning of future costs

While small increases in axle loads can generate disproportionately greater wear, the converse is equally true hence better distribution of a given gross weight by using a truck and trailer with one additional axle could radically reduce pavement wear. This enables transport operators to work in with an RCA to establish optimal axle loadings (and possibly long term planning towards axle configurations which will provide optimal solutions).

⁷ Analogy to convey non-technically the impacts of consumption, destruction and occupation.