

CURRENT ISSUES FOR MECHANISTIC PAVEMENT DESIGN

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ABSTRACT

Mechanistic pavement design programs such as CIRCLY are used to calculate elastic strains at subgrade level and at the underside of asphalt and stabilised layers. Pavement life is then calculated using empirical equations that relate these strains to load repetitions that cause unacceptable rutting of the surface, or cracking of the asphalt and stabilised layers. This paper discusses four issues currently faced by designers in using to produce pavement designs that are consistent and appropriate. The issues are:

- the choice of appropriate failure criteria
- the treatment of vehicle wander
- negative vertical subgrade strains that can lead to anomalous design results for some pavement geometries
- design of asphalt-surfaced granular pavements,

The first three issues primarily impact the design of heavy duty pavements. The last issue relates to proposed changes to the Austroads (1992) Pavement Design Guide as published in the 2001 Draft Guide (Austroads, 2001).

INTRODUCTION

Mechanistic pavement design methods, including the Austroads method (Austroads, 1992), typically use layered elastic analysis to calculate traffic-induced elastic strains in pavements. Critical strains are then empirically related to the rate at which pavements deteriorate by calibration against observed performance of test pavements or in-service pavements. The vertical compressive strain at subgrade level is related to the repetitions to cause surface rutting, and the tensile strain at the underside of the asphalt and stabilised layers is related to repetitions to cause cracking of those layers. The strains are usually referred to as 'pavement performance indicators' and the empirical performance relationships are often called 'failure criteria'. For example, the 'rutting criterion' or 'subgrade failure criterion' is presented in the following form:

$$N = \left[\frac{k}{\epsilon} \right]^b \quad (1)$$

where N is the predicted life (repetitions of ϵ), and

k and b are constants determined by calibration against the observed performance of pavements trafficked to failure, and

ϵ is the load-induced elastic strain at subgrade level

Because each failure criterion is derived in the context of its own detailed design procedure, it will only produce sensible pavement designs when used as part of that same procedure. If a failure

criterion is used in conjunction with a different design procedure, the vital empirical link between the design and the original performance data used to calibrate the criterion is broken.

The “context” of a pavement design procedure consists of the following six elements:

The pavement model: Each design method uses its own representation of the pavement structure (called a pavement model) to compute critical strains. This involves following guidelines for assigning elastic moduli to the various pavement layers. Unbound layers are usually “sub-layered” in order to better model their non-linear response. If a different model is used, the computed strains caused by a vehicle will be different, and the failure criterion that is then derived from performance data using the different strains will also be different.

Vehicle loadings: Each design method has within it a procedure for converting the number of vehicle passes along the pavement to strain repetitions. Most highway design methods, such as Austroads (1992), convert the actual traffic mixture of wheel groups and wheel loads to Equivalent Standard Axles (ESAs). This contrasts with methods typically used for heavy duty pavements such as those catering for aircraft and container handling equipment. Here the critical pavement strains are calculated using the actual wheel configurations and wheel loads; no simplifying transformation to greater numbers of “equivalent” smaller loadings is involved.

Vehicle wander: Successive vehicles moving along a wide pavement such as an aircraft runway or a container-loading area do not follow the same path. The degree of channelisation will be much less than that of roads where vehicles tend to move in narrow marked lanes. The spreading of loads across the pavement to different degrees affects the required pavement thickness. Although the Austroads’ procedures takes typical highway wander into account through calibration of the design system against in-service performance, a variable wander parameter is not provided to enable the designer to consider the effect of atypical wanders such as those relevant to container terminal pavements.

Project reliability: Although it is not always explicitly stated, each design method has its own inherent reliability. Different failure criteria can be derived from identical performance data to give designs with different degrees of reliability. For example, the US Army Corps of Engineers design method has a reliability of 50%, which means that pavements designed using the failure criterion are as likely to last for more than the design repetitions as they are to fail before all the design repetitions have been applied. The reliability for the Austroads rutting criterion is based on the empirical thickness design chart for unbound granular pavements with thin bituminous surfacings. This chart, and hence the performance relationship for rutting and shape loss is expected to result in appropriate levels of project reliability across the range of design traffic levels covered in the Guide.

Pavement condition at end of design life: Each design method has its own defined end of life pavement condition. This may be expressed, for example, as a degree of rutting, or pavement roughness that was deemed to be operationally unacceptable on the test pavements or roads used to empirically determine the constants k and b of the failure criterion.

Pavement performance data: A fundamental limitation of any empirical method is that extrapolation beyond the empirical data base used to calibrate the method cannot be made with confidence. For example, if the failure criterion constants k and b in eqn (1) are determined by calibration against the observed performance of pavements trafficked to failure by, say, 4 tonne wheel loads, the criterion is not suitable for pavements trafficked by, say, 20 tonne wheel loads.

All pavement design systems are just that - a system - which requires validation with the performance of real pavements designed using the system. When one or more elements of the system are changed, while these changes may be well justified at a detailed level, the impact of these changes on the whole system needs to be carefully considered. Any change to any element will result in a change to the system’s failure criterion.

This paper discusses four issues currently faced by designers in using mechanistic pavement design programs such as CIRCLY to produce pavement designs that are consistent and appropriate. The issues are:

- the choice of appropriate failure criteria
- the treatment of vehicle wander
- negative vertical subgrade strains that can lead to anomalous design results for some pavement geometries
- design of asphalt-surfaced granular pavements,

The first three issues primarily impact the design of heavy duty pavements. The last issue relates to proposed changes to the Austroads (1992) Pavement Design Guide as published in the 2001 Draft Guide (Austroads, 2001).

PAVEMENT DESIGN FOR HEAVY WHEEL LOADS

The Austroads empirical rutting criterion, having been developed for highway loadings, will not be fully applicable for the much higher wheel loads used on airfields, docks, container terminals and mine haul roads. Criteria based on pavement performance data that is more relevant in terms of loads and loading patterns typical of these off-road applications are available.

Table 1: Comparison of Pavement Life Predictions (N, number of strain repetitions).

Design Method	Subgrade strain				
	0.0005	0.0008	0.0010	0.0015	0.0020
Austroads (1992)	616 x 10 ⁶	22 x 10 ⁶	4.4 x 10 ⁶	240,000	30,000
Shell (1985) (50% reliability)	9.8 x 10 ⁶	1.5 x 10 ⁶	620,000	120,000	38,000
Shell (1985) (95% reliability)	1.7 x 10 ⁶	260,000	105,000	21,000	6,500
Brown and Brunton (1984)	620 x 10 ³	130,000	58,000	14,000	5,000
British Airports Authority (Woodman, 1992)	1.3 x 10 ⁶	90,000	25,000	2,400	460
Wardle and Rodway (1998)	1.5 x 10 ⁶	68,000	15,000	1,000	160

Table 1 lists the pavement life predictions (repetitions of strain) that are obtained by using the failure criteria from several published pavement design methods (for further details of this study see Rodway and Wardle, 1998). As can be seen, there is no agreement between the strain repetitions to failure. Agreement should not be expected, however, because, as explained in the introduction to this paper, each failure criterion has been derived in the context of its own detailed design

procedure, and will only produce sensible pavement designs when used as part of that same procedure.

The nature of the pavement performance data used to derive each failure criterion is an important element of the context. If, for example, the wheel loads used in the test pavements were significantly different from those for which a pavement is now to be designed, the design will not be valid. The importance of wheel load is explained in the following paragraphs.

It has been argued (Woodman, 1992) that the relationship between subgrade vertical strain and permanent deformation of the pavement surface is dependent on wheel load. The reasoning is as follows.

Pavement design methods based on controlling surface rutting by limiting the elastic strain at the top of the subgrade rely on two assumptions. Firstly, it is assumed that most surface rutting is due to subgrade deformation rather than the combined deformation of the overlying pavement layers. Secondly, it is assumed that the subgrade plastic (permanent) deformation is related to the magnitude of its elastic (temporary or recoverable) strain. Given these assumptions, the integral of the elastic strain with depth into the subgrade should provide a better measure of surface rutting than that provided by the strain at the top of the subgrade.

The concept is illustrated in [Figure 1](#). The CIRCLY-calculated vertical strains beneath a 20 tonne and a 4 tonne wheel have been plotted against depth. The heavier wheel represents those typically used on large aircraft, mine-haul vehicles and industrial equipment of the kind used on docks and container terminals. The 4 tonne wheel represents the heaviest highway wheel. The two pavement thicknesses have been chosen so that both loads produce the same maximum vertical compressive strain, 0.008, at subgrade level.

It can be seen that the vertical strains within the subgrade are greater in the case of the heavier wheel load. The permanent deformation at the pavement surface due to the heavier wheel will be greater by an amount related to the area between the two curves. That is, equal compressive strains at the top of the subgrade should not produce equal surface rutting when the equal strains result from different wheel loads.

The argument presented above suggests that, for the design of pavements that are to be subjected to very high wheel loads, it is preferable to use design procedures that were developed from relevant performance data. Specifically, the loads used to develop the empirical rutting criterion should be as similar as possible to those that are to traffic the pavement. The Austroads empirical rutting criterion, having been developed for highway loadings, is unlikely to be applicable to the design of pavements to cater for the much higher wheel loads used on airfields, docks, container terminals and mine haul roads.

Full-scale pavement testing was conducted over many years by the US Army Corps of Engineers to develop an aircraft pavement design method, designated as S77-1 (Pereira, 1977), to cater for high wheel loads, thick pavement structures, a variety of wheel arrangements, and large and variable degrees of vehicle wander. Data from 37 test pavements trafficked to failure by wheel loads up to 27 tonnes were used to develop the method. A layered elastic design procedure, APSDS (Airport Pavement Structural Design System), has now been calibrated against S77-1 (Wardle, Rodway and Rickards, 2001). This allows the designer to access the full advantages of the layered elastic method, including treatment of wander, to produce pavement designs that are consistent with S77-1.

A feature of the APSDS calibration is that the failure criterion 'constants' depend on the CBR of the subgrade.

Regression analyses using third-order polynomials for the variation of k and b with subgrade modulus (E) in units of MPa give the following:

$$k = 1.64 \cdot 10^{-09} E^3 - 4.31 \cdot 10^{-07} E^2 + 2.18 \cdot 10^{-05} E + 0.00289$$

$$b = -2.12 \cdot 10^{-07} E^3 + 8.38 \cdot 10^{-4} E^2 - 0.0274 E + 9.57$$

As discussed in the Introduction, each rutting criterion is developed in the six-element context of a particular detailed design procedure, and will only produce valid pavement designs when used as part of that same procedure. For example, if the rutting criterion from one procedure is used in conjunction with the pavement model of another procedure, the design outcome is invalid. This is because the vital empirical link between the design and the original performance data used to calibrate the rutting criterion has been broken. Therefore the rutting criteria shown above must be used within the context of the procedures detailed in Wardle et al. (2001).

In summary, APSDS rutting criteria have now been developed from the observed performance of aircraft test pavements subjected to wheel loads of up to 27 tonnes. These loads are comparable to those typically applied to heavy duty pavements applicable to docks, container terminals and mine haul roads. Consequently the APSDS rutting criteria are more suited for the design of these pavements than the Austroads empirical rutting criterion developed for highway loadings.

LATERAL VEHICLE WANDER

Field observations have shown that successive passes of vehicles along a pavement are statistically normally distributed about the pavement or lane centreline. The degree of 'wander' is typically characterised by a standard deviation (SD). For example Ho Sang (1975) found aircraft wander to be significantly different for runways (SD 1600 mm), taxiways (SD 800 mm) and aircraft docking bays (SD about 200 mm). This transverse spreading of load to different degrees due to aircraft 'wander' significantly affects pavement life, and is now routinely taken into account when designing aircraft pavements.

Research on the influence of the width of highway traffic lanes on the wheelpath distribution showed that the lateral wander could be represented by a normal distribution. A typical standard deviation for a 3.66 m (12 ft) wide lane on a freeway was reported to be about 300 mm (Buiter, et al. 1993).

Although the Austroads procedures allow for typical highway wander through calibration of the design system against in-service performance, a variable wander parameter is not provided to enable designers to consider the effect of atypical wanders such as those relevant to container terminal pavements. However, there is widespread recognition of the importance of wander in pavement deterioration models. ARRB Transport Research's Accelerated Loading Facility (ALF) is capable of applying various degrees of wander, and a more rapid rate of deterioration of test pavements has been observed when they are loaded using the narrower distributions.

There may be value in incorporating wander as a design parameter in future road design methods to take account of the effect of lane width and other conditions where traffic may be more channelised, such as on steep grades and around traffic calming devices.

APSDS was developed from the CIRCLY road pavement design program (Wardle, 1999), to include treatment of wander. It is based on a concept described by Monismith et al. (1987). Subgrade strain, the indicator of the rate at which deformation develops at the pavement surface, is computed for all points across the pavement in order to capture all damage contributions from all the wheels in all their wandering positions. This contrasts with the Austroads rutting design procedure in which only single maximum values of the subgrade strain are calculated. The empirical rutting criterion is then derived by calibration against pavement performance data (Wardle and Rodway, 1995). In using the APSDS program, the designer can nominate the standard deviation of wander that is appropriate for a particular pavement and compute its effect on pavement life. Before using APSDS for highway design, it would be necessary to calibrate against highway pavement performance. The calibration would produce a rutting performance relationship that is different from the current Austroads' relationship.

The reduction in pavement damage due to vehicle wander is found to depend upon pavement thickness. It is greater for thinner pavements. This is because the load intensity at subgrade level is spread to a greater degree by thicker pavements, making the additional load-spreading effect of

wander relatively less dramatic. An example (Wardle and Rodway, 1995) showed the effect of aircraft wander upon damage for two depths, as calculated using APSDS. For a 500 mm thick pavement, taxiway wander reduced damage by 80% of that caused in the channelised, no wander case. This contrasted with a 1500 mm thick pavement, where taxiway wander reduced the channelised damage by only 30%.

In open areas of container loading facilities where transporters and loaders are not constrained to move within narrow lanes, there is a considerable degree of wander. In these areas, a thinner pavement is required relative to that needed in areas subjected to channelised trafficking.

THE NEGATIVE STRAIN EFFECT

In dealing with large, non-highway vehicles such as those used on airports, container terminal pavements and mine haul roads, designers typically model the actual wheel arrangements. But as will be explained below, care needs to be taken in choosing how many wheels to include in the model, particularly when subgrade vertical strain is used as a pavement damage indicator.

Pavement damage calculated from subgrade vertical strain can produce anomalous design results for some pavement geometries. This is because, unlike deflections, computed vertical subgrade strains become negative at a radial distance from the load that depends upon pavement thickness and the moduli of the pavement layers and the subgrade (see Figure 2 for an example). The significance when calculating interactions between wheels and also between wheel groups is that, for some geometries, the zone of negative strain generated by one wheel or wheel group falls beneath other wheels or wheel groups and consequently reduces the strain. In these cases adding fully loaded wheels or wheel groups to the model increases rather than decreases pavement life. This seems to be counter-intuitive; it is hard to accept that extra loads on a pavement can increase pavement life. Currently there is no empirical multiple wheel group data available from full-scale accelerated pavement tests that would clarify this issue. The negative strain problem is a reminder that the design model has limitations.

The negative strain problem became apparent in aircraft pavement design several years ago following the introduction of mechanistic methods that, like Austroads, base pavement life predictions on subgrade strains calculated using layered elastic analysis. The arrival of the Boeing B777 in 1995, which has two 6-wheel landing gears, and proposals for future large aircraft with four multiwheeled gears, had focused attention on the need for pavement design methods which could take account of interaction between wheels of multiwheeled gears and also account for the interaction between all gears of the aircraft. The apparent anomalies caused by negative strain have been described previously (Rodway, Wardle and Wickham, 1999). Two examples were provided.

Boeing 777 example: For the 2 metre thick pavement cited, the zone of negative strain occurred at a horizontal distance from the 6-wheel gear of approximately 10 metres, placing it beneath the opposite gear spaced almost 11 metres away. The effect of including both gears rather than a single gear in the layered elastic computation was to reduce the maximum subgrade strain beneath each gear by about 1%, which resulted in an increase in predicted pavement life of about 10%.

Boeing B747 example: The B747 has four 4-wheel main gears. The centre-to-centre spacing between the two rear gears is 3.84 m. This relatively close spacing means that the negative strain effect will be most pronounced for a thinner pavement than the 2 metre pavement used in the B777 example. For the 2 metre thick pavement cited, the centre of the zone of negative strain occurred at a horizontal distance from the gear centre of about 4 metres. The effect of including all four gears rather than a single gear in the layered elastic computation was to reduce the maximum subgrade strain beneath the rear gears by nearly 5%, which resulted in an increase in predicted pavement life of about 40%.

The US Federal Aviation Administration’s full-scale Aircraft Pavement Testing Machine at Atlantic City can accommodate twelve test wheels capable of being configured to represent two complete landing gears having from one to six wheels per gear and adjustable to vary the distance between the gears up to six metres forwards and sideways. Thus the test machine has the potential to investigate gear interaction effects, including the negative strain issue. However, to date the interaction complexities have not been resolved. The current design practice is that where aircraft pavement designs use subgrade strains computed using the layered elastic method, the designs are based on single landing gear loadings. The uncertain interaction effects caused by the aircraft’s other landing gears are not incorporated.

In summary, for heavy duty pavements, where actual wheel groups rather than ‘equivalent’ smaller standard loads are typically used to compute subgrade strains, the negative strain effects can be much larger than those that can arise using the Austroads procedures. Consequently it is recommended that design of off-road pavements be based on subgrade strains caused by single wheel groups. This recommendation is in line with current aircraft pavement design practice where designs are based on single landing gear loadings.

The subgrade negative strain effect also comes into play with proposed changes to the Austroads mechanistic flexible pavement design procedure. The 2003 revision to the Guide [Austroads (2001) and subsequent unpublished drafts] uses a full Standard Axle loading, whereas the current Guide (Austroads, 1992) uses only one half of the Standard Axle. The impact of the subgrade negative strain effect in this case is believed to be minimal because the subgrade damage model has been calibrated using the full axle loading.

STRESS DEPENDENCE OF GRANULAR LAYERS

The design of granular pavements with relatively thin (<100 mm) of asphalt as a wearing surface using the Austroads mechanistic design procedure is often a difficult task. This due to:

- the nature of the relationship between the modulus of the upper sublayer of the granular material and the design thickness of granular material that results; and
- the fact that within this thickness range for asphalt the behaviour changes gradually from controlled strain to controlled stress.

This means that there are certain combinations of design parameters where dual thicknesses of asphalt are obtained from the design process. The reason for this is explained in Appendix 8.1 of Austroads (2001) and illustrated in [Figure 3](#).

For relatively thin asphalt layers (<100mm) it is often difficult to reconcile which design thickness to adopt. For example, from Example Design Chart EC03 of Austroads (2001), for a design traffic of 10⁶ ESAs, the designs in [Table 2](#) all satisfy the structural design criteria.

Table 2 – Acceptable Design Criteria from Example Chart EC03 (Austroads, 2001)

Asphalt thickness	85	75	50	25
Granular thickness	275	350	350	275
Total thickness	360	425	400	300

Which combinations of values should be selected? Before a selection is made, the design assumptions should be considered and, in particular, the likelihood of achieving these design assumption in practice.

The design assumptions include:

- the asphalt is homogeneous in terms of thickness and modulus (and hence density); and

- the loading on the pavement is vertical only and of uniform stress. (This is not the case in many situations and particularly in high stress areas, such as intersections and roundabouts where there are heavy vehicles turning on sharp radii curves, where there will be high shear and torsion stresses, and increased vertical loads due to centrifugal forces. Increased dynamic loads may also occur on rough roads and near traffic calming devices. Increased shear forces also occur on climbing lanes and in areas of acceleration and deceleration such as near intersections.

Construction and maintenance issues also need to be considered. The fatigue life of asphalt is dependent on the support provided by the underlying layers and so it is important to ensure that granular supporting layers have high stiffness which is maintained throughout the life of the pavement. Water ingress into the granular layers may cause rapid deterioration of the pavement.

The use of thicker layers of asphalt will assist in alleviating many of these problems. There is less chance of variations in density, and thicker asphalt is generally more stable than thin layers and also more impermeable. If thicker layers are used and there is still concern about deformation resistance, Polymer Modified Binders may be applicable.

If asphalt layers less than about 40 mm in thickness are proposed, unless they are used in lightly-trafficked situations with low traffic stresses, they should really only be considered as a wearing surface and little heed paid to their structural contribution.

While the thinnest pavement in Table 2 may appear to be initially attractive, for design traffic of 10^6 ESAs, unless there is excellent control over construction and well planned proactive maintenance in a dry environment with a benign traffic regime, it may not provide the optimum whole-of-pavement cost.

The sensitivity between granular layer thickness and modulus of the top granular sublayer needs very careful consideration when using the automated layer thickness design procedures that are incorporated into CIRCLY 4.0 and later versions. If the model is set up using the procedure suggested above and the automated thickness design routine is used for the asphalt layer, an erroneous result may occur if the final design is not rechecked with the moduli values suggested in Austroads (2001) Table 6.3.

CONCLUSIONS

APSDS rutting criteria have now been developed from the observed performance of aircraft test pavements subjected to wheel loads of up to 27 tonnes. These loads are comparable to those typically applied to heavy duty pavements used at docks, container terminals and on mine haul roads. Consequently the APSDS rutting criteria are more suited for the design of these pavements than the Austroads empirical rutting criterion developed for highway loadings.

Although the Austroads' procedures takes typical highway wander into account through calibration of the design system against in-service performance, a variable wander parameter is not provided to enable the designer to consider the effect of atypical wanders such as those relevant to container terminal pavements. Wander is important for heavy duty pavement design where large and different degrees of wander occur on different areas of the pavement. APSDS rationally incorporates wander into the pavement design procedure and is now widely used for airports and container terminals.

For heavy duty pavements, where actual wheel groups rather than 'equivalent' smaller standard loads are typically used to compute subgrade strains, negative strain effects can give anomalous behaviour. Consequently it is recommended that these designs be based on subgrade strains beneath single wheel groups, that are due to the group itself; interactions with other wheel groups should not be included. This recommendation is in line with current aircraft pavement design practice where designs are based on single landing gear loadings.

The difficulties in modelling asphalt on granular pavements using Austroads (2001) are illustrated and assistance is provided in selecting the most appropriate design solution where more than one solution is available. Care needs to be exercised in the design of such pavements, particularly for asphalt thicknesses < 100 mm.

REFERENCES

Austroads (1992). *Pavement Design – A Guide to the Structural Design of Road Pavements*. Austroads Publication No. AP-17/92.

Austroads (2001). *2001 Austroads Pavement Design Guide (Final Draft)*. Austroads Publication No. AP-T10/01.

Brown, S. and Brunton, J. (1984). *Improvements to pavement subgrade strain criterion*. Journal Trans. Eng., ASCE Vol. 110, No 6.

Buiter, R., W.M.H. Cortenraad, A.C. Van Eck, and H. Van Rij (1993). *Effects of Transverse Distribution of Heavy Vehicles on Thickness Design of Full-Depth Asphalt Pavements* Transportation Research Record 1227, Transportation Research Board, National Research Council, Washington, D.C.

Ho Sang, V.A. (1975). *Field survey and analysis of aircraft distribution on airport pavements*. Report No. FAA-RD-74-36. U.S. Federal Aviation Administration.

Monismith, C.L., Finn, F.N., Ahlborn, G. and Markevich, N. (1987). *A general analytically based approach to the design of asphalt concrete pavements*. Proc. 6th. Int. Conf. on the Structural Design of Asphalt Pavements, Ann Arbor.

Pereira, A.T. (1977). *Procedures for development of CBR design curves*. Instruction Report S-77-1, US Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Miss.

Potter, D.W. and Youdale, G.P. (1998). *Review and Recommendation of Improvements to Australian Heavy Duty Pavement Design Practices*, Australian Asphalt Pavement Association, Project Report 3 IET 1.

Rodway, B. and Wardle, L.J. (1998). *Layered Elastic Design of Heavy Duty and Industrial Pavements*. Proc. AAPA Pavements Industry Conf., Surfers Paradise, Australia.

Rodway, B., Wardle, L.J. and Wickham, G. (1999). *Interaction between wheels and wheel groups of new large aircraft*. Airport Technology Transfer Conference, Atlantic City, U.S.A., April 1999, Federal Aviation Administration.

Shell International Petroleum Company (1985). *Addendum to the Shell pavement design manual*. London.

Wardle, L.J. (1999). *CIRCLY 4 Users' Manual*, MINCAD Systems Pty Ltd, Richmond, Vic., Australia. (www.mincad.com.au)

Wardle, L.J. and Rodway, B. (1995). *Development and Application of an Improved Airport Pavement Design Method*. ASCE Transportation Congress, San Diego, 22-26 October, 1995.

Wardle, L.J. and Rodway, B. (1998). *Recent Developments in Flexible Aircraft Pavement Design using the Layered Elastic Method*. Third Int. Conf. on Road and Airfield Pavement Technology, Beijing, April 1998.

Wardle, L.J., Rodway, B. and Rickards, I. (2001). *Calibration of Advanced Flexible Aircraft Pavement Design Method to S77-1 Method. in Advancing Airfield Pavements*, American Society of Civil Engineers, 2001 Airfield Pavement Specialty Conference, Chicago, Illinois, 5-8 August 2001 (Buttlar, W.G. and Naughton, J.E, eds.), pp. 192-201.

Woodman, G. (1992). *Failure criteria for flexible pavements*. PSA report for BAA Technical Services Division. Surrey, UK.

AUTHOR BIOGRAPHIES

Dr. Leigh Wardle is the author of the leading pavement analysis programs, CIRCLY and APSDS. His research interests include layered elastic analysis, mechanistic pavement design and development of pavement design methods for airports and heavy duty loads.

Bruce Rodway has thirty eight years experience in the design, construction and maintenance of road and aerodrome pavements, gained initially with the Commonwealth Departments that had engineering responsibility for Australia's civil and defence aerodromes and then, from 1989 as Chief Engineer-Pavements for the Federal Airports Corporation until its closure in 1998. Since then he has been a private consultant. His special interest in recent years has been the mechanistic design of airfield pavements using the layered elastic method. He was the Australian representative on the International Civil Aviation Organization's (ICAO) committee examining interaction effects between multi-wheeled undercarriages of large aircraft. He has been a consultant aircraft pavement adviser to the Royal Australian Air Force for the past eight years.

Geoff Youdale is a consulting engineer with over 30 years experience in the roads industry. He is a past member and chairman of the Austroads Pavement Reference Group, as well as a former Austroads Technology and Environment Program Manager. He was a co-author of the 1987 and 1992 versions of the Austroads Guide to the Structural Design of Road Pavements.

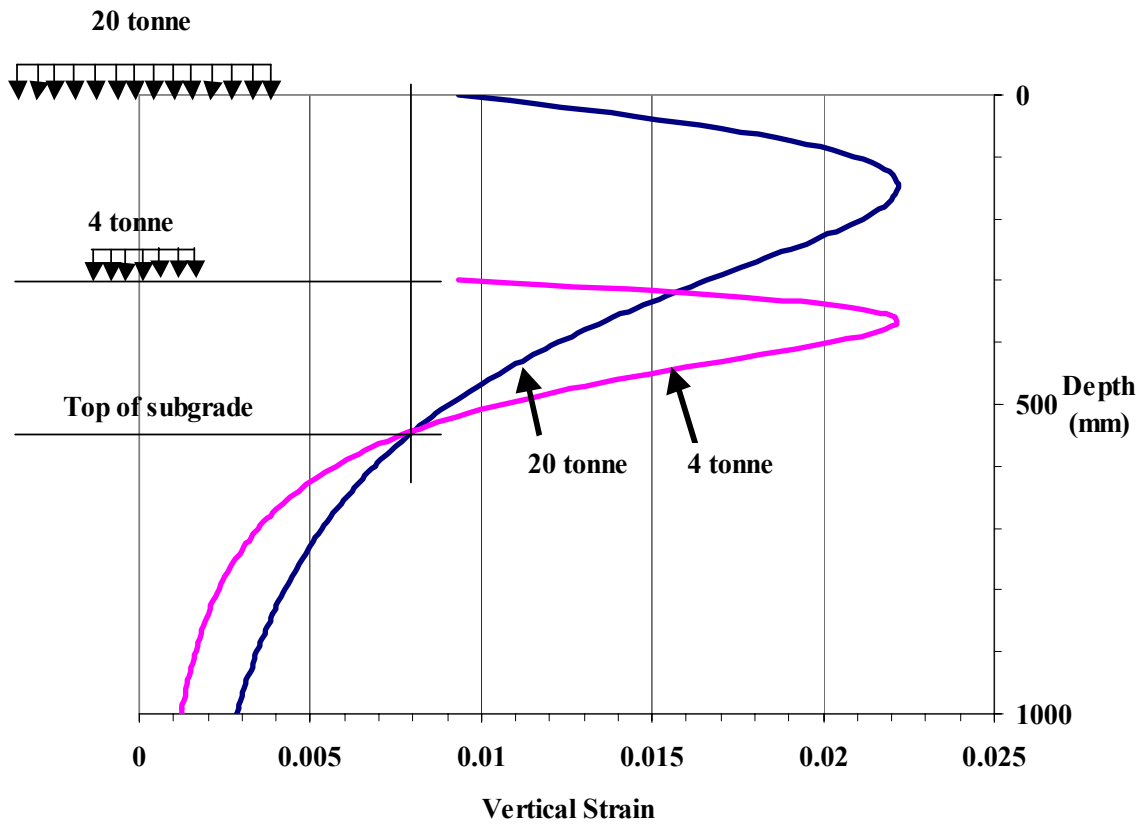


Figure 1: Effect of wheel load on pavement rutting for equal subgrade strains.

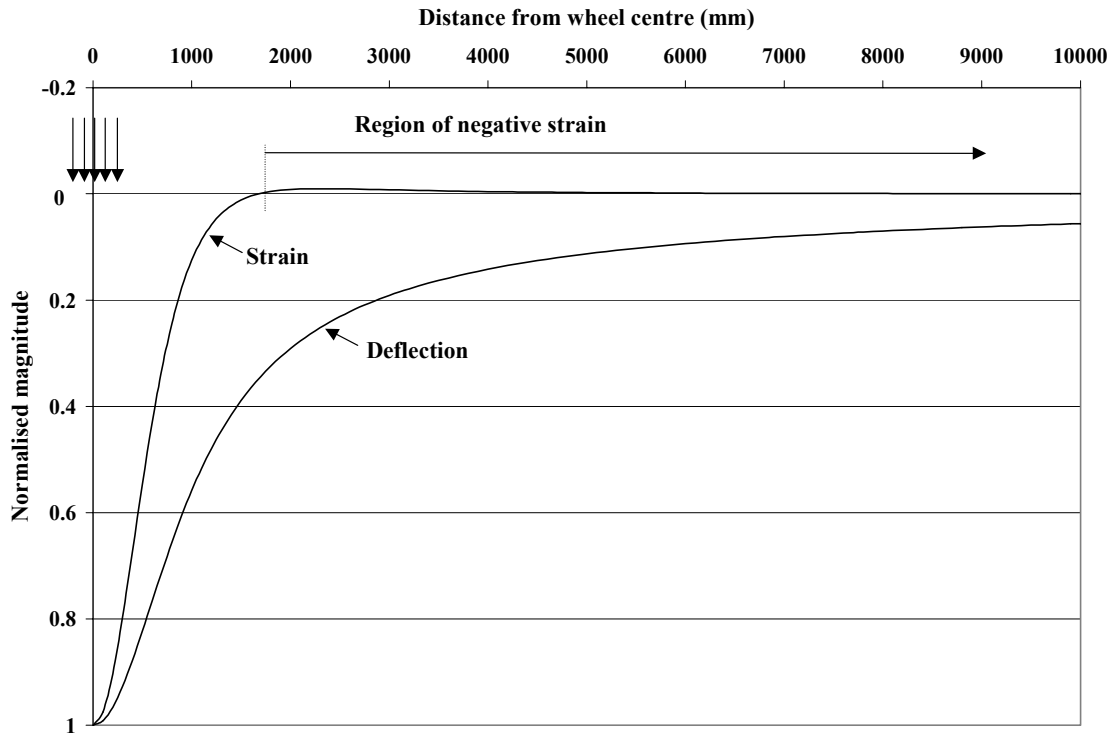


Figure 2: Example of negative subgrade vertical strains (from Rodway, Wardle and Wickham, 1999).

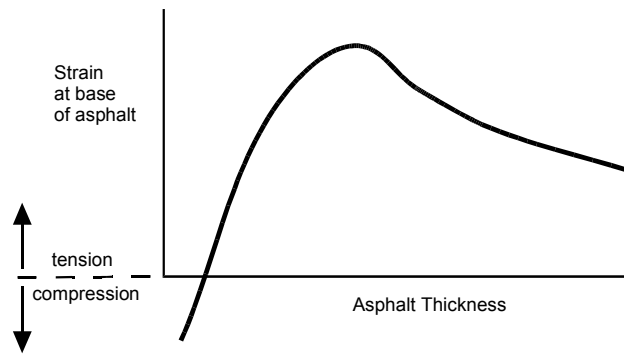


Figure 3: General Relationship Between Asphalt Thickness and Horizontal Strain at the Base of an Asphalt Layer (from Austroads (2001))