EQUIVALENT LOAD FOR A QUAD AXLE

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ABSTRACT

The National Road Transport Commission (NRTC) and Austroads are developing a Performance Based Standards (PBS) approach to the regulation of heavy vehicles in Australia. There has been general agreement to adopt the performance measure of Gross Mass per vehicle Standard Axle Repetitions (SAR) for PBS vehicles. The calculation of SAR requires the use of equivalent loads of common axle groups (single axle, tandem axle, tri-axle and quad axle), which cause same damage as a Standard Axle. Currently, equivalent loads for quad axle have not yet been developed for use in the Austroads pavement design procedures for flexible pavements (Austroads 1992, 2001). This paper provides a summary of current equivalent axle loads being adopted for flexible pavements by different road authorities throughout the world. In addition, it examines various experimental and theoretical procedures for deriving equivalent loads for various axle groups. This paper makes a number of recommendations on theoretical procedures to estimate equivalent loads for quad axle as well as interim equivalent loads for a quad axle that can be adopted in the Austroads pavement design procedures for the calculation of SARs for flexible pavements.

INTRODUCTION

The National Road Transport Commission (NRTC) and Austroads are sponsoring two major projects that are central to the development of a Performance Based Standards (PBS) approach to the regulation of heavy vehicles in Australia. The two projects, 'Specification of Performance Standards for Heavy Vehicles (Project A3)' and 'Documentation of the Performance of the Current Fleet (Project A4)', have the primary aims of:

1) determining and establishing agreement with the jurisdictions and industry on the 'standards' to apply for an agreed set of Performance Measures; and
2) documenting the performance of nominated vehicles within the current heavy vehicle fleet using cost-effective sources, including available records, calculation and the results of computer simulation.

There has been general agreement to adopt the performance measure of “Gross Mass per Vehicle Standard Axle Repetitions (GM/SAR)” for PBS vehicles. In the Austroads (1992) Pavement Design Guide, the calculation of Standard Axle Repetitions (SAR) requires the use of equivalent loads of common axle groups, which cause the same damage as the Standard Axle, as follows.

<table>
<thead>
<tr>
<th>Axle Group</th>
<th>Single Axle/Single Tyres (SAST)</th>
<th>Single Axle/Dual Tyres (SADT)</th>
<th>Tandem Axle/Single Tyres (TAST)</th>
<th>Tandem Axle/Dual Tyres (TADT)</th>
<th>Triaxle/Dual Tyres (TRADT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load (kN)</td>
<td>53</td>
<td>80</td>
<td>90</td>
<td>135</td>
<td>181</td>
</tr>
</tbody>
</table>

Whilst procedures for assessing quad axle damage to rigid pavements have been suggested in the draft 2001 Austroads Guide, equivalent loads for quad axle have not yet been developed for flexible pavements.
This paper presents a summary of current equivalent axle loads being adopted for flexible pavements by different road authorities throughout the world. In addition, various experimental and theoretical procedures for deriving equivalent loads for various axle groups are presented. A method for estimating the equivalent load for a quad axle that could be adopted for the calculation of SARs for flexible pavements using the Austroads Pavement Design Procedures is also presented.

EQUIVALENT AXLE LOADS ADOPTED IN VARIOUS COUNTRIES

Foley (2001) and Vuong (2002) compared the equivalent axle loads being adopted for both flexible and rigid pavements by different road authorities in different countries throughout the world. Table 1 summarises the equivalent axle loads (or axle loads of equal damage) for flexible pavements being adopted by different road authorities. The results indicate that:

- Australia (Austroads), USA (AASHTO) and South Africa (Department of Transport South Africa (DOTSA)) define the Standard Axle as a single axle with dual tyres (SADT) that transmits a load of 80 kN to the pavement. However, the Ministry of Transportation, Canada, adopts a slightly lower SADT load of 78 kN, whereas, in France, a much higher SADT load of 130 kN is adopted.
- Equivalent loads for single axle/single tyre, tandem axle/dual tyre and triaxle/dual tyre are different.
- Equivalent loads for quad axles have not yet been developed for use in any pavement design procedures.

Table 1: Comparison of Equivalent Loads for Axle Group Types for Flexible Pavements

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>SAST</td>
<td>53 kN</td>
<td>NA ⁴</td>
<td>≡ 61 kN</td>
<td>≡ 61 kN</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>SADT</td>
<td>80 kN</td>
<td>80 kN</td>
<td>80 kN</td>
<td>≡ 78 kN</td>
<td>130 kN</td>
<td>NA</td>
</tr>
<tr>
<td>TADT</td>
<td>135 kN</td>
<td>≡ 151 kN</td>
<td>≡ 134 kN</td>
<td>≡ 126 kN</td>
<td>275 kN</td>
<td>NA</td>
</tr>
<tr>
<td>TRIDT</td>
<td>181 kN</td>
<td>≡ 214-205 kN</td>
<td>≡ 187 kN,</td>
<td>≡ 172 kN</td>
<td>383 kN</td>
<td>NA</td>
</tr>
</tbody>
</table>

Note 1: Tyre pressure of 550 kPa and axle spacing of 1320 mm used in Austroads (1992).
Note 2: Axle spacing of 1219 mm (4 ft) used in the AASHTO Road Test.
Note 3: Values derived using tyre pressure of 520 kPa and axle spacing of 1400 mm.
Note 4: AASHTO (1993) and LCPC and SETRA (1997) provide no guidance for SAST.
Note 5: UK DoT (1993) do not use axle load equivalencies for individual axle groups.

Table 2 compares the procedures for determining/estimating equivalent axle loads. It can be seen that there are different pavement damage criteria and different procedures for the determining equivalent axle loads. As such, the procedures for estimating equivalent axle loads adopted in other pavement design procedures may not be readily applied to the Austroads (1992, 2001) procedures for estimating equivalent loads for a quad axle.

Australia

The Austroads (1992) equivalent axle loads are based on the assumption that axle groups that induce the same maximum deflection in a given pavement would cause equal pavement damage. This principle was reasonably well supported by limited data from the AASHO Road Test, from which Scala (1970a)
estimated relative destructive effects on a ‘number of pavements of known construction’. Given that the pavement damage is not specifically defined, the comparison is strictly based on relative damage (rather than absolute damage). The axle loads of equivalent damage for SAST, TADT and TRIDT (see Table 1) were derived from deflection data produced by field testing with different axle groups on granular and thin asphalt-surfaced pavements (Scala 1970a, 1970b). In this field study, actual trucks with different axle configurations were loaded to different loads to determine the load for each axle configuration that produced the same vertical pavement deflections as that produced by the Standard 80 kN SADT. Austroads (1992, 2001) uses these values to calculate the Standard Axle Repetitions (SAR) to estimate design traffic from mixed traffic for all pavement types. In this case, SAR is the number of Standard Axles that will provide the same ‘damage’ as that caused by the various group types and various values of damage exponents (4, 5, 7, 12) are used depending on the distress type (5 – asphalt fatigue; 7– subgrade deformation; 12 – cemented fatigue). When a damage exponent of 4 is adopted, the Standard Axle Repetition is called the Equivalent Standard Axle (ESA).

Table 2: Comparison of Procedures for the Derivation of Equivalent Loads for Axle Group Types

<table>
<thead>
<tr>
<th>Pavement Design Procedure</th>
<th>Pavement Damage Criteria</th>
<th>Experimental Procedures to Derive Axle Load of Equal Damage</th>
<th>Theoretical Procedures to Calculate Equivalent Axle Loads</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austroads (1992)</td>
<td>Equal maximum surface deflection cause equal pavement damage</td>
<td>Response to load on pavements with chip seal and thin asphalt surfacing using SAST, SADT, TRIDT and TADT (one level of tyre pressure)</td>
<td></td>
</tr>
<tr>
<td>AASHTO (1993)</td>
<td>Total pavement damage in terms of terminal serviceability value ($p_t$), $[p_t = 2.0 - 3.0]$</td>
<td>Performance data obtained from AASHO Road Test using SADT and TADT (one level of tyre pressure)</td>
<td>Apply the fourth power law to estimate equivalent loads for TRIDT from performance data of in-service pavements (expressed in terms Equivalent Standard Axle Load (ESAL))</td>
</tr>
<tr>
<td>Dept of Transport (South Africa)</td>
<td>Total pavement damage from damage of individual layers in the pavement, in terms of fatigue failure for bound layers and deformation (or shearing) failure for granular layers and subgrade</td>
<td>Use DOT SA mechanistic design procedures to estimate equivalent loads for SAST, TADT, TRIDT (expressed in terms of Equivalent Damage Factor (EDF))</td>
<td></td>
</tr>
<tr>
<td>Ministry of Transpn (Canada)</td>
<td>Equal maximum surface deflection cause equal pavement damage</td>
<td>Estimate equivalent loads for SAST, TADT, TRIDT from performance data of in-service pavements (expressed in terms of Equivalent Standard Axle Load (ESAL))</td>
<td></td>
</tr>
<tr>
<td>Highways Directorate (France)</td>
<td>Fatigue failure of surface layer</td>
<td>Estimate equivalent loads for TADT and TRIDT from Axle Aggressiveness (A) Procedures</td>
<td></td>
</tr>
</tbody>
</table>
USA

The AASHTO (1993) equivalent axle loads were derived from data collected during the AASHO Road Test, by referencing pavement damage to a terminal serviceability value ($p_t$). In the AASHTO Road Test, the number of repetitions of the SADT and TADT (with loads up to 133 kN and 214 kN respectively) that caused pavement damage to a terminal serviceability value could be determined. From these test results, it was possible to deduce the equivalent load for TADT (see Table 1) that produced the same damage as the Standard 80 kN SADT. AASHTO (1993) first used the ‘Equivalent Standard Axle load (ESAL)’ procedure to compare the damage caused by different axle configurations. In this procedure, the damage caused by a passage of a given axle over the pavement is described in terms of a unit damage caused by the standard 80 kN SADT. Using this concept, each axle type will have a Load Equivalency Factor, which is defined as:

\[
\text{unit damage caused by the passage of the axle/unit damage caused by the passage of a Standard Axle load (expressed in ESALs)}.
\]

This concept can be extended to determine the load equivalency for each vehicle, which is the sum of the LEFs of each axle group constituting the vehicle. The equivalent load for TRIDT (see Table 1) was estimated using the EASL procedures and performance data observed from in-service pavements.

South Africa

The South African method (Prozzi and de Beer 1997) derives total pavement damage from the damage of individual layers in the pavement: fatigue failure for bound layers and deformation (or shearing) failure for granular layers and subgrade. As such the total life of, for example, an asphalt pavement with cement-treated subbase may have different phases, including fatigue failure of the cement-treated subbase in phase 1, fatigue failure of the asphalt surface in phase 2 and shearing of the granular subbase and/or subgrade in phase 3. DOTSA (1997) used the procedures developed by Prozzi and de Beer (1997) to determine the Equivalent Damage Factor (EDF), which is the number of repetitions of the Standard Load Configuration (identical to a Standard Axle) that will cause the same damage as the given axle group. In this procedure, the EDF recognises the influence of the axle spacing within an axle group (Group Equivalence Factor), the mass on the axle group (Axle Load Factor) and the tyre contact stress (Contact Stress Factor):

\[
\text{EDF} = \text{GEF} \times \text{ALF} \times \text{CSF}
\]

where

- EDF = Equivalent Damage Factor,
- GEF = Group Equivalence Factor,
- ALF = Axle Load Factor, and
- CSF = Contact Stress Factor.

GEF takes into account the effects of inter-axle spacing; it represents the ratio between the allowable loading under the single axle to the life under a group with multiple axles (tandem and tridem axles). ALF assesses the influence of axle load; it is the ratio between the allowable loading under an 80 kN single axle to the life under an axle of any given group. CSF considers the effect of contact stress; it is the ratio between the allowable loading under a contact stress of 520 kPa to the life under any given contact stress at the same axle load of 80 kN.

Prozzi and de Beer (1997) incorporated the EDF procedures into the South African mechanistic design procedures to predict equivalent loads for SAST, TADT and TRIDT (see Table 1) that produced the same the total life as the Standard Load Configuration. In this method, the fatigue life of a bound layer and the deformation life of a granular layer or subgrade are predicted from the critical strain or stress in the layers concerned, which are calculated using a linear-elastic layered model. Material inputs into this model are
determined from a suite of laboratory tests. Relationships between fatigue/deformation life and critical stress/strain (Transfer Functions) are developed based on both laboratory material performance data and pavement performance data from accelerated pavement testing with the Heavy Vehicle Simulator (HVS).

**France**

The Highways Directorate of France relates pavement damage to the *fatigue damage* of the surface bound layers caused by the applied axle loads. The method considers the ‘Aggressiveness of an Axle’, which is based on the fatigue damage caused to the pavement. Aggressiveness, $A$, corresponds to the damage caused by one passage of an axle load ($P$) compared to the damage due to one passage of the reference isolated$^1$ axle load ($PO$). Aggressiveness ($A$) is determined using the following relationship (LCPC and SETRA 1997):

$$A = k \left( \frac{P}{PO} \right)^{\alpha}$$

(2)

where

- $A$ = Aggressiveness;
- $P$ = load on each axle of the axle group;
- $PO$ = reference axle (dual-wheel isolated [single] axle, weighing 130 kN);
- $\alpha$ = constant depending on pavement type (flexible, semi-rigid or concrete); and
- $k$ = constant depending on axle type (single, tandem or triaxle).

As the reference axle load is different from a Standard Axle, the French equivalent axles cannot be readily compared to values derived using other pavement design procedures.

**Canada**

The Ministry of Transportation, Canada, established a set of LEFs following a nation-wide experiment conducted during the late 1980s. These LEFs are as follows:

- SAST: LEF = $0.004836 \times \text{Load}^{2.9093}$
- SADT: LEF = $0.002418 \times \text{Load}^{2.9093}$
- TADT: LEF = $0.001515 \times \text{Load}^{2.5403}$
- TRIDT: LEF = $0.002363 \times \text{Load}^{2.1130}$

where ‘Load’ is the axle group mass in tonne.

The equivalent axle group loads given in Table 1 have been calculated using these relationships.

**EQUIVALENT LOADS FOR QUAD AXLE (FLEXIBLE PAVEMENTS)**

**Austroads ‘Mechanistic’ Pavement Design Procedures**

The Austroads (1992) ‘mechanistic’ pavement design procedure for flexible pavements is based on sem-empirical approach and has two components:

- a pavement response model to predict the critical strains in pavement layers under standard loads; and

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$^1$ Isolated axle [group] is when the nearest axle is greater than 2 m distant.
various empirical performance relationships to estimate the allowable number of loading cycles of standard loads on the selected pavement.

For practical reasons, Austroads adopts the simple linear elastic layered model CIRCLY with the following considerations in the selection of loading input and critical strains.

Loading input is expressed in terms of standard axles of equivalent damage, which equate to a standard single axle, dual tyre arrangement loaded to 8.2 tonne. In the standard analysis procedure with CIRCLY, the loading is simulated as a half-standard axle (i.e. only one pair of tyres) and only vertical loading (i.e. no shear force) is applied.

For pavements with bound layers that have a high capacity to sustain high vertical and horizontal stress (asphalt, cemented material and concrete), material fatigue is the major failure mode. CIRCLY can be used to model the linear elastic behaviour of bound materials; it produces consistent estimations of the maximum tensile strain in each bound layer, the critical parameter for fatigue failure.

For predicting permanent deformation, the Austroads design method uses the maximum compressive strain at the top of the subgrade as the ‘performance index’ parameter.

The vehicle-pavement conditions applied in the standard analysis procedures using CIRCLY are equivalent to steady-speed travel without consideration of horizontal tyre force for uphill grade, turning, start-up and breaking operations. Based on the above considerations, Austroads has established three empirical pavement allowable loading-critical strain relationships to predict fatigue cracking in bound layers and deformation performance, viz.

\[
N_{\text{Deform}} = \left( \frac{K_{\text{Deform}}}{\varepsilon_{SG}} \right)^{7.14} \tag{3}
\]

\[
N_{\text{AC}} = \left( \frac{K_{\text{AC}}}{\varepsilon_{AC}} \right)^{5} \tag{4}
\]

\[
N_{\text{CT}} = \left( \frac{K_{\text{CT}}}{\varepsilon_{CT}} \right)^{12} \tag{5}
\]

where:

- \( N_{\text{Deform}} \) = pavement deformation allowable loading, i.e. number of loading repetitions (Standard Axle) which produce a terminal rutting and shoving (say 20 mm);
- \( N_{\text{AC}} \) = asphalt fatigue allowable loading, i.e. number of loading repetitions (Standard Axle) which produce a terminal cracking of the asphalt layer;
- \( N_{\text{CT}} \) = cemented material fatigue allowable loading, i.e. number of loading repetitions (Standard Axle) which produce a terminal cracking of the cemented material layer;
- \( \varepsilon_{SG} \) = the magnitude of the peak vertical compressive strain at the top of the subgrade – calculated under vertical loading (without shear force) using CIRCLY;
- \( \varepsilon_{AC} \) = the magnitude of the peak horizontal tensile strain at the bottom of the asphalt layer – calculated under vertical loading (without shear force) using CIRCLY; and
- \( \varepsilon_{CT} \) = the magnitude of the peak horizontal tensile strain at the bottom of the cemented material – calculated under vertical loading (without shear force) using CIRCLY.

In these relationships, deformation life or cracking life is expressed in terms of the ‘loading index’ Standard Axles of allowable loading. Austroads (1992) also assumes that there is a linear relationship between vertical loading and critical strain, which means that the damage exponents (DE) and criteria given in Table 3 may also be applied to the load-damage relationships for analyses with different vertical loads (without shear forces).

It is imperative that the Austroads procedure for the determination of the equivalent axle loads (i.e. field
testing to determine equal maximum surface deflection) be used if the equivalent load for quad axles is to be consistent with the current Austroads accepted values for SAST, SADT, TADT and TRIDT. However, it was commented by Prozzi and de Beer (1997) that:

the Austroads approach is only valid, or approximately valid, when the performance of the pavement is governed by the behaviour of the lower layers, i.e. selected layers or subgrade. The approach has some shortcomings due to the surface deflection not being directly related to some pavement response parameters.

Therefore, there is a need to investigate the effects of material properties on the validity of the Austroads approach.

### Table 3: Damage Exponents for All Pavement Types (Austroads 1992)

<table>
<thead>
<tr>
<th>Distress Mode</th>
<th>Critical Strain Criterion</th>
<th>Constant (K)</th>
<th>Damage Exponent (DE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asphalt fatigue</td>
<td>Maximum tensile strain at bottom of asphalt layer</td>
<td>A function of binder content and mix stiffness</td>
<td>5</td>
</tr>
<tr>
<td>Cemented material fatigue</td>
<td>Maximum tensile strain at bottom of cemented material layer</td>
<td>A function of layer stiffness</td>
<td>12</td>
</tr>
<tr>
<td>Total permanent deformation</td>
<td>Maximum compressive strain at top of subgrade</td>
<td>8511</td>
<td>7.14</td>
</tr>
</tbody>
</table>

As discussed previously, the DOTSA has incorporated the Equivalent Damage Factor (EDF) procedure into their mechanistic pavement design to predict equivalent loads for SAST, TADT and TRIDT. This EDF procedure may also have the potential to be developed further for incorporation into the Austroads mechanistic design procedures to predict equivalent loads for different axle configurations, particularly for bound pavements. Therefore, there is a need to investigate the incorporation of the South African EDF procedure into the Austroads mechanistic design to determine validity of this approach.

### Estimates from Theoretical Procedures

The following four theoretical procedures could be used to estimate the equivalent load for a quad axle as applied to flexible pavements:

- **Procedure 1**: Extrapolation of the existing Austroads relationships between axle group load and the number of tyres per axle group.
- **Procedure 2**: Extrapolation of the relationship between predicted surface deflection and the number of tyres per axle group, with the Austroads mechanistic design procedures used to calculate the surface deflection.
- **Procedure 3**: Extrapolation of the relationship between predicted critical strain and the number of tyres per axle group, with the Austroads mechanistic design procedures used to calculate the critical strain.
- **Procedure 4**: Calculation of Group Equivalence Factor using the South African method, with the Austroads mechanistic design procedures used to predict pavement deflection, critical strain and design life.

### Extrapolation of Austroads Equivalent Loads for Common Axle Groups

Figure 1 shows the relationship between the current Austroads accepted values of Equivalent Loads for axle groups with dual tyres (SADT, TADT and TRIDT) and the number of tyres per axle group. The
relationship in Figure 1 is best presented by the power function:

$$Y = 28.559 \times X^{0.7444} \quad (R^2 = 0.9999) \quad (6)$$

where $Y =$ equivalent load per axle group (kN); and

$X =$ number of tyre per axle group.

The estimate of the equivalent load for a quad axle ($X = 16$ tyres) based on an extrapolation of the above relationship is $225$ kN.

![Axle Group Load versus Number of Tyres](image)

**Figure 1** – Extrapolation of equivalent load of a quad axle based on existing Austroads relationship between load per axle group and number of tyres

**Extrapolation of Predicted Surface Deflection**

Three granular pavements with a thin surface seal and which have thicknesses in the range of 250-480 mm and subgrade CBRs in the range of 5-15%, a full depth asphalt pavement and an asphalt pavement with A cemented subbase were considered in this study. Their details are given in Table 4.

For each pavement, the Austroads mechanistic design procedures were used to calculate the maximum surface deflection (between or under the tyres) using the Austroads accepted values of Equivalent Loads for axle groups with dual tyres (SADT, TADT and TRIDT).

Referring to Table 5, for granular pavement with thin surface seals (Pavements 1, 2 and 3), the Austroads accepted Equivalent Loads for SADT, TADT and TRIDT produced similar maximum surface deflections. However, for bound pavements (Pavements 4 and 5), the Austroads accepted Equivalent Loads for SADT, TADT and TRIDT produced different maximum surface deflections. This may indicate that the Austroads approach for the determination of equivalent axle loads based on equal maximum surface deflection (Scala 1970a, 1970b) may be applicable for granular pavement with thin surface seals, but not for pavements with bound materials.

Figure 2 shows the relationship between the predicted surface deflections for axle groups with dual tyres (SADT, TADT and TRIDT) and number of tyres per axle group. The relationships in Figure 2 are best presented by the linear function:

$$Y = a \times X + b \quad (7)$$

where $Y =$ predicted surface deflection for a given axle group;

$X =$ number of tyre per axle group; and

$a$ and $b$ are fitting constants.
Table 4: Pavements Used in the Analysis

<table>
<thead>
<tr>
<th>Pavement No.</th>
<th>Surface Thickness and Type</th>
<th>Base Thickness and Type</th>
<th>Upper Subbase Thickness and Type</th>
<th>Lower Subbase Thickness and Type</th>
<th>Subgrade (CBR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sprayed seal</td>
<td>250 mm crushed rock</td>
<td></td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>Sprayed seal</td>
<td>320 mm crushed rock</td>
<td></td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>Sprayed seal</td>
<td>480 mm crushed rock</td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>40 mm Size 14 mm Mix (2,200 MPa)</td>
<td>180 mm Size 20 mm Mix (2500 MPa)</td>
<td></td>
<td>120 mm CTCR (2000 MPa)</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>40 mm Size 14 mm Mix (2,200 MPa)</td>
<td>110 mm Size 20 mm Mix (2500 MPa)</td>
<td>120 mm CTCR (2000 MPa)</td>
<td>200 mm granular</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 5: Estimates of Equivalent Loads for Quad Axle Based on Extrapolation of Equivalent Surface Deflection

<table>
<thead>
<tr>
<th>Pavement No.</th>
<th>Equivalent Surface Deflection (mm)</th>
<th>Equivalent Axle Load, EAL (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SADT  TADT  TRIDT  QUAD</td>
<td>SADT  TADT  TRIDT  QUAD</td>
</tr>
<tr>
<td>1</td>
<td>0.58  0.57  0.56  0.55</td>
<td>80   135   181   222</td>
</tr>
<tr>
<td>2</td>
<td>0.71  0.70  0.70  0.69</td>
<td>80   135   181   224</td>
</tr>
<tr>
<td>3</td>
<td>0.93  0.96  1.00  1.04</td>
<td>80   135   181   231</td>
</tr>
<tr>
<td>4</td>
<td>0.57  0.64  0.72  0.79</td>
<td>80   135   181   243</td>
</tr>
<tr>
<td>5</td>
<td>0.47  0.56  0.64  0.73</td>
<td>80   135   181   247</td>
</tr>
</tbody>
</table>

Figure 2 – Extrapolation of equivalent surface deflection of a quad axle based on existing relationships between calculated surface deflection per axle group and number of tyres
These relationships were used to estimate the equivalent surface deflections for quad axles (that have 16 tyres). The Austroads design procedures were then used to calculate the quad axle loads that produced these equivalent surface deflections. These results are also given in Table 5. It can be seen that, for granular pavements with thin surface seal (Pavements 1, 2 and 3), the estimated equivalent quad axle loads are in the range of 222-231 kN, with an average value of 226 kN. For bound pavements (Pavements 4 and 5), the estimated equivalent quad axle loads are much higher (in the range 243-247 kN). This indicates that the deflection-extrapolation procedure produces different estimates of equivalent load for different pavement compositions.

**Extrapolation of Predicted Critical Strain**

The Austroads mechanistic design procedures were used to calculate the equivalent critical strains (maximum horizontal tensile strain at the bottom of a bound layer and the maximum vertical compressive strain at the top of the subgrade under/between the tyres) using the Austroads accepted values of Equivalent Loads for axle groups with dual tyres (SADT, TADT and TRIDT). The results are given in Table 6.

<table>
<thead>
<tr>
<th>Pavement No</th>
<th>Distress Mode</th>
<th>Equivalent Critical Strain (micro-strain)</th>
<th>Equivalent Axle Load, EAL (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>SADT</td>
<td>TADT</td>
</tr>
<tr>
<td>1</td>
<td>SG strain</td>
<td>709</td>
<td>597</td>
</tr>
<tr>
<td>2</td>
<td>SG strain</td>
<td>682</td>
<td>563</td>
</tr>
<tr>
<td>3</td>
<td>SG strain</td>
<td>710</td>
<td>599</td>
</tr>
<tr>
<td>4</td>
<td>tensile strain in AC Base</td>
<td>201</td>
<td>156</td>
</tr>
<tr>
<td>5</td>
<td>tensile strain in CTCR Subbase</td>
<td>158</td>
<td>121</td>
</tr>
</tbody>
</table>

Figure 3 shows the relationships between the predicted critical subgrade strain for axle groups with dual tyres (SADT, TADT and TRIDT) and the number of tyre per axle group for all granular pavements with thin surface seal (Pavements 1, 2 and 3). Similarly, Figure 4 shows the relationships between the predicted critical tensile strain for SAST, SADT, TADT and TRIDT and number of tyre per axle group for all bound pavements (Pavements 4 and 5).

The relationships in Figures 3 and 4 are best presented by the power function

\[ Y = aX^b \]  

where \( Y \) = predicted critical subgrade strain for a given axle group;  
\( X \) = number of tyre per axle group; and  
a and \( b \) are fitting constants.

Using the regression relationships in Figure 3 and 4, the equivalent critical subgrade strain and critical tensile strain for quad axle (that have 16 tyres) were extrapolated. The Austroads design procedures were then used to calculate the quad axle loads that produced these equivalent critical subgrade strains and critical tensile strains. These results are also given in Table 6. It can be seen that, for granular pavements with thin surface seals (Pavements 1, 2 and 3), the estimated equivalent quad axle loads are in the range...
222-231 kN, with an average value of 222 kN. For bound pavements (Pavements 4 and 5), the estimated equivalent quad axle loads are slightly lower (in the range 215-217 kN).

**Figure 3 – Extrapolation of equivalent critical subgrade strain of a quad axle based on existing relationships between calculated critical subgrade strain per axle group and number of tyres**

**Figure 4 – Extrapolation of equivalent critical tensile strain of a quad axle based on existing relationships between calculated critical tensile strain per axle group and number of tyres**

**Estimates Based on South African Damage Equivalence Factor Procedures**

As discussed earlier, (also see eqn (1)), the South African Equivalent Damage Factor (EDF) is the product of the Group Equivalence Factor (GEF), the Axle Load Factor (ALF) and the Contact Stress Factor (CSF). For a group consisting of multiple single axles at a given axle spacing (SP) and a given tyre pressure (σ):

- The Group Equivalence Factor (GEF) is defined as the ratio between the allowable loading (NISO) under an isolated single axle of an axle group and the allowable loading (NG) under the axle group:
  \[
  GEF = \frac{N_{ISO}}{NG}
  \]

  (9)

  The allowable loading under the group (NG) was determined using the following equation:
  \[
  NG = \frac{N_{CR}}{(1+Fc)}
  \]

  (10)

  Where
\( N_{CR} \) is the number of repetitions of the critical axle (most damaging axle) of the group.

\( F_c \) is the contribution factor, which was developed to take into account the contribution of other minor axles (less damaging axle) of the group to the critical axle, and is defined as:

\[
F_c = n_A - \Delta
\]

Where

- \( n_A \) is the number of axles of the group
- \( \Delta \) is the ratio between the peak surface deflection of critical axle and the peak surface deflection of minor axle

- The Axle Load Factor (ALF) is defined as the ratio between the allowable loading \((N_S)\) under the Standard 80 kN SADT and the allowable loading under an isolated single axle \((N_{ISO})\) of an axle group:

\[
ALF = \frac{N_S}{N_{ISO}}
\]

- The Contact Stress Factor (CSF) is defined as the ratio between the allowable loading \((N_S)\) under the Standard 80 kN SADT with standard tyre pressure and the allowable loading \((N_{S\sigma})\) under a single 80 kN SADT with the tyre pressure \((\sigma)\):

\[
CSF = \frac{N_S}{N_{S\sigma}}
\]

In this study, the following conditions were applied to be consistent with the Austroads Equivalent Loads for SAST, SADT, TADT and TRIDT (see Table 1):

- an axle spacing \((s_p)\) of 1350 mm for all axle groups TADT, TRIDT and QUAD;
- a Standard SADT of 80 kN; and
- a tyre pressure \((\sigma)\) of 550 kPa to all axle groups (SADT, TADT, TRIDT and QUAD).

It should be noted that the current Austroads design procedures (Austroads 1992) do not cater for changes in the elastic properties of pavement layers with the level of axle load. It was therefore assumed in this study that the elastic properties remained unchanged. Similarly, the draft Austroads Guide (Austroads 2001) adopts a constant tyre pressure of 750 kPa for the Standard Axle load whilst Scala’s work in developing axle load equivalencies was conducted at a pressure of 555 kPa. Therefore, there is a need to consider the influence of non-linear material properties on the estimates of equivalent axle load and also the influence of tyre pressure on the equivalent axle loads currently recommended by Austroads.

Vuong (2002) has shown that, for the conditions applied in the Austroads design procedures (Austroads 1992), the equivalent load of an axle group \((EGL)\) is expressed as:

\[
EGL = n \times \frac{SADT}{GEF}^{1/DE}
\]

Where

- \( N \) = number of single axles in the group
- \( SADT \) = Standard Axle load of 80 kN
- \( GEF \) = Group Equivalence Factor
- \( DE \) = damage exponents

GEF and EGL values for TADT, TRIDT and QUAD for all the pavements in Table 4 were calculated using the above procedure (Vuong 2002) and the results are given in Table 7.

Referring to Table 7, for granular pavements with thin surface seal (Pavements 1, 2 and 3), the estimated equivalent quad axle loads were in the narrow range of 266-268 kN, which is much lower than the estimates for bound pavements (282 kN and 339 kN for Pavements 4 and 5 respectively). This indicates
that the South African procedure produces different estimates of equivalent load for different distress modes.

Table 7: Estimates of Equivalent Axle Loads for Granular Pavements using Group Equivalence Factor (GEF)

<table>
<thead>
<tr>
<th>Pavement No.</th>
<th>Distress Mode</th>
<th>DE</th>
<th>Group Equivalence Factor (GEF)</th>
<th>Equivalent Axle Load (EGL) (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>TADT</td>
<td>TRIDT</td>
</tr>
<tr>
<td>1</td>
<td>critical SG strain</td>
<td>7.14</td>
<td>1.86</td>
<td>2.79</td>
</tr>
<tr>
<td>2</td>
<td>critical SG strain</td>
<td>7.14</td>
<td>1.81</td>
<td>2.70</td>
</tr>
<tr>
<td>3</td>
<td>critical SG strain</td>
<td>71.4</td>
<td>1.79</td>
<td>2.64</td>
</tr>
<tr>
<td>4</td>
<td>critical tensile strain in asphalt base</td>
<td>5</td>
<td>0.96</td>
<td>1.33</td>
</tr>
<tr>
<td>5</td>
<td>critical tensile strain in CTCR subbase</td>
<td>12</td>
<td>0.38</td>
<td>0.39</td>
</tr>
</tbody>
</table>

Comparison of Estimates of Equivalent Loads of Quad Axle

Figure 5 compares the equivalent load for axle groups with dual tyres (SADT, TADT and TRIDT) adopted in various pavement design procedures. It can be seen that the AASHTO values for TADT and TRIDT are significantly higher than the others. It can also be seen that the Austroads and Canadian Design procedures produced comparable estimates of equivalent load for the quad axle (approximately 225 and 219 kN respectively), which are much lower than those produced by the South African and AASHTO procedures (approximately 241 kN and 279 kN respectively).

**Figure 5 – Comparison of equivalent axle loads**

Figure 6 compares the estimates of equivalent load of a quad axle derived using the extrapolation procedures adopted in this study (i.e. load-extrapolation, deflection-extrapolation and critical strain-extrapolation). It can be seen that the load-extrapolation (Procedure 1) and critical strain-extrapolation (Procedure 3) procedures produced comparable estimates of equivalent load for the quad axle (in the range 215-226 kN), which were lower than those produced by the deflection-extrapolation (Procedure 2) (in the range 222-247 kN).

Figure 7 compares the estimates of equivalent load for the axle groups with dual tyres (SADT, TADT and
TRIDT) produced by the Austroads and South African mechanistic design procedures, both using the South African EDF (see eqn (1)). It can be seen that the Austroads procedures, with the South African EDF, consistently produced higher estimates of equivalent loads for the axle groups with dual tyres than the South African procedure. It should also be noted that the equivalent loads for TADT, TRIDT and QUAD produced by the Austroads procedure, with the South African EDF, were consistently higher than those currently adopted accepted by Austroads (9%, 15% and 21% for granular pavements, 19%, 26%, 30% for full-depth asphalt pavements and 28%, 43% and 54% for asphalt pavements with CTCR subbases).

Given that the Austroads mechanistic design procedures, with the South African EDF, consistently produce higher estimates of equivalent loads for all axle groups than the values currently adopted by Austroads, it is considered that this method should not be adopted at this stage and will need to be investigated further. As discussed previously, there is also a need to investigate the influence of non-linear material properties on the estimates of equivalent axle loads. There is also a need to investigate the influence of damage criteria on the estimates of equivalent axle loads (i.e. the ‘total damage’ criterion – the
combined fatigue life of bound layers and the deformation life of granular layers and the subgrade and the ‘limited-damage’ criterion – either the fatigue life of bound layers or the deformation life of the subgrade).

In summary, there are two scenarios that could be considered for determining the equivalent axle loads of a quad axle:

- **Scenario 1:** Adopt a single value of equivalent load for each Standard Axle group as currently adopted in the Austroads Pavement Design Guide. This will not address the influence of axle spacing, tyre pressure, material type and damage criteria (for different pavement types and classes).

- **Scenario 2:** Adopt different values of equivalent load for each Standard Axle group in order that the influence of axle spacing, tyre pressure, material type and damage criteria is addressed. However, further work is required before the above effects of these parameters can be quantified and the Austroads mechanistic pavement design procedures revised accordingly.

In the interim, given the small variation between the load-extrapolation and critical strain-extrapolation procedures, and the estimated equivalent load for a quad axle derived using these procedures (in the range of 215-226 kN) an interim equivalent axle load for a quad axle of 221 kN (22.5 tonne) be considered to cause equivalent damage to a Standard Axle.

**SUMMARY AND RECOMMENDATIONS**

A literature review of current equivalent axle loads being adopted for flexible pavements by different road authorities throughout the world indicated that different procedures adopt different Standard Axle loads, different pavement damage criteria, and different procedures for the determination of equivalent axle loads. As such, the procedures for estimating equivalent axle loads adopted in other pavement design procedures can not readily be applied to the current Austroads pavement design procedures for the purpose of deriving an equivalent axle load for quad axles.

Four procedures were used to estimate the equivalent load of a quad axle, namely:

- Extrapolation of the existing relationships between axle group load and the number of tyres per axle group as adopted by different road authorities.
- Extrapolation of the relationship between predicted surface deflection and the number of tyres per axle group, with the Austroads mechanistic design procedures used to calculate the surface deflection.
- Extrapolation of the relationship between predicted critical strain and the number of tyres per axle group, with the Austroads mechanistic design procedures used to calculate the critical strain.
- Calculation of the Group Equivalence Factor using the South African method, with the Austroads mechanistic design procedures used to predict pavement deflection, critical strain and design life.

Comparison of the estimates of equivalent load of a quad axle derived using the different procedures suggested that the load-extrapolation and critical strain-extrapolation procedures produced consistent estimates of equivalent load of a quad axle in the range 215-226 kN. These estimates were slightly lower than the estimates produced using the maximum deflection-extrapolation procedure (222-247 kN) and much lower than the estimates produced using the South African approach (266-339 kN). Given that the South African approach consistently also produced higher estimates of equivalent loads for the tandem and triaxle than the values currently adopted by Austroads, it is considered that this method is not suitable for estimating equivalent quad axle loads. However, the South Africa approach needs to be investigated further, particularly the influence of axle spacing, tyre pressure, material type and damage criteria (for different pavement types and classes).
It is recommended that

- An interim equivalent axle load for a quad axle of 221 kN (22.5 tonne) be considered to cause equivalent damage to a Standard Axle.
- Further investigation of the South African approach for estimating equivalent axle loads is warranted.
- Further analysis needs to be undertaken to confirm that the equivalent load for a quad-axle load is appropriate pavements incorporating bound materials.

REFERENCES


AUTHOR’S BIOGRAPHY

Binh Vuong holds a Bachelors Degree in Civil Engineering, a Masters Degree in Geotechnical Engineering and a Ph D degree in the field of Pavement Engineering. He is a well-known international expert and Australia’s leading investigator in the field of pavement technology.

Binh worked as a geotechnical engineer before joining ARRB TR in 1983. In the past 19 years, he has developed and undertaken numerous research works for the Austroads National Strategic Research
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Binh has published more than 100 conference and journal papers and research reports in the above areas. He is the developer of microcomputer programs EFROMD2 and NONCIRL for pavement analysis and design, and Finite Element models for analysis of foundation/sub-surface structure.