Equivalent Damage Factors (EDFs) for multiple load and axle configurations

J A Prozzi and M de Beer
Division of Roads and Transport Technology, CSIR
P O Box 395, Pretoria, 0001, South Africa
e-mail: jprozzi@csir.co.za

Paper prepared for presentation at the “Pavements” Session of the 1997 XIIIth IRF World Meeting
Toronto, Ontario, Canada

ABSTRACT

The recent increase of the maximum legal axle load limit in South Africa, as well as the increase in overloading observed in rural roads, have renewed the interest into methods of quantifying traffic load associated damage on road pavements. For pavement engineers the main interest lies in the design and management of the network, while road authorities’ interest lies in their desire to recover the cost of the damage. Since equivalent damage factors (EDFs) are used to convert the actual traffic spectrum into equivalent standard axles (ESAs), methods for calculating EDFs should be evaluated in terms of their ability to deal with all practical load and axle configurations of mixed traffic.

Extensive research with the Heavy Vehicle Simulator (HVS) over the past 20 years has led to improved fundamental understanding of pavement response and performance and has permitted the development of effective EDFs for single-axle loads. A major limitation of this approach, however, is that it does not directly facilitate the calculation of EDFs for multiple axle configurations.

This paper describes the procedure developed for extending the existing HVS-based method. The method is then applied to the assessment of the effects of: wheel load, contact stress, single and dual wheels, and single, tandem and tridem axles. As a result, the procedure enables determination of EDFs for accurate estimation of equivalent traffic for design purposes and performance analysis. This, in principle, may facilitate the development of guidelines on permissible axle loads and tyre pressures for different axle configurations.

The basic principle pertinent to this approach is that equal response implies equal damage. The formulation is based on a rational mechanistic evaluation of pavement-traffic load interaction. In this approach, the dependence on empirical formulae is minimized.

INTRODUCTION

From 1991 to 1993 a study was conducted to evaluate the performance of several of the pavement structures found in the South African’s Road Catalogue of TRH. The evaluation was carried out by applying the criteria given in the South
African Mechanistic Design Method (SAMDM)\(^3\)\(^4\)\(^5\)\(^6\)\(^7\). Findings from that investigation enabled the formulation of a method of determining damage factors for different wheel and axle load configurations on different pavement types\(^8\). The method is based on the concept of equal pavement response implying equal pavement damage. Equal pavement response implies that the pavement is subjected to the same level of strain, stress or deflection, whichever is critical.

Each pavement is associated with a particular distress mode governed by a specific pavement response (strain, stress or deflection). This response, in turn, controls the performance of the pavement. Thus, for example, if a load generates a specific amount of strain (or stress) at a specific position in the pavement which governs the pavement performance, that pavement is defined as having equal response only if the same strain (or stress) level is reached at the same position under a different load configuration.

**DEFINITIONS**

**Equivalent Damage Factor (EDF)** is defined as the number of standard axles which would cause the same damage to a specific pavement as a group of axles (single, tandem or tridem) of any given load and tyre pressure. The standard axle (SA) is a single 80 kN axle with dual wheels and 520 kPa tyre pressure.

Thus, the EDF of a given vehicle (EDF\(_v\)) is the number of repetitions of the standard axle that should be applied to a pavement to cause the same damage as one pass of such vehicle. The EDF\(_v\) is the sum of the EDFs of each axle group constituting the vehicle, thus:

\[
EDF_v = \sum_{i=1}^{n} EDF_i
\]  

where \( EDF_v \) = Equivalent Damage Factor of the vehicle.

\( EDF_i \) = Equivalent Damage Factor of the axle group \( i \).

\( n \) = number of axle groups of the vehicle.

Traditionally, EDF has been expressed using the Load Equivalency Factor\(^9\) (LEF) calculation based on \((P/80)^n\). Although the terms EDF and LEF are equivalent, the new terminology was introduced to distinguish between the different approaches followed in the analysis of the AASHO Road Test data and in the present procedure. A number of aspects that were previously included into one coefficient \( n \) are now assessed individually by means of partial factors. To date, three partial factors have been developed, however, new factors can easily be incorporated into the definition in order to assess other aspects such as loading rate, temperature, etc. The EDF\(_i\) for the individual axle groups is calculated by:

\[
EDF_i = GEF_i \times ALF_i \times CSF_i
\]  

where \( GEF \) = Group Equivalency Factor

\( ALF \) = Axle load Factor

\( CSF \) = Contact Stress Factor
**Group Equivalency Factor (GEF)** is defined as the ratio between the life of the pavement under a single axle to the life of the pavement under a group of axles. The load of the individual axles of the group should be the same as the load of the single axle. This factor only takes into account the number of axles and the inter-axle spacing, and expresses the number of single axles that would cause the same damage to the pavement as the group. Per definition the Group Equivalency Factor (GEF) of a single axle is one (1).

These factors are developed for specific pavements. Each pavement type is associated with a specific failure mechanism, variations on the selected layer thicknesses or elastic properties of the materials may cause a change in the failure mode and therefore the GEF will change accordingly.

**Axle Load Factor (ALF)** is defined as the ratio between the life of the pavement under a single axle of 80 kN and the life of the pavement under a single axle of different load (in both cases the tyre pressure is the same). The name ALF is proposed (instead of LEF) because this factor only takes into account the effect of axle load while LEF which includes all aspects. It is calculated as follows:

\[
ALF = \left( \frac{P}{80} \right)^\alpha
\]

where \( P \) = axle load (kN) and \( \alpha \) = load damage coefficient.

**Contact Stress Factor (CSF)** is the ratio between the life of a pavement under a dual-wheel single axle with a tyre pressure of 520 kPa and the life of the pavement under a dual-wheel single axle with a different tyre pressure (the axle load is the same in both cases). It is calculated by the following equation:

\[
CSF = \left( \frac{o}{520} \right)^\beta
\]

where \( o \) = contact stress (kPa) and \( \beta \) = stress damage coefficient.

For single axles with single wheels GEF is one and ALF is replaced by SWF, so Equation 2 becomes:

\[
EDF_i = SWF_i \times CSF_i
\]

where SWF is the Single Wheel Factor defined as the ratio of the life of the pavement under the standard 80 kN dual-wheel axle to the life of the pavement under an axle of a given load with single wheels.

It is important to state that the entire procedure is based on the assumption of linear-elastic material behaviour. Since all the partial factors (i.e. GEF, ALF, CSF and SWF) defined above are relative comparisons, it is the authors' opinion that this characterization is adequate in the short term. Further research is suggested in order to assess the applicability of this working method to actual material behaviour, for example, by incorporating the use of non-linear material models in the mechanistic method or by applying non-linear dynamic analyses.
CALCULATING THE EQUIVALENT DAMAGE FACTOR FOR A HEAVY VEHICLE

To assess the damaging effect of a typical heavy vehicle in terms of the standard axle configuration, the Equivalent Damage Factor (EDF) should be calculated. The EDF of a given vehicle is calculated as the sum of the EDFs of the respective axle groups as defined by Equations 1 and 2. The flow chart in Figure 1 is given to clarify the procedure.

As indicated in Figure 1, the first step is to determine the number of axle groups forming the specific heavy vehicle. A group is constituted by one, two or three axles whose inter-axle spacing is less than 3.0 metres. This limit was established during the original study since it was found that for spacings greater than 3.0 m the interaction between axle loads was less than 10 per cent. The groups are then classified according to their configuration into one of the following types: single axle with single wheels, single axle with dual wheels, tandem axle with dual wheels or tridem axle with dual wheels.

As can be seen in Figure 1, the procedure and formulae are slightly different depending on the axle configuration. The procedure was applied for a number of pavements and load configurations to illustrate the potential uses and type of results. The full description of the procedure is given elsewhere9.

Load Configurations

Four different axle and wheel configurations are evaluated in this paper:

- Single axle with dual wheels: a single axle with dual wheels on each side is considered as the standard axle. Wheel loads varying from 10 to 40 kN (representing axle loads from 40 to 160 kN) were used.
- Single axle with single wheels: in this case the wheel load used varied from 20 to 60 kN, representing axles loads from 40 to 120 kN.
- Tandem axle: a tandem axle is a group of two single dual-wheel axles separated by an inter-axle spacing of approximately 1360 mm.
- Tridem axle: a tridem axle is a group of three single dual-wheel axles with equal inter-axle separations of approximately 1360 mm.

Tyre inflation pressures from 400 kPa to 1000 kPa were used in order to assess the effect of the pavement/tyre contact stress on pavement performance. It should be noted that during the analysis the tyre inflation pressure was assumed to be equal to the contact stress and evenly distributed over a circular area. However, current research indicate that actual pavement/tyre contact stress is generally higher than the inflation pressure10 11.

Pavement Types And Material Properties

Three different asphalt concrete base pavements were analysed in order to assess the influence of pavement design in the determination of EDFs. Subsequently, three granular base pavements (typical South African designs) were also analysed in
order to establish some comparisons with the former ones. Material properties used in the analysis of the selected pavement structures were chosen according to the guidelines given in the latest updated SAMDM®. The pavement structures are shown in Figure 2 and are described below:

**Asphalt base pavements:**

Pavement A: 40 mm gap-graded asphalt surface, 80 mm continuously graded asphalt base, 250 mm lightly cement-treated base (0,75 MPa ≤ UCS ≤ 1,5 MPa), 150 mm of selected granular material (CBR ≥ 15) on top of a natural soil with a CBR ≥ 7 at 100 % mod AASHTO. The pavement design bearing capacity is 3 million standard 80 kN axles with a 95 percentile performance reliability.

Pavement B: 40 mm gap-graded asphalt surface, 140 mm continuously graded asphalt base, 300 mm lightly cement-treated base (1,5 MPa ≤ UCS ≤ 3,0 MPa), 150 mm of selected granular material (CBR ≥ 15) on top of a natural soil with a CBR ≥ 7 at 100 % mod AASHTO. The pavement design bearing capacity is 30 million standard 80 kN axles with a 95 percentile performance reliability.

Pavement C: 30 mm gap-graded asphalt surface, 80 mm continuously graded asphalt base, 200 mm lightly cement-treated base (0,75 MPa ≤ UCS ≤ 1,5 MPa), 150 mm of selected granular material (CBR ≥ 15) on top of a natural soil with a CBR ≥ 7 at 100 % mod AASHTO. The pavement design bearing capacity is 3 million standard 80 kN axles with a 90 percentile performance reliability.

**Granular base pavements:**

Pavement D: 40 mm gap-graded asphalt surface, 125 mm graded crushed stone base (100-102 % mod AASHTO), 150 mm lightly cement-treated base (1,5 MPa ≤ UCS ≤ 3,0 MPa), 150 mm of selected granular material (CBR ≥ 15) on top of a natural soil with a CBR ≥ 7 at 100 % mod AASHTO. The pavement design bearing capacity is 3 million standard 80 kN axles with a 95 percentile performance reliability.

Pavement E: 50 mm gap-graded asphalt surface, 150 mm graded crushed stone base (86-88 % apparent relative density), 250 mm lightly cement-treated base (1,5 MPa ≤ UCS ≤ 3,0 MPa), 150 mm of selected granular material (CBR ≥ 15) on top of a natural soil with a CBR ≥ 7 at 100 % mod AASHTO. The pavement design bearing capacity is 30 million standard 80 kN axles with a 95 percentile performance reliability.

Pavement F: 10 mm surface treatment, 150 mm graded crushed stone base (98-100 % mod AASHTO), 150 mm lightly cement-treated base (0,75 MPa ≤ UCS ≤ 1,5 MPa), 150 mm of selected granular material (CBR ≥ 15) on top of a natural soil with a CBR ≥ 7 at 100 % mod AASHTO. The pavement design bearing capacity is 3 million standard 80 kN axles with an 80 percentile performance reliability.
RESULTS

Partial factors and coefficients

The partial factors and coefficients given in Table 1 were calculated by applying the procedure to the pavements and materials described in Figure 2. The values given in Table 1 are by no means all-encompassing. However, they were developed for a number of typical South African pavement structures.

On average, very close agreement exists between the GEF determined by this procedure and those values suggested in the 1986 AASHTO Guide\textsuperscript{10} where the GEF suggested are 1.38 and 1.66 for tandem and tridem axles respectively. However, while the AASHTO values are independent of the pavement structural number and the adopted terminal condition, the present values are not. There is not a significant difference between asphalt and granular base pavements.

For all pavements, the effect of load increase has a much more pronounced effect than the increase of contact stress. The load damage coefficient (\( \beta \)) indicates that granular base pavements are more sensitive to overloading than asphalt base pavements. They are also more sensitive to contact stress.

\textbf{TABLE 1: Summary of partial factors and coefficients for typical pavement structures.}

<table>
<thead>
<tr>
<th>Pavement</th>
<th>G E F</th>
<th>*</th>
<th>( \beta )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>tandem</td>
<td>tridem</td>
<td></td>
</tr>
<tr>
<td>Granular pavements</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pavement A</td>
<td>1.31</td>
<td>1.91</td>
<td>1.56</td>
</tr>
<tr>
<td>Pavement B</td>
<td>1.29</td>
<td>1.57</td>
<td>2.28</td>
</tr>
<tr>
<td>Pavement C</td>
<td>1.28</td>
<td>1.56</td>
<td>1.98</td>
</tr>
<tr>
<td>Mean</td>
<td>1.29</td>
<td>1.68</td>
<td>1.94</td>
</tr>
<tr>
<td>Asphalt pavements</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pavement D</td>
<td>1.44</td>
<td>1.69</td>
<td>5.11</td>
</tr>
<tr>
<td>Pavement E</td>
<td>1.23</td>
<td>1.40</td>
<td>7.88</td>
</tr>
<tr>
<td>Pavement F</td>
<td>1.58</td>
<td>2.02</td>
<td>3.91</td>
</tr>
<tr>
<td>Mean</td>
<td>1.42</td>
<td>1.70</td>
<td>5.63</td>
</tr>
<tr>
<td>Overall mean</td>
<td>1.35</td>
<td>1.69</td>
<td>3.79</td>
</tr>
</tbody>
</table>

Notes:  
* \( ALF = (P/80) \), where \( P \) represents axle load in kN.  
** \( CSF = (& /520)^\beta \), where \( & \) is the tyre pressure in kPa.
Equivalent Single Wheels Axle Load (ESWAL)

In an attempt to quantify the damage of axles with single wheels, the concept of Equivalent Single Wheels Axle Load (ESWAL) was developed. The ESWAL is defined as the load on a single axle with single wheels which it is predicted will cause the same damage to a given pavement as the standard axle. ESWAL is, therefore, the load of the single axle with single wheels corresponding to a Single Wheel Factor of one.

ESWAL should not be mistaken with Equivalent Single Wheel Load (ESWL) which was developed for converting multiple wheel arrangements into one equivalent wheel load, it is used mainly for design purposes\(^\text{12}\). There are a number of existing techniques and formulae that can be used to calculate ESWL. However, these do not necessarily agree well with the SAMDM approach since the equivalency is defined in terms of an equal response, whether it be deflection, stress or strain. For the determination of ESWAL, the equivalency is considered in terms of pavement performance (cumulative effects of pavement response) and therefore is more suitable for the purposes of this study.

In Table 2, the calculated ESWAL values for the different pavements are given. It should be noted that the same load configuration has different ESWAL values depending on the type of pavement.

**TABLE 2: Equivalent loads (kN) for various axle configurations to give the same performance**

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Asphalt pavements</th>
<th>Granular pavements</th>
<th>Mean (Std. deviation)</th>
<th>Legal limit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
</tr>
<tr>
<td>Single axle, single wheels*</td>
<td>70</td>
<td>64</td>
<td>68</td>
<td>52</td>
</tr>
<tr>
<td>Single axle, dual wheels**</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Tandem axle, dual wheels</td>
<td>135</td>
<td>143</td>
<td>141</td>
<td>149</td>
</tr>
<tr>
<td>Tridem axle, dual wheels</td>
<td>159</td>
<td>197</td>
<td>192</td>
<td>217</td>
</tr>
</tbody>
</table>

Notes:
* Equivalent Single Wheels Axle Load (ESWAL).
** Standard axle (SA)

According to these findings, on average a single axle with single wheels loaded to 60 kN is equivalent to a dual wheel axle loaded to 80 kN. Therefore, for equal pavement damage, if single wheels are replaced by dual wheels, the load on a single axle may be increased, on average, one third.

**Determination of equivalent loads for tandem and tridem axles**

The present method can also be applied to the determination of equivalent tandem and tridem axle loads. These loads represent the load on a tandem or tridem axle which causes the same damage to a pavement as the standard 80 kN dual-wheel single axle. In other words, they are the loads having an Equivalent Damage Factor of one (EDF = 1). The calculated values given in Table 2 tend to agree well with those indicated by the Austroads Guide\(^\text{13}\). This holds especially in the case of
asphalt base pavements.

The values in Table 2 show that, in order to have the same performance, the allowable weight on an tandem or tridem should be greater than that for a dual-wheel single axle. This finding supports conclusions from the 1986 AASHTO Guide but does not agree well with more recent investigations by Hajek et al\textsuperscript{14} which showed that tandem and tridem axles are more damaging than single axles.

It should also be noted that the new legal axle load limits used in South Africa will produce more damage than the standard axle. This, in turn, will accelerate the deterioration of the road network.

**CONCLUSIONS**

The EDFs permit the prediction of the performance of pavement and materials under multiple wheel and axle load configurations. Pavement performance is expressed in relative terms by comparison of the performance of the pavement under a standard axle (SA) to its performance under the vehicle loading configuration being investigated. By using the SA, the EDF of a given heavy vehicle represents the equivalent number of 80 kN axles per such heavy vehicle (ESAs or E80s per heavy vehicle).

It is the authors' opinion that the determination of the EDF according to the new procedure is a more rational approach than the previous determination of E80s per axle based on the power law function. A number of aspects that were previously incorporated into only one coefficient, i.e. the coefficient of the so called \textit{fourth power law}, are now assessed and evaluated independently. The aspects directly considered in this procedure are:

- Number of axles
- Number of wheels per axle
- Inter-axle spacing
- Load per axle
- Contact stress

There are also a number of other aspects which are indirectly incorporated in this procedure, such as pavement types, material properties and environmental conditions.

All the above aspects are taken into account at different stages in the proposed procedure for the calculation of the EDF of the vehicle. The procedure is, however, straightforward and simple to use without the need of highly sophisticated engineering calculations. Tables, formulae and/or graphs facilitate its application.

For the pavements and loading conditions evaluated here, it was found that the load for an individual axle which is part of an axle group (tandem or tridem) could be greater than that for a single axle to produce the same (equivalent) damage. In other words, two single axles of a given load are more damaging to a pavement than a tandem axle with the same total load. The
same concept is applicable to tridem axle groups.

This study also enables the loads on different wheel and axle configurations to produce the same damage as the standard single 80 kN axle to be calculated. These load values may help to determine permissible axle loads for single axles with single wheels, as well as for tandem and tridem axles with dual wheels.

The findings from this investigation strongly confirm the advantages of using dual wheels on single axles rather than single wheels. Theoretically this could allow an increase of approximately one third in the permissible axle load for the same pavement damage.

Use of the proposed method for the determination of Equivalent Damage Factors (EDFs) is recommended. Its formulation is based on a rational mechanistic-empirical evaluation of pavement-traffic load interaction. This approach minimises dependence on other empirical formulae and can therefore be more generally applied than most previous methods. However, to use the new approach in the design stage, more detailed information is required than for the application of the fourth power law approach, i.e. number of axles, load per axle, inter-axle spacing and tyre pressure. Nevertheless, bearing in mind than heavy vehicles, specifically overloaded vehicles, are responsible for most of the pavement damage, all investments made on precise traffic characterization will be recovered from potential savings in maintenance and rehabilitation work.

The increase in overloading on roads, since the power law approach was formulated, indicates that significant underestimation of predicted equivalent traffic volumes and, therefore, overestimation of pavement lives could easily occur.

The scope of this study did not include calculation of costs for the use of the country's roads infrastructure, although, this procedure can form the basis for such calculations. By providing a rational approach to the determination of the degradation of the infrastructure component, it may facilitate an objective estimation of such costs.

The initial work done during the development of the method revealed the difference in sensitiveness to load of the various pavement structures analysed. It was clear that, for equal design reliability, lighter pavement structures (designed to carry light traffic) were more sensitive to overloading than stronger structures. In this paper, however, that distinction is not so clear. The main difference lies in the fact that presently, heavier structures are designed with higher confidence levels (lower risk) than lighter structures. This fact seems to override the former one. In other words, the introduction of appropriate standards for the design of roads overshadows the fact that lighter roads are more sensitive to overloading.
REFERENCES


Figure 1: Flow diagram for the determination of the Equivalent Damage Factor (EDF) of a vehicle.

Figure 2: Pavement structures and material properties used in the study.

2 Committee of State Road Authorities (CSRA), TRH 4: 1985, Structural design of interurban pavements, Pretoria, Department of Transport, 1985.


