Feasibility of Using 4th Power Law in Design of Plastic Deformation Resistant Low Volume Roads

Volkan Emre UZ 1* Mehmet SALTAN 2 İslam GÖKALP 1
1Adana Science and Technology University
2Süleyman Demirel University
vemreuz@adanabtu.edu.tr mehmetsaltan@sdu.edu.tr igokalp@adanabtu.edu.tr

Abstract

A low volume road (LVR) structural design has two phases: first one is selection of appropriate construction materials and second is the determination of layer thicknesses under the certain traffic and environmental conditions with considering the subgrade bearing capacity. Pavements are prompted to serve the traffic without reaching the terminal serviceability index over its design life. Rut accumulation (plastic deformation) is the most common pavement deterioration type of flexible pavements. Therefore the main goal of the design is prevent rutting. Many low volume road design manual assume that plastic deformation occurs only in subgrade. Construction of overlying layers by selective high performance materials according to the related material and construction specifications is the reason of this assumption. In fact, the assumption is not much reasonable especially for with no, or thinly overlaid low volume road pavements, where the major structural strength is comprised of unbound granular pavement materials and where the principal distress mechanism is rutting in the aggregate layers.

Subgrade bearing capacity and the traffic are the main input parameters in the design stage of low volume roads. Subgrade bearing capacity is expressed with California Bearing Ratio (CBR) or Resilient Modulus (Mr). The “traffic” term is determined by Equivalent Standard Axle Load (ESAL) repetitions which is often admitted as 80 kN single axle load. Although it is not too difficult to determine an axle load for an individual vehicle, it becomes quite complicated to determine the number and types of axle loads that a particular pavement will be subjected over its design life. For calculation of Load Damage Factors of different vehicle types, which have various axle load and configurations, a generalized fourth-power law has been used for more than a half century. The objective of this study is to indicate the limitations and difficulties faced on reliably applying a power law relationship in design of LVRs with no, or only thin seals. If a power law relationship to be used due to its simplicity, several parameters must be considered in selection of the power value. Such as stress dependent behavior of unbound granular materials and the selected distress type.

Keywords: 4th Power Law, Plastic Deformation, Equivalent Single Axle Load, Granular Pavement

* Corresponding Author
1 Introduction

Low Volume Road (LVR) structural design consists of the selection of construction materials pursuant to predetermined material specifications for pavement layers and the determination of layer thicknesses according to design charts with consideration subgrade bearing capacity, traffic and climate conditions. As with other pavement types, LVRs are expected to serve traffic without reaching the terminal serviceability index over their design life. Design factors can be divided into four main categories. These are: Traffic, environment, materials, and failure types.

- The axle loads, configurations, and number of repetitions are the traffic related parameters which considered in pavement design (Adlinge and Gupta, 2013; Tarafder, 2003). Although it is clearly known that pavement performance is affected by other traffic-related parameters such as vehicle speed, wander and tire inflation pressures, they are not considered in design. (Uz, 2012; Papagiannakis and Massad, 2007; Saltan and Findik, 2005; Hatipoğlu, 1998). In the design, the “traffic” term is determined by Equivalent Standard Axle Load (ESAL) repetitions.
- The environmental factors are temperature and precipitation. Since hot mix asphalt (HMA) layers have elastic and viscoelastic properties, the resilient modulus of asphalt layers is affected by temperature. In cold climates, resilient modulus of materials varies with freeze-thaw cycles. Precipitation affects the quantity of surface water infiltrating into the subgrade and the groundwater level. Briefly, environmental factors cause seasonal variations on materials behavior.
- Material specifications regulate the acceptance of materials as road construction materials. But, mostly these material specifications seek appropriate construction aggregates with relatively simple index test methods such as grading, abrasion resistant, durability and etc. These tests are generally classified as characterization tests as they do not directly measure resistance to deformation of aggregates under a repeated load. Granular materials commonly show a wide range of performances under plastic deformation tests even though all comply with the same specification limits.
- LVRs have a number of deterioration types which may be classified as cracking, rutting, patching and potholes, surface defects (polishing, bleeding), and etc. (Cebon, 2007; Adlinge and Gupta, 2013; Addis, 1992; Huang, 1993; El-Korcgi, 2013; Mallick and El-Korcgi, 2013; Lu et al., 2014). Each deterioration type is affected by many factors including pavement design, construction errors, material properties, loading and environmental conditions. Major traffic-related deterioration type of LVRs is rutting. And one of the objectives of the LVRs structural design is to limit the permanent deformation for design life.

At the design stage of low volume roads main input parameters are bearing capacity of subgrade and traffic. Subgrade bearing capacity is usually expressed with California Bearing Ratio (CBR) or Resilient Modulus (Mr). The “traffic” term is determined by Equivalent Standard Axle Load (ESAL) repetitions. The standard axle load is usually 80 kN single axle load. Although it is not too difficult to determine an axle load for an individual vehicle, it becomes quite complicated to determine the number and types of axle loads that a particular pavement will be subject to over its design life. A generalized 4th Power Law has been used for more than a half century to calculate Load Damage Factors of different load and axle configurations.

The aim of this study is to indicate the limitations and difficulties faced on reliable application of a power law relationship in design or evaluation of LVRs against rutting. Furthermore, if a power law relationship should be used due to its simplicity than, the value of the power may vary over a large range as a function of several parameters. Such as stress dependent behavior of unbound granular materials and the selected distress type.
2 Structural Design of LVRs in Turkey

All flexible pavement design methods aim to control or restrain the distress caused by traffic and environment conditions within a limit. There are two basic approaches: Empirical and Mechanistic-Empirical (M-E) design methods. Empirical methods relies more on empirical correlations which established with the past performance observations. Material selection strategy generally based on relatively simple laboratory tests which presenting material’s index properties rather than the mechanical properties. The M-E design procedure relies on predicting pavement responses such as stresses, strains and deflections under the load and empirically relating these to field performance. The pavement responses are then converted through transfer functions into pavement life predictions (Nf) and damage (D). The environmental conditions are taken into account with change in material properties as a function of changing temperatures and moisture contents. Further, the M-E design is a more robust analysis and design approach that can adapt new materials and varying traffic patterns.

Main design consideration of LVR is to prevent subgrade from plastic deformation due to load repetitions. Many LVR design manual assume that plastic deformation only occurs in subgrade since the overlaying materials are selected according to a material specification. Road authorities ensure the long term pavement performance through compliance with their relevant material and construction specifications. But accelerated pavement tests show that 30% to 70% of the surface rutting is attributed to the granular layers (Pidwerbesky, 1996; Korkiala-Tanttu et al, 2003).

In Turkey, LVR design guide is more empirical and based on AASHTO 1993 Design Guide. The thickness of the LVR layers is determined by using design charts (Fig 1). The objective of the design chart is to limit the permanent deformation by keeping the shear stress on subgrade a level below the bearing capacity of soil. For thin-surfaced pavements the granular material contributes to the full structural strength of the pavement. In the chart, there are two input parameters. These are subgrade Resilient Modulus (MR) and the design traffic which is determined by Equivalent Single Axle Load repetitions. Equivalent Standard Axles (ESAs) are used in design as a means of combining the many different axle types and loads into one axle type and load. In Highway Technical Specification (KTŞ) of Turkey the properties of materials to be used in pavement layers are defined. These material specifications regulate the acceptance of road materials.

![Figure 1: Design Chart of LVRs in Turkey (KGM, 1995)]
2.1 LVRs Distress and Rutting

LVR pavement structure generally consists of a surface layer and unbound granular layers. Surface layer is generally a chip seal or a thin Hot Mix Asphalt (HMA) layer. The pavement structure is expected to effectively carry traffic and transfer wheel loads to the subgrade. Rutting, cracking, potholes, bleeding, polishing, raveling are general LVR deterioration types which cause a reduction in service life. Repetitive and/or excessive traffic loads, environmental conditions and construction errors are the main reasons of deteriorations (Adlinge and Gupta, 2013).

The main deterioration type of thinly surfaced LVRs is rutting. Rutting can be defined as the displacement of the pavement material that creates channels in the wheel path, and usually a failure in one or more layers in the pavement. The potential causes of rutting in flexible pavements are given in Table 1. Traffic related rutting is generally the result of repeated loading which causes accumulation, and increase of permanent deformations. Rutting does not only affect the pavement ride quality but also leads to a serious safety issue for road users. Water on the pavement surface fill in the wheel paths and obstruct the visibility of ruts may cause hydroplaning or uncontrollable sliding of vehicles with a high potential for traffic accidents (Walubita et al., 2012).

<table>
<thead>
<tr>
<th>Cause</th>
<th>Factor</th>
<th>Example of Distress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic-Load Related</td>
<td>Single or comparatively few excessive loads</td>
<td>Plastic Flow/Shear Deformation</td>
</tr>
<tr>
<td></td>
<td>Repetitive traffic loading</td>
<td>Rutting</td>
</tr>
<tr>
<td></td>
<td>Soil volume change</td>
<td>Swell/Shrinkage</td>
</tr>
<tr>
<td>Non Traffic Associated</td>
<td>Compressive material underlying pavement structure</td>
<td>Consolidation settlement</td>
</tr>
<tr>
<td></td>
<td>Frost susceptible material</td>
<td>Heave</td>
</tr>
</tbody>
</table>

**Table 1**: Causes of Rutting (Adlinge and Gupta, 2013)

The rutting of thinly surfaced LVRs is considered to be one of the main problems in Turkey as well as worldwide. Usually, rutting occurs predominantly under the action of heavy vehicles and under slow moving traffic conditions. Especially, intersections where stop and go movements are often done and upward sections where the speed is reduced are more sensitive to rutting because of loading periods (Li and Li, 2012). A typical rutting profile is shown in Fig. 2.

![Figure 2: a:Typical Rutting Profile, b: Rutting in an asphalt pavement.](image)

In low-volume roads, the permanent deformation resistance of unbound granular layers and the subgrade plays a significant role in rutting deterioration. The Road Structure Research Program (TPPT) have specified the following factors may cause permanent deformation of unbound granular
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materials: void ratio, effective shear/mean stresses and stress history, saturation degree, grain size distribution and max grain size, the level of the deformations, mineralogy of the grains, and the structure of the soil sample (Korkiala-Tanttu, 2009). Stress levels in unbound granular layers are much higher in low volume roads because chip seal is considered to be lack of load carrying capacity.

3 Equivalent Single Axle Load Approach

To determine the thickness of layers for LVRs, design charts are used. The main input parameters in the LVR design are subgrade bearing capacity (CBR, Mr, σd) and the design traffic (Prozzi and Madanat, 2003; Sweere, 1990). So, it is by far crucial to determine traffic loads which pavement section will serve over the design period. Pavement engineers and researchers had long had trouble dealing with various axle loads in pavements design. ESAL is a concept developed from data collected at the American Association of State Highway Officials (AASHO) Road Test to establish a relationship with axles carrying different loads and road damage. The developed empirical equations in the design guide related with loss in serviceability, traffic, subgrade bearing capacity, and pavement thickness. To determine the loss of serviceability before and after the road tests, raters who were experts or researchers were asked to ride in an automobile to assign pavement conditions. A relationship was developed between the mean Present Serviceability Ratio (PSR) assigned by the panel, and the objective roughness, rutting, cracking and patching measurements. The index which based on objective measurements was called Present Serviceability Index (PSI). The traffic used to develop the equations were operating vehicles with specific axle loads and configurations and they traveled on a path with constant speed as opposed to mixed traffic. The structural number is calculated from the AASHO equation with considering subgrade bearing capacity, reliability, and variability. The structural number from which the required pavement thickness is determined is an abstract number expressing the structural strength of a pavement required over the design period. The concept of equating various vehicles to the standard axle to calculate accumulated damage and traffic has been commonly adopted in transportation practices for decades. ESAL is by far the most widely pavement concept in the world. Determination of the damaged caused by particular loads is roughly related to the load by a power of four which often referred to as the fourth power law is given in Eq.1.

\[
\text{ESAL} = \left( \frac{\text{Actual Axle Load}}{\text{Standard Axle Load}} \right)^4
\]

Many equivalent factors were developed by various agencies, researchers either by equating pavement stresses, surface deflections, or fatigue damages (Prozzi and Madanat, 2003; Kuo & Lin, 2011). Equivalent Damage Factor (EDF) or LEF is influenced by pavement type (flexible or rigid), surface thickness, and type of distress or failure. So, even roadways with fairly constant loads and traffic volumes may produce significantly varying LDFs along their lengths, depending on the interaction of these factors. Hence, some researchers have concluded that the use of ESALs with mechanistic-based performance models produces less than desirable predictions and have recommended the use of axle load and vehicle classification data instead (Al-Yagout, 2005; Hajeck, 1995; Rauhut, et al., 1984; Evenseni, 2008).

4 Power Law Exponent “n” for LVRs

This fourth power relationship has been investigated by many researchers throughout the world. Power values between 1 and 8 were found for different pavement structures and failure mechanisms (Cebon, 2007; Kinder and Lay, 1988; Pidwerbesky, 1996; Arnold et al, 2004; Arnold, 2004).
Atkinson (2006) identified damage factor for designing road pavements on UK’s strategic road network in a study. As a result of the study, a wide range of exponents were determined for different types of construction and deterioration parameters. The range of exponents used in power law is given in Table 2. As can be seen the range of exponent changes significantly according type of pavement, and mode of deterioration. Besides in UK, other countries are using different exponents for power law in design phase. For example, the exponent ranges from 4 to 5 is used for fully-flexible type of pavement in Europe, 5 is used for fully-flexible but 12 is used for other kind of pavement in France, 4 is used for fully-flexible but 33 is used for semi-rigid pavements in Belgium, and 4 is used for fully-flexible but 8 is used for semi-rigid pavements in Spain (Atkinson et al., 2006; Dawson, 2008).

<table>
<thead>
<tr>
<th>Mode of Deterioration</th>
<th>Range of Exponents</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flexible Pavement</strong></td>
<td></td>
</tr>
<tr>
<td>Non Structural Rutting</td>
<td>1.0 – 1.5</td>
</tr>
<tr>
<td>Cracking</td>
<td>1.3 – 3.1</td>
</tr>
<tr>
<td>Serviceability</td>
<td>4.4</td>
</tr>
<tr>
<td>Rutting</td>
<td>4.0 – 9.6</td>
</tr>
<tr>
<td>Asphalt Fatigue</td>
<td>4.0 – 5.0</td>
</tr>
<tr>
<td><strong>Rigid Pavement</strong></td>
<td></td>
</tr>
<tr>
<td>Rigid Pavement Cracking</td>
<td>5.5 – 18.0</td>
</tr>
<tr>
<td>Faulting at joints</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Table 2: Power law exponents for different modes of deterioration (Atkinson et al., 2006)

Little (1993) had a research on plastic deformations of unpaved granular pavement and the possibilities of denoting the plastic deformation in terms of load damage factor (n=4). In the study, 3 different trucks with different double axle loads had been used. All trucks defined as by ESAL with using exponential of “4” and LDF was computed as 1.01, 1.58, and 6.38, respectively. 16 unpaved granular pavements in Bothkennar region of Scotland were tested. The pavements being tested had different base materials (gravel and crushed stone) with different layer thickness (260 – 580 mm). Plastic deformation measurements had been taken in response of certain transition of the trucks. The result of the study showed that LDF had found between 1 and 20 according to test section.

Douglas (1997) had a study on unpaved granular pavements. Pavements had same subbase, but different layer thicknesses (200, 350, 560 mm). Pavements were loaded with different magnitudes (44, 80 kN), and tire inflation pressures (310, 690 kPa). The road structures were subjected to repeated wheel loads up to a maximum of N= 10000. The main objective of this study was to determine permanent deformation on industrial forestry and mining road which exposed to different loads, and predict the permanent deformation (rutting) as a function of tire load, internal tire pressure, thickness of subbase layer and ESAL repetitions. At the end of the study, the following results were indicated.

- For all combination of wheel load, tire inflation pressure, and subbase thickness, the rate of rut depth accelerated continuously.
- The lower inflation pressure generally produced flatter rut cross sections (From 1.74 to 2.11 mm for low inflation pressure and high inflation pressure, respectively).
- Increasing wheel load by 82 % (80 kN/44 kN = 1.82) resulted in ruts, averagely, 5.7 times deeper than for given subbase thickness and number of passes.

Vuong and Sharp (1999) pointed out that seal coated pavements contributed 90% of total road network of Australia, and there was no adequate information about the behavior of those pavements under heavy vehicle traffic (different axle load, type of wheel and tire inflation pressure). In this
regard, seal coated pavements on three different regions were tested with accelerated loading tests. The tests were performed under different axle loading conditions (40-50-60 kN). In the study, researchers mentioned that up to 70% of plastic deformations can be associated with granular layers. Moreover, load damage factors (LDF) had been identified according to the results which vary between 6 and 8. They indicated that the 4th power law is incapable in the design of seal coated flexible pavements.

Korkiala-Tanttu et al. (2003) investigated the effects of adverse climate conditions and excessive axle loads to the bearing capacity of low volume roads. The test performed in a closed environment with 10 °C and under heavy vehicle simulation device (Maximum Load: 110 kN, Speed: 12 km/h). The flexible pavements consisted of 1600 mm subgrade (Sand), 260 mm subbase (crushed gravel), 200 mm base (crushed stone) and 60 mm asphalt concrete (AC). The pavement sections divided into three part and each of the sections had been tested under certain wheel load (50 – 70 kN) and water level depth (500 mm and 1000 mm under AC surface). The objective of this research is concentrated on validity of using 4th Power Law in low volume roads design against rutting under spring conditions. At the end of this research, following outputs had been pointed out.

- Ruth depths increased 2.8 to 3 times when the axle load increased from 50 kN to 70 kN.
- Ruth depths increased 2.2 to 2.5 times when the certain water level rose from 500 mm to 1000 mm.
- Development of rutting accelerated with excess of certain stress limit
- ESAL exponent value can be adjusted between 5.5 and 8.5 for low volume road design against rutting.
- In all pavement sections the major permanent deformations occurred in the subgrade sand (47 to 59 %) and 23-27, 15-23, and 3.5-6 % of total deformation occurred in the subbase, base, and AC layer, respectively.

Yeo et al (2004) reported the effect of increasing axle loads on performance of seal coated unbound granular pavements which constituting 95% of total road network of Australia and New Zealand. Accelerated pavement testing devices had been used. The project scope included three granular pavements (two of them were high quality while the other was low quality) subjected to three different axle loads (40, 60, 80 kN). At loading, dual wheel which is half of standard axle was used. All tests were performed in dry conditions to minimize the effect of environment. Subgrade was sand with 10% CBR. Base layer thickness was 200 mm and surface coat was double layer seal coat with 7/14 mm chips. Structural Number was used to determine the strength of pavements. Performance evaluation of pavement was done by using surface deformations, deflections, roughness, surface texture depth, and base layer compression values. Maximum plastic deformation observed in the pavement constructed with low quality material. The researchers developed a model that predicts the pavement rutting as a function of structural number, load magnitude and number of repetitions. According to test results, exponent of “n” was found 2, 2.4, 4.4 for each three materials under different loading conditions for the same rutting depth.

Alabaster (2004) investigated the most suitable exponent of ESAL “n” for unbound flexible pavement in New Zealand, and have questioned whether such an alternative approach to be brought or not. Also, it was searched that the effect of increasing of permitted axle load on pavement in the scope of the study. The tests performed in CAPTIF, and performed on one type subgrade (Silty Clay with 11 % CBR). Five different type of material with maximum grain size of 200 or 400 mm had been used with different thickness (250, 300, 320 mm). Material quality of base layer was high quality for 3 of them, while one was low quality and other was recycled material. Different loads (40, 50, 60 kN) had been used to perform tests. Vertical surface deformation (VSD) had been used as a criteria to compare the performance. Exponent of “n” which is used in the equality to calculate ESAL is determine for each tabs of test pavement. Consequently, exponent of “n” was found between 2 to 9.
Martin (2010) developed an accelerated loading test program to determine relative performance factors of seal coated flexible pavements. Single, double and geotextile-reinforced double layer seal coats are used in the tests. Rutting and International Roughness Index (IRI) had been used for performance criteria. In the experiments, double wheel load applied to the surface with 700 kPa tire inflation pressure. The first 9000 cycles with 40 kN load is determined as conditioning level after conditioning level 50kN wheel load applied in dry and wet conditions. In the study, the development of plastic deformation divided into three levels. First level was conditioning level, in the 2nd level there was a linear relationship between load repetitions and plastic deformation and this level is used for the performance comparisons and the third level is where a nonlinear relationship between number of load repetitions and plastic deformation and plastic deformation development rate is 2-3 times higher than the second level. Accumulated rutting ($\Delta$ rut) for any kind pavement is computed according to Million Equivalent Standard Axle Loads (MESAL) and Modified Structural Number (SNC). As expected, rutting in the tests conducted in wet environment is higher than in dry ones.

5 Results and Discussion

Pavements are not subjected only to axle loads which are all at the ‘standard’ level, but for structural design the designer must predict the spectrum of the axle masses and the number of passes of each axle type will be applied. A generalized 4th Power Law has been extensively using for more than a half century to calculate Load Damage Factors of different load and axle configurations. Thus the input parameter ESALs repetitions can be calculated. The objective of this study is to indicate the limitations and difficulties faced on reliably applying a power law relationship to design or evaluation of LVRs ( thinly surfaced) against rutting which obtain their structural strength primarily from the unbound granular layers. The power value is highly dependent on pavement structure itself and the selected distress type. Researches show that it is sometimes impossible to model real pavement response by any power relationship. And when it is possible the power values are highly variable with construction material and ‘failure’ criterion even in controlled experiments.

In the light of the information derived from previous studies in the literature. Following conclusion can be reported,

- In low-volume roads, the permanent deformation resistance of unbound granular layers plays a significant role in rutting deterioration. Accelerated pavement tests show that 30% to 70% of the surface rutting is attributed to the granular layers (Pfidwerbesky, 1996; Korkiala-Tanttu et al, 2003). Building these unbound layers thick may not be an appropriate solution for rut resistant LVR design.
- The exponent changes significantly according type of pavement and mode of deteriorations.
- If a power law relationship should be used due to its simplicity than, the value of the power may vary over a large range as a function of several parameters, Such as stress dependent behavior of unbound granular materials and the selected distress type. For rutting deteriorations of granular pavements different power law exponents are encountered ranging between 2 and 9.
- The 4th power exponent is obtained from AASHO road tests where pavements were constructed reasonably thick, and not represent thinly sealed LVRs Moreover, vehicle type, axle configuration and loading magnitude pattern was not wide enough.
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