Session 6
Paper (a)

Off-Highway Experience Casts Doubt on Fourth Power Rule

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Abstract

The AASHTO road test conducted during 1958-1961 provided a comprehensive database on structural damage and load equivalencies. This resulted in a simplified fourth power rule that describes the effect of increasing load on pavement condition. This has been used for pavement design and allocating road user charges, without regard to original conditions and assumptions of the AASHTO road test. But since then, tyres, suspensions, axles and vehicles have changed.

Performance of a private sealed forestry road commonly known as the "off-highway" places further doubt on the fourth power law and current pavement design theory. Strain measurements on the subgrade gave values 3 times higher than the limiting subgrade strain, although the pavement depth is calculated so that this limiting strain is not exceeded under a standard axle load.

Substantially more research is required for New Zealand pavements to develop a suitable pavement behaviour model that allows for different; axle weights, suspensions, tyres and vehicles. This is especially so considering the New Zealand system of road user charges.

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Introduction

The results of the AASHTO road test conducted during 1958-1961 produced a suite of formulae for calculating pavement thicknesses and load equivalency factors. Subsequently, engineers have simplified the procedure, usually without regard for the original assumptions and application. One of the most important simplifications has been the "Fourth-power Law". Existing pavement design theory in New Zealand is discussed and this is compared to measurements made on the "off-highway" (a private, sealed, forestry road). The conclusion shows a need for further pavement research in New Zealand, to develop a suitable pavement behaviour model to account for different axle weights, suspensions, tyres and vehicles for a more accurate road user charges allocation model.

Experience on the "off-highway" does not disprove the fourth power rule, which is used to compute the relative damaging effect of an individual axle to determine the total pavement loading. However strain measurements on the "off-highway" are vastly different from what the theory suggests. This places doubt on the current New Zealand pavement design procedure, which incorporates the fourth power rule to determine the pavement loading.

AASHTO Road Test

The AASHTO (American Association of State Highway and Transportation Officials) Road Test was undertaken to study a number of pavement design factors, during 1958-1961. The test sections consisting of six loops, were located near Chicago, Illinois. The test included flexible pavements, rigid pavements, and short span bridges. In the flexible pavement test sections, the surface course was a bituminous mix; the base course, a well - graded crushed limestone; and the subbase, a uniformly graded sand-gravel mixture. Major design factors were surface, basecourse, and subbase thicknesses. Only one subgrade soil, a silty clay, was used in the pavements.

Each section was subjected up to one million load repetitions by two of the ten possible vehicle combinations. These included single and tandem axle vehicles. Single axle loads ranged from 9000 to 14000 kg, and tandem axle loads, from 11,000 to 22,000 kg.

The AASHTO Road Test is still the most comprehensive pavement experiment conducted. It yielded a wealth of data that has heavily influenced pavement engineering.

Fourth Power Rule

The results of the AASHTO Road Test were analysed using a complex regression technique, which produced a suite of formulae for calculating pavement thicknesses and load equivalency factors. Subsequently, engineers have simplified the procedure, usually without regard for the original assumptions and application. One of the most important simplifications has been the "Fourth-power Law".

This is represented by the formula below:

$$\frac{A}{B} = \left[\frac{L}{S}\right]^y$$

where;

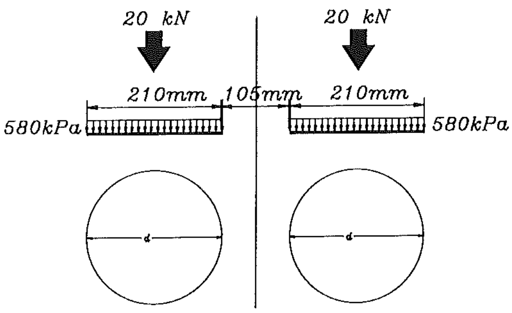
A is the number of load repetitions of magnitude S

B is the number of load repetitions of magnitude L.

Y is an exponent

The exponent y was found to be 4.15 (AASHTO, 1962), derived from the AASHTO Road Test, where all the equivalency factors for rigid and flexible pavements were combined. This exponent has been modified by various roading authorities, and "4" is the value most commonly used. Thus, the relationship is referred to as the "fourth power law".

In New Zealand a wheel load model that was commonly used at the time of the AASHTO Road Test is used in pavement design and is shown in figure 2 below. The tyre dimensions represent a modified loading area under a 10.00 x 20, 12-ply tyre. The dual-tyred single axle, loaded to 8.2 tonnes, was chosen as the standard axle that causes one unit of wear effect during one passage over a point on the road. This axle load configuration was the most common legal load limit condition in the U.S. in the 1950's. The load is assumed to always be evenly distributed between the tyres in an axle group.



Circular Tyre Imprint: Area = $\frac{\pi d^2}{4}$

Figure 2 - Loading Model

This wheel model was used in development of the Transit New Zealand pavement thickness design charts. Linear elastic theory is used to determine the strain at the base of the subgrade under this wheel load. Pavement thickness is then calculated by limiting the subgrade strain to a critical value which is based on the pavement loading (EDA). Linear elastic theory is discussed later in more detail.

The term EDA (Equivalent Design Axle) is used in New Zealand as an equivalency factor. EDA is calculated using the fourth power rule based on a 8.2 tonne standard axle and wheel load (shown above). As all vehicles are different in size and load, the number of EDA's per vehicle is calculated to determine the pavement loading. The total EDA's to travel over the pavement during its life is used to calculate pavement depth from the Transit New Zealand design charts. The formula that defines EDA is shown below:

$$EDA = \left[\frac{\text{Axle Load}}{\text{Reference Axle Load}}\right]^4$$

where the reference axle load
= 6.7 tonnes for a single tyred single axle.
= 8.2 tonnes for a dual tyred single axle.

Studies in Australia, Europe and North America have all demonstrated that the load equivalency exponent varies from 1 to 8, with the most common values between 2 and 6 (OECD, 1988; Kinder & Lay, 1988). The load equivalency exponent was shown to be different for each type of pavement failure (eg. rutting, cracking or loss of serviceability), pavement type (eg. unbound granular basecourse, cemented basecourse or asphaltic concrete), and tyre-axle arrangement (eg. number of tyres and axles, axle spacing, or tyre type). However these tests used a limited number of vehicle characteristics and pavements that are uncommon in New Zealand.

Research (since the AASHTO test) carried out in South Africa [Walker et al] has revealed that the fourth power relationship may be only appropriate for asphaltic concrete pavements. While an exponent greater than four for cemented base/subbase layers and an exponent less than four for unbound pavements may be more appropriate.

These tests were conducted on pavements similar to those used in New Zealand.

The recommendations of AASHTO Road Test reports emphasised that "the findings of the AASHTO Road Test relate specifically to the physical environment of the project, to the materials used in the pavements, to the range of thicknesses and loads and number of load applications included in the experiments, to the construction techniques employed, to the specific times and rates of application of test track, and to the climatic cycles that occurred during construction and testing of the experimental pavements. Generalisation and extrapolations of these findings to conditions other than those that existed at the road test should be based upon experimental or other evidence of the effects on pavement performance of variations in climate, soil type, materials, construction practices and traffic." (AASHTO, 1962).

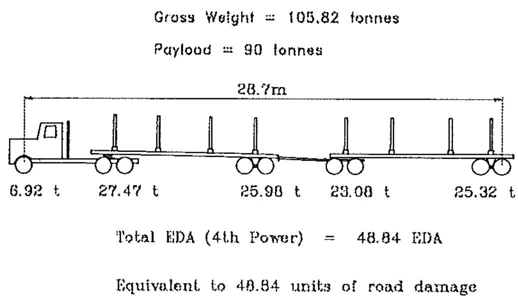
Standard pavement design procedures for New Zealand roads have been adopted from the AASHTO road test. These being National Roads Board, Highway Standards S/4 (October 1974) and more recently the "State Highway Pavement Design and Rehabilitation Manual" (July 1987). Since 1974 there has been little research on New Zealand pavements to justify using our current design procedure for pavements.

Off-Highway

In the central North Island there is a privately owned sealed highway used by forestry trucks. This road predominantly services a pulp and paper mill in Kawerau and is commonly known as the "off-highway". There are no limits to the weight and dimensions of trucks using this off-highway and consequently axle weights are high. Typically single axle weights in a tandem or tri-axle group of 14 tonnes are not uncommon. On public highways the legal axle limit is only 8.2 tonnes per axle.

Typical of the trucks using the off-highway is the double and treble bailey unit, with gross weights of 100 and 120 tonnes respectively. Figure 1 below shows a configuration of double bailey unit and typical axle weights that were measured in 1991. Approximately 1.1 million tonnes per annum of forest products are transported by truck on the off-highway. This is approximately 50 truck passes per day.

Figure 1 : Off-Highway Double Unit



Combined with the extreme traffic loadings experienced on this off-highway, weather conditions are harsh. Freezing temperatures in the winter and above 30 degrees celsius in the summer. However this pavement is performing exceptionally well and will provide many more years of service. This creates the question; is the current New Zealand road design standards relevant for this off-highway as they were developed from experimental data for axle loads up to 8.2 tonnes. It may be dangerous to interpolate using the fourth power rule for axle loads of 14 tonnes or more.

Linear Elastic Theory: Strain Measurements on the Off-Highway.

During 1992, a Civil Engineering masters student, Bruce Stevan from the University of Canterbury studied "The Response of an Unbound Granular Flexible Pavement" as the topic for his thesis. This involved measuring strains in the basecourse and subgrade under a logging truck on the "off-highway". The project was financed by Tasman Forestry Ltd.

The objectives of his thesis were:

1. Set up a portable acquisition system that could measure the response of a pavement as it was loaded by logging trucks.

2. Compare the measured data, to the calculated response of the pavement model that was used to determine the design of the road used in this investigation.

3. Develop a different pavement performance model that more closely suited the requirements of the forestry industry.

Bison strain inductance coils were selected to measure the strains induced in the pavement. These were placed at the base of the subgrade and basecourse by digging a trench and then backfilling using the original material. These inductance coils were chosen as they are ideally suited for measuring strains for different combinations of axle weight, vehicle speed and axle configuration.

Five hundred and twenty-four vehicle passes were recorded. Axle weights varied from 8 tonnes to 16 tonnes, vehicle speeds ranged from 5 km/hr to 60 km/hr, single and tandem axle configurations were used.

Comparison between the Design Life and Subgrade Strain

The amount of subgrade permanent deformation that occurs depends on the number of load applications and the degree of vertical compressive strain induced at the top of the subgrade by a single load application (Dormon, 1962). The single load considered is an 80 kN dual tyred standard axle. Permanent deformation in the subgrade is reflected upward and manifests itself as rutting in the road surface.

For subgrade deformation the relationship between number of load applications (N) and the critical strain level ε_v takes the form:

$$N = a\varepsilon_v^{-b}$$

in which a, b are constants.

The numerical values for a and b are found by laboratory experiments and the observed behaviour of actual pavements. Regarding the constants a & b for the subgrade strain, different authorities have chosen different values, obtaining different thicknesses. For example, the Shell 1978 method gives significantly thinner structures than the Shell 1963 method.

Subgrade deformation is controlled by choosing a pavement such that the repeated vertical strain at the top of the subgrade is limited to a value that depends on the estimated design traffic loading. In order to produce design charts that cater for various design traffic loadings it is necessary to have a relationship between traffic loading N (in EDA units) and the repeated vertical compressive strain in the subgrade induced by a single standard wheel load.

The particular formula used by the Shell group in 1963 was revised for the Shell Pavement Design Manual, 1978 on the basis of taking the surface load to be two circles (for dual wheels) and taking Poisson's ratio to be 0.35 for all materials (instead of the previously used value of 0.5). The new criterion was

$$\varepsilon_c = 0.021N^{-0.23}$$

This strain criterion was used in the development of the TNZ design charts for pavement thicknesses. Figure 3 gives a summary of the elastic characteristics of the pavement used in the development of the design chart as shown in figure 4.

For the off-highway in question the design was for:

Design life =15 years
Annual log volume =1,100,000 tonnes
Average truck payload =80.5 tonnes
Calculated EDA/tonne payload =0.426
Number of axles per truck =9
Design EDA (N) =7.03×10^6

Therefore allowable strain in the subgrade from $\varepsilon_v = 0.021N^{-0.23}$ is:

ε_v = 559 microstrain

The TNZ model uses 8.2 tonnes as the standard axle weight, but in this investigation, the test vehicle was loading the pavement with axle loads of up to 16 tonnes. The road that was used for this investigation was designed for a total of 7.03×10^6 Equivalent Design Axles over a period of 15 years. Based on the expected number of EDA, the TNZ model recommended a maximum vertical compressive strain at the top of the subgrade of 559 microstrain. The strain that was measured under a 8 tonne axle was 1500 microstrain, nearly three times the recommended level.

The total number of EDA that the road design was based on was calculated using 12 tonne axle loads, and the measured strain for the 12 tonne axles was 1800 microstrain, 3.2 times the recommended value calculated from the critical strain criterion in the Shell Pavement Design Manual, 1978. The strain values were determined at a vehicle speed of 60 km/hr. Therefore, it was found, in this investigation, that the strains induced in the subgrade are up to nearly four times greater than the strains that the TNZ model predicts.

Figure 3

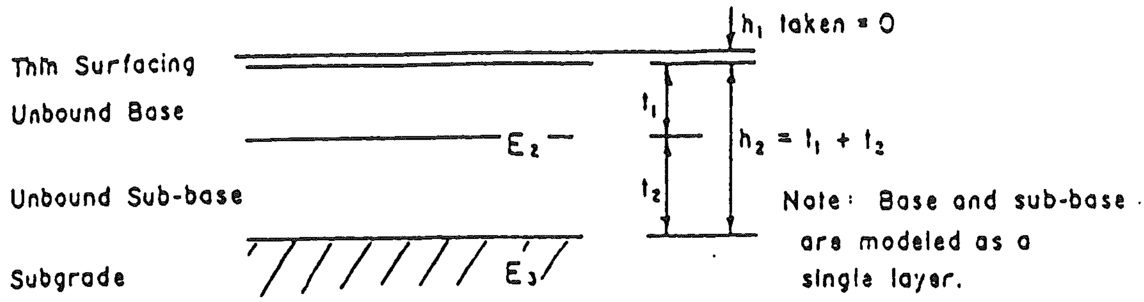
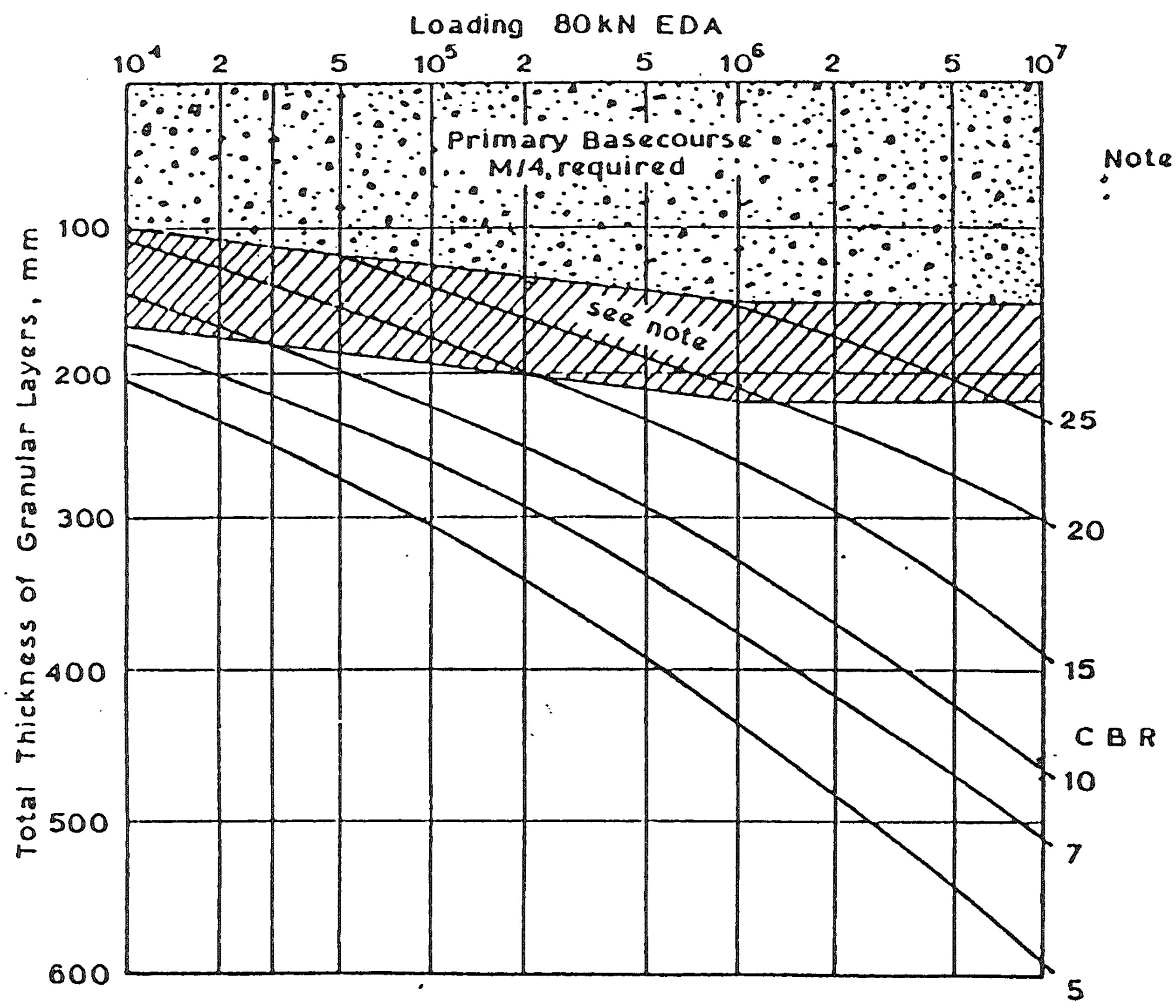


FIG. 1 ELASTIC CHARACTERISATION OF LAYERS

*Figure 1 Notes

ELASTIC CHARACTERISATION	Surfacing : not considered to contribute to structural capacity Unbound base-course and subbase layers : base and subbase taken together with thickness h_2 and modulus E_2, where $E_2 = kE_3$, $k = 0.2h^{0.45}$ $2 < k < 4$ Subgrade : $E_3 = 20\ (CBR)^{0.64}$, CBR < 13 $E_3 = 8$ CBR , CBR > 13
DESIGN CRITERIA	Subgrade strain criterion for premium (Class I and II) pavements: $\epsilon_c = 0.021\ N^{-0.23}$ Subgrade strain criterion for lower grade (Class III and IV) pavements: $\epsilon_c = 0.025\ N^{-0.23}$ ϵ_c is the strain due to a standard dual wheel load, and N is the design traffic loading.

Figure 4



Note : The curves give minimum cover required above the subgrade. Allowance must be made for loss of material through penetration into soft subgrades and construction tolerances.
Materials for use in hatched zone must satisfy permeability requirements SE>40

FIG.2. DESIGN CHART FOR PREMIUM FLEXIBLE PAVEMENTS WITH THIN SURFACINGS

Discussion

It is dangerous to use the fourth power rule derived from the AASHTO Road Test for comparing the relative damaging effect for different vehicles on New Zealand Roads. Substantially more research is required, to determine load equivalency factors for allowable axle weights for different tyres, suspensions, and vehicles for a road user charges allocation model. The current linear elastic theory is unsuitable for evaluating the relative effects of different vehicles.

The "off-highway" is performing extremely well, structurally. Benkelman beam deflections under a 8.2 tonne axle load are from 0.5 to 1.0mm. There are no visible signs of rutting and major potholing. Any pavement failures are localised and the cause is moisture in the pavement rather than overloading. It appears that the initial design for pavement depth is conservative as this pavement is approaching its total design loading already, but it seems it will still be able to provide many more years of service. The design traffic loading calculated from the fourth power rule could overestimate the traffic loading and thus a conservative pavement depth will be calculated. Another reason is the design assumptions used and theory does not represent this "off-highway".

Pavement design in New Zealand and the road user charges are based on the AASHTO Road Test in 1962. For pavement loading a simplified "Fourth Power Rule" was used without regard for the original assumptions and application. Consequently this fourth power rule has been used for our road user charges allocation system. The linear elastic theory for development of the Transit New Zealand design charts uses a wheel load commonly used in the 1950's and is based on simplified theory such as a perfect circular wheel load. Therefore, there is doubt that the fourth power rule and the design charts (based on overseas research) are relevant to New Zealand conditions.

Strain measurements on the "off-highway" under a 8 tonne axle load give a value of 1500 microstrain. Whereas the pavement thickness for this off-highway was designed to limit the strain under a standard 8.2 tonne axle to 559 microstrain and is only approximately 1/3 of the actual measured strain. This means that the theory and design assumptions used are not relevant for this "off-highway".

The "fourth power" concept used for comparing the relative damaging effect of different vehicular loading conditions is based on test data with major limitations, obtained three decades ago and altered little since. The concept's main load equivalency conversion exponent (the "fourth power law") is derived through generalised and simplified assumptions that still need to be confirmed for New Zealand conditions. Substantially more research is required on New Zealand pavements to determine load equivalency factors and pavement behaviour models that allow for different axle weights, tyres, suspensions, and vehicles, especially considering the unique system of road user charges.

At CAPTIF (Canterbury Accelerated Pavement Testing Indoor Facility), there is current research to determine the relative effects of two suspension types on the condition of the same flexible pavement. This is the first element of the OECD DIVINE project, which is a cooperative international research effort, in studying vehicle-pavement interaction. The combined research effort will tackle some of the issues mentioned in this paper.

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