Development of Optimised Investment Strategies Using Traffic Speed Deflectometer Data for Sustainable Road-Asset Management

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DEVELOPMENT OF OPTIMISED INVESTMENT STRATEGIES USING TRAFFIC SPEED DEFECTOMETER DATA FOR SUSTAINABLE ROAD-ASSET MANAGEMENT

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ABSTRACT

If road agencies are to manage their available road maintenance funding more efficiently, then they must improve their investment strategies and develop their works programs.

If they do so, they will improve the performance and safety of road networks, and at the same time maximise the return on investment and improve the safety of the road users.

A road's performance is influenced by several factors:
- the structural bearing capacity of the pavement
- the number of heavy vehicles using the road
- climate
- surface and drainage conditions.

Due to the limited availability of structural data, road agencies are forced to use rutting data as a substitute for structural bearing capacity to identify rehabilitation treatment options.

However, this approach fails to assist in the development of investment strategies to reduce the life-cycle cost of the road asset, nor will it maximise the safety of vulnerable road users. The introduction of the traffic speed deflectomer (TSD) has made it more affordable for many road agencies to collect defects data. The use of TSD has created a knowledge gap on methodology/mechanism as road agencies are yet to identify the best means of utilising and incorporating this structural data at network level investment analysis.

This study's findings will assist to:

- Bridge the knowledge gap in TSD structural data usage in network level investment analysis, through the development of a structural deterioration curve.
- Simplify the process to use structural data effectively, and in turn develop optimised investment strategies for road agencies to manage their ageing road assets.

Keywords: Adjusted Structural Number (SNP), Maximum Deflection (D_0), Equivalent Standard Axle (ESA) and Traffic Speed Deflectometer (TSD).

1. INTRODUCTION

Roads are unique horizontal infrastructure assets. Predicting their performance is complex particularly due to the existence of several variables. Transport infrastructure is critical for any nation's economy, and a huge burden for them to manage. Australian road network is an important component of the economy and is vital for economic growth as it facilitates the mobility of people, goods and services. In a country like Australia with a low population and extensive road needs, it is difficult to maintain sustainable road networks. Australia is the sixth-largest country in the world; approximately 40% of its road networks have been constructed with sprayed seal and asphalt pavement [1].

Predicting a pavement's performance is critical for maintaining this asset. Intervening with appropriate treatment at the right time will minimise its whole-of-life cost. Performance is based on a combination of functional and structural deterioration of the pavement. Well-defined functional performance models have been developed locally and internationally. Many sophisticated functional models have been developed and incorporated in pavement-management systems. These models are available to assist asset managers make informed decisions and manage the functional performance of their road assets.

Structural modelling plays a vital role in the prediction of pavement performance. Structural performance is also important for predicting the remaining life and overall health of a road network. Thus, it is essential that pavement performance be evaluated correctly by adopting the appropriate methodology.

Maintaining assets to meet functional performance is not economical nor sustainable in the longer term. Furthermore, this would require significant investment by road agencies — resulting in road users incurring additional costs. The best performance models must be included for structural and functional predicting capabilities, as a means of precisely assessing needs and the time-frame of those needs.

The aim of this study is to develop structural deterioration models, using TSD data to enhance and improve the reliability of the pavement management system (PMS) predictions. This will serve as an effective system for monitoring pavement structural conditions, providing accurate information to make decisions regarding when and how a particular road network needs to be rehabilitated and its costs. The project will focus on flexible pavements in Queensland (Qld), Australia.

Figure 1 — State of Queensland, Australia [2]

Australia has a road network of more than 823,000 km (511,180 mi). This includes 356,000 km (211,118 mi) paved and 466,000 km (289,440 mi) unpaved roads [3]. Qld is Australia's second largest state, covering approximately 1.8 million square kilometres (0.69 million mi^2). The state has approximately 174,000 km (108,074 mi) of road networks, managed by state and local governments [4]. The Department of Transport and Main Roads

(TMR) is responsible for maintaining approximately 33,000 km (20505 mi) of the road network in Qld [2], as shown in Figure 1 (above). The majority of Qld's road network has spray-seal surfacing on granular pavement.

Previously in Australia a falling weight deflectometer (FWD) was used to collect project level deflection data, mainly for pavement-rehabilitation design. At a network level, FWD data collection is prohibitively expensive. The collection of this data particularly on shorter intervals of a larger road network is not practical. Therefore, road agencies have not been able to use structural data to decide how to manage road assets, despite structural data being essential for sustainable road asset management. However, this is not the case anymore due to the recent development of the TSD.

This new state-of-the-art technique was developed by Greenwood Engineering in the early 2000s using Doppler laser technology. This tool is capable of continuously measuring the velocity of the deflection of a pavement while moving at traffic speeds. The device's high accuracy and continuous deflection profiles are useful for network-level applications such as predicting road-rehabilitation needs and remaining pavement life [5]. Thirteen TSD vehicles are in use around the world including in USA, China, UK, South Africa, Poland, Italy, Denmark, Germany, and a vehicle shared between New Zealand and Australia [5].

During TSD operations, Doppler sensors measure the vertical deflection velocities of the pavement surface at discrete points. When divided by the instantaneous vehicle speed, they produce deflection slopes at those points [6] . The accuracy of the deflection bowl is reliant on how the Doppler laser is mounted on the vehicle. A number of studies have been published on TSD technology, data collection and interpretation. Publications referenced in this research are by Rasmussen et al [6], Muller et al [7], Graczyk et al [8] and Zofka et al [9].

2. LITERATURE REVIEW

Considerable literature review was undertaken to provide an insight into the application of this structural data both nationally and globally. The following structural deterioration models are currently available in Australia at a network level application, and these models were developed using the FWD. There has been very little research conducted regarding the use of TSD data. Therefore, it is essential to develop structural deterioration models for Queensland roads, using TSD deflection data as well as available other data that significantly influences structural performance.

2.1. Predicting structural deterioration of pavements at a network level – interim models

The Association of Australasian and New Zealand Road Transport and Traffic Authorities (Austroads), published a report on predicting interim structural deterioration models of pavement at a network level in 2010 [10] . These models were developed based on the 71 long-term pavement performance sites and 595 data samples. Models were developed separately for both asphalt pavement and sealed, unbound, granular pavement types. Those relationships are shown in Equations 1 and 2.

For asphalt pavement:

$$S\mathrm{NC\ ratio} = 0.919 \times [2 - \mathrm{EXP}(0.00132 \times \mathrm{TMIi}\ + 0.256 \times \frac{\mathrm{AGEi}}{\mathrm{DL}}] \qquad (1)$$

For sealed, unbound, granular pavement:

$$\text{SNC ratio} = 0.9035 \times [2 - \text{EXP}(0.0023 \times \text{TMIi} + 0.1849 \times \frac{\text{AGEi}}{\text{DL}}] \quad (2)$$

Where
SNC_{ratio}= current strength of pavement/subgrade relative to its initial strength (SNC ratio = SNCi/SNC_0)
SNCi = modified structural number at the time 'i' of measurement
SNC_0 = modified structural number at the time of the pavement construction (AGE = 0)
TMIi = Thornthwaite moisture index at the time 'i' of assessment
AGEi = age of pavement (number of years since construction or last rehabilitation)
DL = pavement design life (years)

2.2. Model for structural deterioration, by Tim Martin et al

A further similar structural model was developed by Tim Martin et al and presented at the 8th International Conference on Managing Pavement Assets [11] . The appropriate model they developed for thin asphalt (less than 40 mm) and spray-seal road is shown in Equation 3.

$$\text{SNC ratio} = \text{K1} \times 0.919 \times [2 - \text{EXP}(0.242 \times \frac{\text{AGEi}}{\text{DL}} + 0.507 \times \text{MESA}] \quad (3)$$

Where:
SNC_{ratio}= SNC_i/SNC_0
SNCi = modified structural number of the pavement/subgrade strength at the time of pavement age AGEi (SNC_i =3.2*D0$^{\wedge-0.63}$)
D_{0i} = maximum deflection measured at pavement age. AGE using a FWD or heavy weight deflectometer (HWD)
SNC_0 = initial modified structural number of the pavement/subgrade strength at pavement age AGEi
K1 = local calibration factor for structural effects (default = 1)
EXP = exponential function
AGE_i = pavement age, the lesser of the number of years 'i' since construction or last rehabilitation
DL = expected (assumed) design life of the pavement (years)
MESA = millions of equivalent standard axles per year per lane

3. RESEARCH METHODOLOGY

This section briefly outlines the significance of structural models needed for Qld's road network. The concept was formulated by reviewing the literature of existing deterioration models and collecting information from industry experts/practitioners and consideration of how the data was prepared for analysis and the methodology used for the data analysis.

3.1. Significance of developing structural deterioration models for Qld roads

Pavement deterioration occurs due to functional and structural behaviours. This area has been extensively researched, focusing particularly on functional deterioration models. However, structural performance models are limited—even those based on FWD data.

Structural bearing capacity plays a vital role in pavement performance, but not enough data is available to develop models. Collecting network-level structural data is very expensive, compared to collecting other functional data such as roughness, rutting, cracking etc. Limited research has been conducted relating to predicting structural deterioration models for Qld's flexible pavements.

The above research predominantly focused on Qld's flexible road network, as currently no deterministic/probabilistic structural performance models are available specifically for the Qld state road network. The majority of current modelling primarily focused on functional deterioration, without consideration of the structural capacity of the roads. This can be attributed the unavailability of network level structural data.

A study conducted by David Paine [12] highlighted the benefits of including structural data in pavement-management systems to predict treatment strategies. Asset managers/ practitioners acknowledge that structural data application in pavement management will accurately identify pavement rehabilitation needs. Therefore, this study's outcomes will greatly benefit asset managers/practitioners in their preparation of optimised maintenance strategies for long-term management of network, within their available budgets.

3.2. Concept behind the development of structural deterioration models

Roads are unique transport-infrastructure assets and their performance depends on many factors. Developing deterioration models is complicated as it is essential that any road-research funding be used by road-management jurisdictions to meet public expectations.

Thus, the model concept carefully considers the availably of data is available at network level analysis, the frequency of data collection, and how that data can be imported into pavement management software for analysis. Structural deterioration of the pavement can be caused by several factors over time and include traffic volume (number and types of heavy vehicle), rutting, cracking, pavement materials, subgrade type and climatic conditions such as rainfall and lower-soil moisture content.

The significant factors in models are:

- equivalent standard axle (ESA)
- moisture content (MC)
- pavement age (PA)
- pavement depth (PD)
- subgrade type (ST)
- subgrade strength (CBR)
- linear rate of rutting progression (Delta_ Rut)
- base-layer index (BLI)
- curvature function (CF)
- lower layer index (LLI).

Therefore, structural deterioration is dependent on the function of many independent variables, as shown in Equation 4, below.

$$(\Delta)\mathrm{SNP} = \int (\mathrm{MESA}, \mathrm{CP}, \mathrm{MC}, \mathrm{ST}, \mathrm{PA}, \mathrm{PD}, \mathrm{Rut}, \mathrm{Rou}, \mathrm{Delta\_Rou}\ \mathrm{Delta\_Rut}_{,}\mathrm{BLI}, \mathrm{CuF}, \mathrm{LLI}, \mathrm{SA}) \qquad (4)$$

Where:
delta (Δ)SNP = structural deterioration per year
MESA = millions of equivalent standard axle/year
CP = cracking (crocodile) percentages
MC = moisture content
ST = subgrade type (reactive/non-reactive)
PA = pavement age
PD = pavement depth
Rut = rutting
Rou = roughness
Delta_Rut = linear rate of rutting progression per year
Delta_Rou = linear rate of Roughness progression per year
BLI = base-layer index (D0-D300)
CF = curvature function (D0-D200)
LLI = lower layer index (D600-D900)
SA = seal age

The initial analysis will be carried out with all the significant attributes to scrutinise their impact on structural deterioration. Several analyses will be carried out, using data-mining techniques to identify the most significant attributes influencing deterioration. The deterioration model will then be refined by incorporating the most significant attributes. Lastly, simplified structural deterioration models will be developed which will be incorporated in the PMS for investment decision-making.

3.3. Data preparation for analysis

In 2010, for the first time in Australia a TSD trial was undertaken by TMR and the Roads and Traffic Authority of New South Wales (RTA) [13] to assess the suitability of TSD for future deflection data collection at network level. Due to the success of this trial, TMR commenced the collection of structural data using TSD since 2014.

Consequently, defection data from the last for the last five years was analysed. The Qld road network consists of a variety of different types of pavement materials, climate, terrain, subgrade types (reactive and non-reactive). Furthermore, sections of the network have different traffic volumes including a percentage of heavy vehicles. Therefore, structural performance varies across the road network based on construction types and geographical localities; thus, one structural deterioration model does not fit for all road sections.

The entire network is categorised into clusters, using the following main attributes (Table 1), which influences the structural degradation of road pavements.

Table 1 — Cluster identifiers and attributes

Pavement identifier	Seal type	Pavement type
A	open-grated, dense-grated asphaltic concrete	semi-rigid or semi-rigid composite
B	open-grated, dense-grated asphaltic concrete	flexible
C	spray seal, geotextile seal, slurry seal	semi-rigid or semi-rigid composite
D	spray seal, geotextile seal, slurry seal	flexible
Traffic identifier	AADT (annual average daily traffic)	
1	0< = AADT< = 5000	
2	5000< = AADT< = 10,000	
3	AADT>10,000	
Zone identifier	Zone	Description
A	WR (wet reactive)	expansive clay soil type with annual average rainfall >800 mm
B	WNR (wet non-reactive)	stable (non-reactive) soil type with annual average rainfall >800 mm
C	DR (dry reactive)	expansive clay soil type with annual average rainfall <800 mm
D	DNR (dry non-reactive)	stable (non-reactive) soil type with annual average rainfall <800 mm

For example, cluster D1C is flexible pavement with spray seal, AADT less than 5000 and dry reactive subgrade; D1D is flexible pavement with spray seal, AADT less than 5000 and dry non-reactive subgrade.

Despite the entire network being divided into clusters, just five of these represent approximately 87% of the network: D1B, D2B, B3B D1C and D1D. In this study, the D1B, cluster is considered in the development of structural deterioration curve.

This study considered 100m sections of the road network that had five years of consecutive data. Once a road network is grouped into a cluster, it is presumed that all road sections and structural deterioration within that cluster is similar. Then the structural data was converted to the adjusted structural number (SNP) using Equation 5 below, developed by Manoharan et al [14] for each section.

$$\mathrm{SNP} = 3.2 * \mathrm{D}_{0(\mathrm{TSD})}^{-0.52} \tag{5}$$

Where:
SNP is the adjusted structural number
D_0 is the maximum deflection measured by TSD in millimetres (1 in = 25.4 mm)

For example, to find out the slope of the five SNP data points, as shown in Figure 2 (below):

$$\Delta\mathrm{SNP} = \mathrm{Slope}\ (6.792, 6.642, 6.245, 6.374, 6.345)\ =\ -0.116 \qquad (6)$$

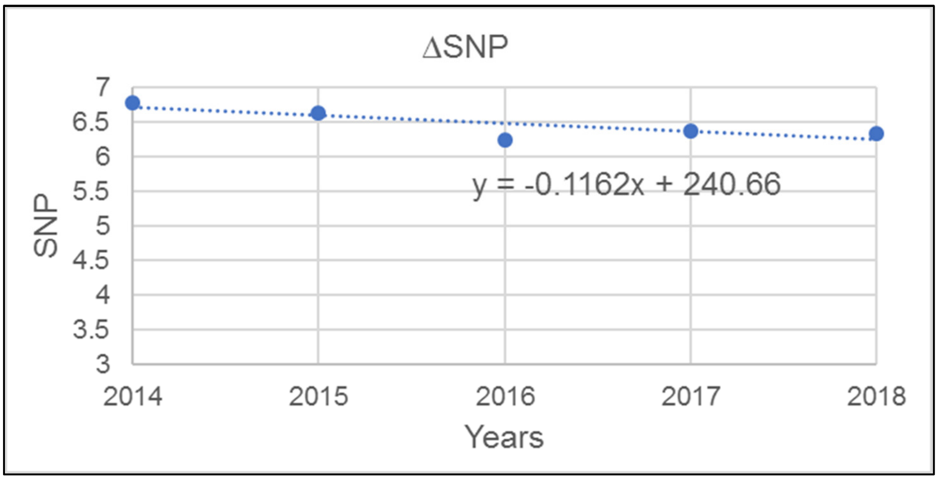

Figure 2 — Structural deterioration

The equivalent standard axle (ESA) was calculated; Current year ESA equal to 365 x AADT x % HV x ESA/HV x lane distribution factor.

Linear rutting progression is calculated as the slope of the previous five year's rutting data in a 100 metres section in millimetres. For example, 0.7 mm/year (0.28 in/year).

The lower soil moisture content data information was download from the Australian Government Bureau of Meteorology (BOM) [15]. The five years' gradient of lower soil moisture content for each hundred-metre section was calculated by using the lower moisture content at the same date as TSD data collected. This data is useful as there is a relationship between moisture content and deflection.

The deflection bowl parameter values are premeditated in accordance with the methodology developed by Horak et al [16]. The base-layer index (BLI), curvature function (CF) and lower-layer index (LLI) values are computed D0-D300, D0-D200 and D600-D900 respectively.

3.4. Data analysis

The cluster D1B was considered initially for predicting structural performance trends. This required data to be extracted from five years of TSD data consisting of cluster code and all five data points for each one hundred metre section. The number of sections consists of all five-year time series data, cleansed by investigating the data more closely and removing any outliers.

All sections were critically examined, one by one for each year's SNP value and the rate of deterioration (SNP slope) over five years. For these sections, the possible independent variable, dependent on SNP slopes were tabulated for further examination. The independent variables considered were:

- pavement age
- seal age

- roughness
- gradient of lower moisture content
- linear rate of rutting progression
- total number of MESA/year
- pavement depth
- cracking.

In addition to these independent variables, additional variables were included in the analysis. These included base layer index (BLI), curvature function (CF) and lower layer index (LLI) [16].

Once all the independent variables were complied with the dependent variable of SNP slope. Then by performing numerous regression analyses using the "Trial and Error" method using Alteryx Designer software [17] to explore how each independent variable influenced structural deterioration. Through examination of each attribute's influence the most insignificant variables were removed from the analysis.

The most sensitive attributes were selected for regression analysis to develop a structural deterioration model for cluster D1B. Firstly the linear regression methodology was adopted to establish the correlation. However, some P-values were greater than 0.05. Therefore, the Stepwise regression tool is used to determine the best predictors and eliminate unnecessary predictive variables.

The analysis was concluded with the following successful outcomes. The regression analysis summary output from Alteryx software for cluster D1B is shown in Table 2 below.

The coefficients for the various attributes are detailed in the estimate column. For example, MESA's coefficient is -0.00917. Furthermore, the number of starts denotes the significance of the attribute.

Table 2 — Summary output for the cluster D1B

Variable	Coefficient	Std. Error	t value	Pr(>|t|)	
Intercept	4.228e-02	9.283e-03	4.554	1e-05	***
Seal width	-2.870e-03	6.172e-04	-4.651	3.39e-06	***
Seal age	6.429e-04	3.074e-04	2.091	0.03656	*
Rutting	-1.948e-03	3.740e-04	-5.208	1.97e-07	***
Slope _roughness	-3.229e-03	1.342e-03	-2.407	0.01614	*
Roughness	2.565e-04	6.076e-05	4.221	2e-05	***
Pavement depth	-1.827e-05	9.836e-06	-1.857	0.06337	.
Pavement age	2.422e-04	9.552e-05	2.535	0.01126	*
MESA	-9.173e-03	3.722e-03	-2.465	0.01374	*
Delta_LSM	-2.343e-01	4.966e-02	-4.719	2.43e-06	***
Delta_CF	3.234e-03	6.076e-04	5.322	1.06e-07	***
Delta_BLI	-7.584e-03	4.742e-04	-15.995	< 2.2e-16	***
Delta_LLI	-1.645e-02	3.893e-04	-42.258	< 2.2e-16	***
Residual standard error: 0.088964 on 5291 degrees of freedom Multiple R-squared: 0.7257, Adjusted R-Squared: 0.725 F-statistic: 1166 on 12 and 5291 degrees of freedom (DF), p-value < 2.2e-16					

4. DISCUSSION OF RESULTS

The regression analyses results confirm that structural deterioration can be predicted by using mathematical models such as goodness-of-fit measures and regression coefficients demonstrate the predicted models fit well with the sample data.

From Table 2, Qld flexible pavement with spray seal less than 5000 AADT and wet non-reactive subgrade (D1B) structural deterioration equation would be as detailed in Equation (7).

$$\Delta\mathrm{SNP} = -0.00287\mathrm{x\,SW} + 0.00064\mathrm{xSA} - 0.00194 \times \mathrm{Rut} - 0.003220 \times \mathrm{Delta\_Rou} + 0.00025\,\mathrm{x\,Rou} + 0.00002 \times \mathrm{PD} + 0.00024 \times \mathrm{PA} - 0.00917\mathrm{xMESA} - 0.2343\mathrm{x\,Delta\_LSM} + 0.00323\mathrm{xDelta\_CF} - 0.00758\mathrm{xDelta\_BLI} - 0.01645\mathrm{xDelta\_LLI} + 0.04228 \quad (7)$$

The regression analysis demonstrates that the R^2 value is 0.725 and residual standard error is 0.0.088. In addition, all the P-values are significantly less than 0.05.

Where:
ΔSNP = structural deterioration per year
SW = Seal width
SA = Seal age
Rut = Rutting
Delta_Rou = Linear rate of roughness progression per years
Rou = Roughness
PD = Pavement depth
PA = pavement age (years)
SA = seal age (years)
MESA = Millions equivalent standard axle per year
Delta_LSM = Lower-soil moisture content rate of change per year
Delta_CF = curvature function (D0-D200) rate of change per year
Delta_BLI = Base layer index (D0-D300) rate of change per year
Delta_LLI = lower layer index (D600-D900) rate of change per year

The above structural deterioration model was developed using the Qld road networks data. However, this model can be used globally by calibrating the models to suit local conditions.

5. CONCLUSIONS

Pavement performance is a combination of functional and structural behaviours; however, it is difficult to distinguish those behaviours separately for modelling. Asset practitioners widely recognise that a structurally sound pavement has a longer life and reduced maintenance costs. Historically, network level structural data collection was performed in the same manner as project level data using FWD. For network level data collection the use of FWD data is a slow and costly process. Consequently, very little research has been conducted using structural data for managing the pavement asset at a network level.

Despite the use of TSD been relatively new to the transport industry. It is anticipated that this will be adopted by many road agencies in the future. Therefore, it is essential that well-defined simple models are developed which can be easily incorporated into a pavement-management system. This will then enable road authorities to minimise the whole-of-life cost of the assets and maximise benefits for road users.

Thus, the newly developed TSD based structural deterioration model demonstrate that the rate of change of structural bearing capacity can be predicted by utilising the available data for that section. This study's outcomes provide robust and simplified structural models to effectively use data that will help road agencies make more informed decisions. The findings of this study will assist in reducing the knowledge gap of using TSD structural data at network level investment analysis and monitoring structural road performance.

In conclusion, the study's findings will advance the application of TSD data and are extremely beneficial for road agencies. The findings will assist the prediction of road performance and maintenance of road assets sustainably, by developing more appropriate optimised investment strategies for their available funds.

6. ACKNOWLEDGMENTS

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