VEHICLE-PAVEMENT INTERACTION MODELLING





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Abstract

This paper presents a new user friendly software architecture that can be used to model the interaction between vehicles and pavements and the effects of dynamic vehicle loading and environmental factors on pavement performance and life. Users can use the software as supplied, or the software's modular structure is designed to allow users to add-in alternative modules, developed by themselves or others.

The intention is to provide a modelling environment that can be used to investigate a wide range of issues in vehicle-pavement interaction without needing the user to be expert in all areas. It is also planned that the software package will be freely distributed, with the code for the modules being open source.

The structure of the software and the basic set of modules are presented, along with example results and details of the graphical user interface (GUI) and user-module generation. A case study using the calculations, investigating the effects of static load levels and air suspension maintenance is presented.

Additional details of the software are available from http://www.pavementsimulation.org.

Keywords: Pavement, Damage, Whole Life, Performance, Vehicle, Dynamic Model, Interaction, Software.

1. Introduction

One challenge that researchers, planners and designers in the field of pavement engineering face is that of predicting how pavements perform throughout their service life under variable conditions of traffic and environment. Sophisticated pavement models have been developed by researchers and practitioners and have often been implemented into software packages of varying degrees of complexity. These tools can range from a simple elastic analysis of a sample cross section of the pavement under some static loading conditions to more detailed simulations of nonlinear damage models with dynamic loads and varying environmental conditions.

The idea behind this project is to develop a new user friendly software tool that can be used to model the interaction between vehicles and pavements. At the same time, the structure of the software is being made modular to allow expert users to modify or replace individual software components easily. The intention is to provide a simulation environment that can be used to investigate a wide range of issues in vehicle-pavement interaction. The vision is that a community of users will develop new modules for the software and share them online in such a way that the software might become a common platform.

Much existing work on the subject of vehicle-pavement interaction simulations is detailed by Cebon (1999) including an extensive list of references with in excess of 500 entries. Some more recent work is detailed by Goodrum (2011).

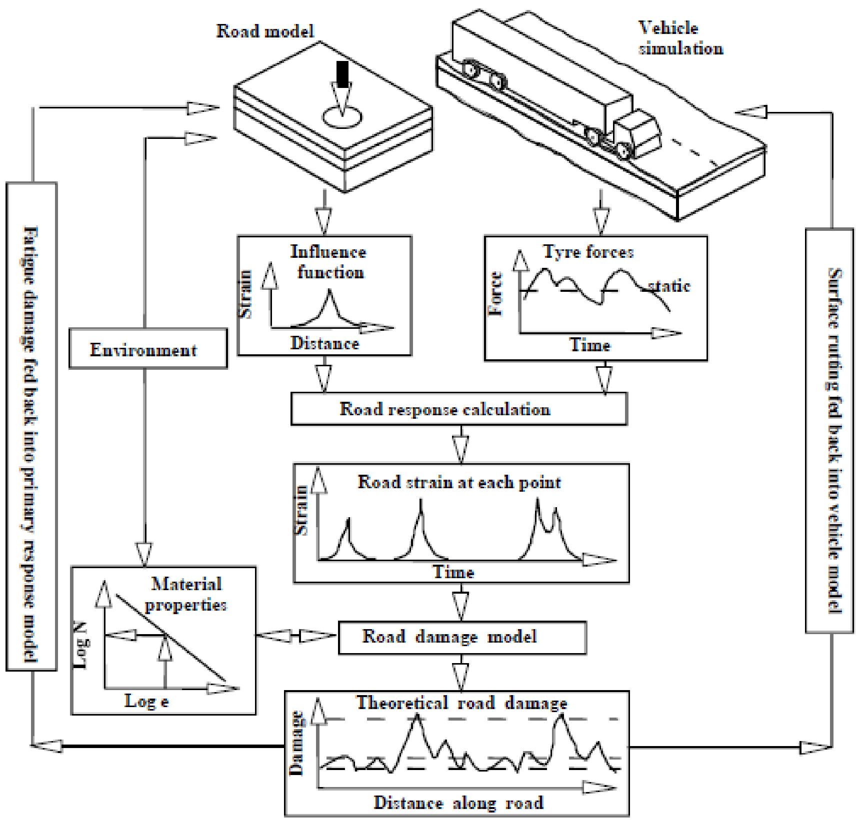

Figure 1 – Schematic diagram of pavement damage calculation. (Collop and Cebon, 1995.)

Figure 1 is a schematic diagram showing previous long-term pavement damage simulation work by Collop and Cebon (1995). The simulation was used to calculate the theoretical damage generated over time in a flexible pavement structure, by a dynamic vehicle model. The diagram shows a pavement response model used to calculate the strain influence functions due to a unit vertical load. Also shown is a vehicle simulation which was used to calculate the dynamic tyre forces generated by each axle, in response to a pavement roughness input. The combination of dynamic tyre forces with influence functions was used to calculate the strain histories at regularly spaced points along the pavement. The strain histories at each point were combined with material damage properties (fatigue or permanent deformation) to calculate the damage at each point along the pavement. The process was then repeated for a series of time steps, with the cumulative record of fatigue damage being fed back as parameter changes in the primary pavement response model, and the surface rutting deformation fed back as changes to the surface profile input to the dynamic vehicle model. The variation of environmental factors with time was also fed into the materials and pavement models as an input.

This project aims to build on work such as Collop and Cebon's model, but allowing it to be available to the wider community in a more accessible and a significantly more customisable way, whilst at the same time allowing others to share their work for use in the same software tool.

2. Requirements

2.1 Modularity

The structure of the software is modular, so that a range of subroutines can easily be mixed and matched to change the models significantly. It is hoped that a community of users will develop new modules which can be combined with, or used to replace, the default modules supplied with the software.

2.2 Categories of User

It is envisaged that there will be three main categories of users of the software package:

- Users who will use the existing basic package as it stands by changing input parameters to meet their specific modelling needs.
- Users who will mix and match modules from the existing basic package with modules written by other researchers. This will allow a significant degree of customisation without the user needing to do any coding work. It will also allow the user to avoid having to learn significant amounts about areas with which they do not need or wish to become familiar: for example the interface between the pavement structure and vehicle dynamics.
- Users who will write some modules for themselves to combine with existing modules from the basic package and/or those written by other researchers. This will enable these users to make a minimum amount of bespoke code, whilst drawing on existing knowledge for the areas already covered by other researchers.

2.3 Graphical User Interface (GUI)

The system has an easy to use front end, with a Graphical User Interface (GUI) being a requirement. In order to fit with the modular nature of the software, one related requirement is that the GUI must be readily reconfigurable to suit any software modules that are 'plugged into' the software.

2.4 Data Management

A large amount of data will be generated by the simulation process. Figure 2 shows a typical layout of a pavement, showing Nz elements down through the structure in the z direction, Nx elements along the pavement in the x direction, and possible left and right hand tracks, Nt. It should also be noted that there will be numerous time steps, Nk, for which data may need to be recorded. For an example of Nz=7, Nx=2000, Nt=2, and Nk=1300 (i.e. circa 1300 weeks in 25 years), this would produce a total of 36 million data records. Each record might contain details such as: the microclimate in terms of element temperature, frost, and moisture level; the primary response (stresses and strains), current materials properties and so on. If each data record contains 100 bytes of data the total amount of data generated in this example would be 3.4 gigabytes.

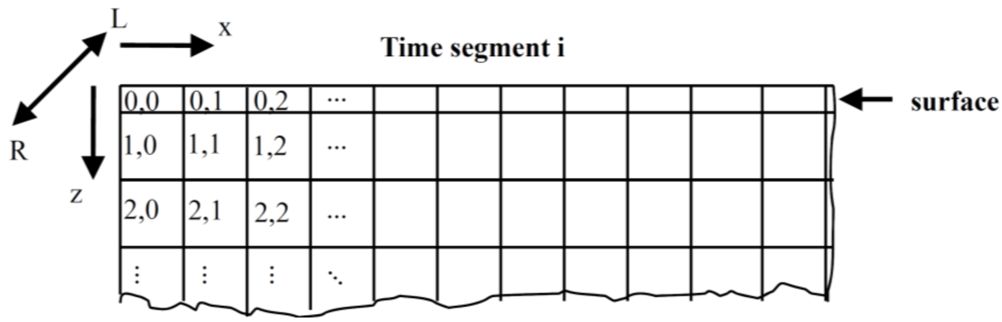

Figure 2 – Diagram outlining database storage requirements.

The data needs to be stored and accessed by numerous queries processed in an appropriate way, so it was felt that storage by database was a requirement.

This approach gives the opportunity to decouple the analysis and reporting from the simulation. This means the user can perform in-depth analyses of the results, without having to specify particular output quantities at run-time.

3. System Architecture

3.1 Concept Overview

Figure 3 shows the concept behind the new software package in more detail.

A pre-processor consisting mainly of a GUI, to allow the user to configure the simulation and enter or import data to the simulation. The GUI is dependent on which software modules are 'plugged into' the software – these are shown as modules A, B, up to the Nth module in the diagram.

The output from the *pre-processor* is passed to the processor framework through a series of interface files. These files carry information relating to the various modules. For example, one may carry information about the structure of the pavement, whilst another might contain information about the vehicle fleet which will be running over the pavement, and a third could be used to detail the environmental conditions along the pavement as a function of the time of day and year.

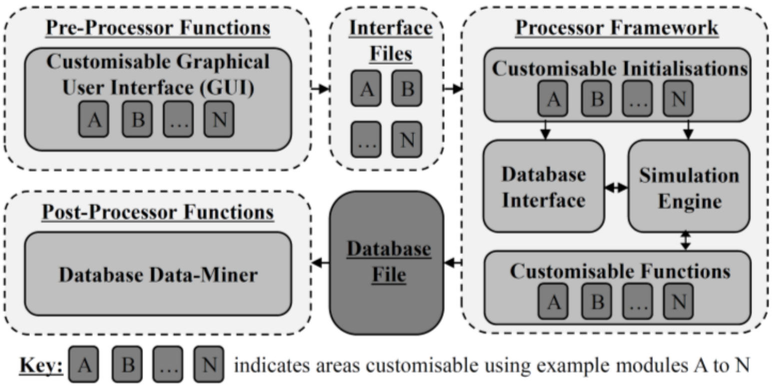

Figure 3 – Diagram showing overall system architecture concept.

The *processor* framework has a simulation engine which performs the simulation calculations for the required number of time steps, feeding the results into a database, which it may also need to access in order to retrieve relevant information. The calculations themselves are contained in the series of customisable modules A, B, though to the Nth module, with there also being a set of custom initialisations, one relating to each module. The output from the processor framework to the post-processor is the filled database of information gathered as the simulation runs.

At present the *post-processing part* of the software is a data exporter, enabling selected sets of data to be exported into third party software, such as Matlab and Excel, which users might normally use to manipulate data. Some rudimentary plotting capabilities are also provided so that the user is able to 'sanity check' the results they have obtained prior to export.

3.2 Detailed Overview of Processor Framework

Figure 4 shows an overview of the operation of the processor framework. It shows the database, used to handle the relatively large quantities of data that is generated. A data buffer is provided to help avoid individual accesses to the database. Instead these are grouped into more time efficient operation for the central processing unit (CPU). A units converter is provided so that the user and modules can work with data in whatever units they desire, although the actual storage within the database uses Système International (SI) units.

A series of example calculation modules are shown 'plugged into' the framework, in this case each calculation cycle starts with a 'weather station' module giving details of environmental conditions in the area around the pavement. This is followed in the sequence of module calculations by a 'pavement instrumentation' module, which determines details of the environment within the pavement – temperature, moisture levels, frost levels, etc.

The traffic module enables modelling of a fleet of vehicles using vehicle dynamics models that may be provided by external programs, or can utilise internal vehicle modelling facilities. Example options shown include:

- Vehicle models provided in state-space form solved using an internal ordinary differential equation (ODE) solver which has been included.
- Vehicle models written or provided in an external package such as Matlab, Simulink, Simpack or similar, which can be linked to via a suitable interface.
- 'Phase shifting' of a 'golden vehicle' response in order to provide spatially-repeatable responses representative of the traffic mix (For more details of this, see Collop et al (1996), Goodrum (2011) and Goodrum and Cebon (2012a)). Code to perform this task is built into the software.

The vehicle models need to provide tyre forces in response to pavement surface profiles provided.

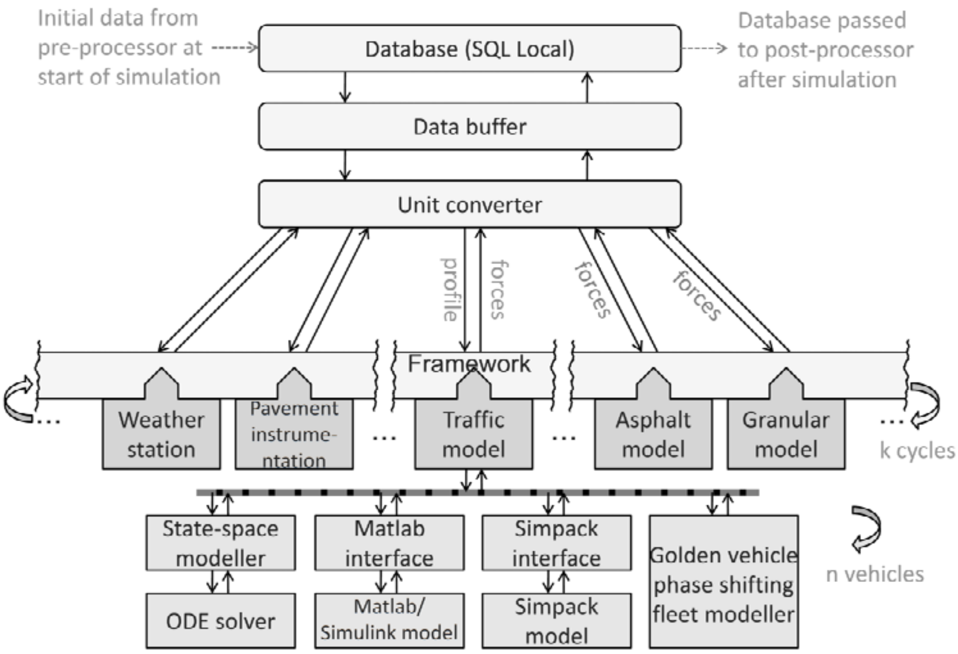

Figure 4 – Diagram outlining details of processor framework.

Further along in the example sequence of modules shown are models for the asphalt layers of the pavement, capable of deforming permanently and accumulating material damage; and for the granular layers, which can deform permanently.

The cycle of modules is repeated as many times as the simulation requires, for example, once per week.

3.3 Software Platform

The new software package has been developed using Microsoft's '.net' framework which runs within Microsoft Windows. The benefit of using this framework is that it provides a wide range of different programming languages which can be intermixed, such as Basic, C++, Java and so on.

3.4 Default Software Modules

The modules coded at the time of writing includes those listed in Table 2. The addition of further modules is on-going, and the aim is to encourage the user community to contribute their own modules to an online resource which will be available for download from the main project website.

Table 2 – Table showing details of default modules provided with the VPI software

Name	Description	References
Traffic	This module uses Spatial Repeatability statistics to generate a vehicle fleet by "phase-shifting" the results from vehicle models by following Collop's method and using Goodrum's enhancements.	Cebon (1999), Cole, Collop et al (1996), Collop and Cebon (1995), Haider et al (2007), Goodrum (2011, 2012)
Temperature	Calculates an energy balance at the pavement's surface estimating the amount of energy entering (or leaving) the pavement due to radiation and convection and then uses a finite differences method to simulate heat transfer through the pavement layers.	ARA Inc. (2004), Dempsey et al (1985), Dusinberre (1961), Jacobs et al (2004)
Asphalt temperature relationship	Relates asphalt stiffness to temperature using a relationship derived from back-calculated Falling Weight Deflectometer (FWD) data.	
Moisture	Simulates moisture changes in the pavement using a variably saturated flow model. This in turn is used to simulate the effect of the moisture level on the performance of the granular layers by scaling their resilient modulus appropriately.	ARA Inc. (1999), Clement et al (1994)
Unbound Granular Materials (UGMs) constitutive model	Resilient modulus is modelled using the following: $M_r = k_1 \cdot \left(\theta / p_0\right)^{k_2}$ Where: M_r is resilient modulus; θ is the bulk stress; p_0 is atmospheric pressure; k_1 and k_2 are fitted parameters. Alternatively the Boyce model is available defining UGM behaviour using bulk and shear moduli.	Lekarp et all (2000)
Asphalt Fatigue	A fatigue model of the following form is used: $N_f = A \cdot \varepsilon_h^B$ Where: N_f is number of cycles to failure (50% stiffness reduction), ε_h is horizontal strain at the bottom of the asphalt layer, and A and B are used for model fitting. Cumulated damage accrues using Miner's Law.	Di Benedetto et al (1996), Ghuzlan et al (2007)
Asphalt Rutting	A multidimensional lookup table of asphalt permanent deformation is generated using a finite element (FE) model. This table stores the permanent deformation for a range of vehicle speeds, temperatures, asphalt layer thicknesses, asphalt layer and base layer stiffnesses.	Costanzi (2009), Deshpande and Cebon (1999), Ossa et al (2005), Goodrum (2011)

UGMs Rutting	The model for predicting UGM's permanent strain in the vertical direction is in the form: $\varepsilon_1^p(N) = f(N) \cdot g(p_{max}, q_{max})$ Where: N is the number of loading cycles, p_{max} and q_{max} are the respectively the maximum mean stress and the maximum deviatoric stress.	Hornych and El Abd (2004)

3.5 User Designed Modules

The software tool allows for the creation of bespoke modules. At every stage it aims to keep the task as simple as possible.

It is strongly preferred that a version of the required calculation is produced in one of the languages that form part of the .net environment. While it is possible to write a 'wrapper' in a .net language which calls a compiled library written in another language, this will not necessarily produce a portable version of the code.

A 'callable' function that represents the calculation needs to be written, with the input and output quantities for the function being packaged into structures which also contain settings that can be seen by the processor framework, such as the units for each quantity.

The 'Visual Studio' developer environment (the Express version of which is available freely from Microsoft) can be used to produce a graphical user interface (GUI) page, which if done in a prescribed way will be compatible with the pre-processor's GUI.

3.6 Example Simulation

In order to demonstrate the functioning of the software, the model detailed in Figure 5 was set-up using the standard modules.

Figure 5 shows a single track of pavement constructed with layers of asphalt at the top and granular material forming the base layers. The pavement is divided depth-ways into ten elements, of which the top two layers are asphalt, and the remaining eight layers are granular material. Along the length of the pavement, there are 250 elements all 0.1 metres long.

The traffic fleet running over the pavement is calculated in a simple way in this example, and is considered to consist of just one type of vehicle, modelled using a quarter-car representation (i.e. a single vehicle wheel station).

The quarter car equations of motion are solved by formulating them as ordinary differential equations (ODEs) in state space form. The pavement profile at the start of the time period is used as the input to the ODE. The resulting tyre force is the output from the ODE. The ODE is solved using an ODE solver coded into the processor framework.

In each time period, the fleet movements are represented by the single vehicle, travelling at 50km/h, traversing the short stretch of pavement 100000 times. Several such periods of time are simulated.

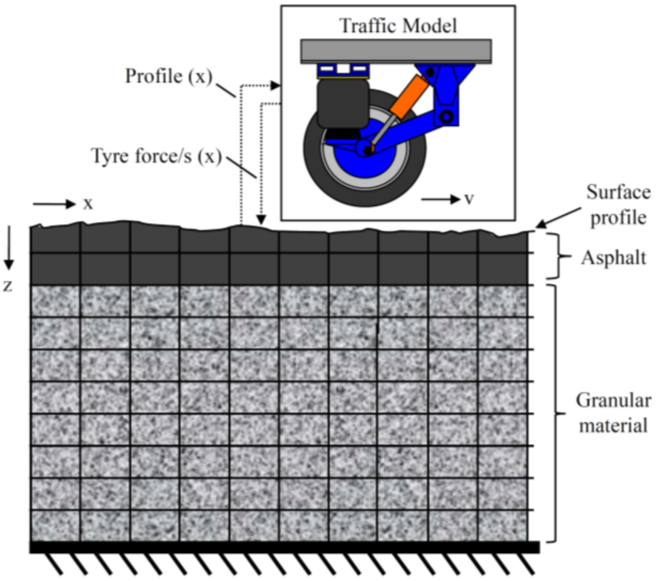

Figure 5 – Diagram summarising details of example simulation presented.

Two example pavement formulations are considered in this section, each being subjected to the passing of the fleet of traffic for several time periods.

Figure 6 shows the results obtained from the passage of the vehicle fleet over a random pavement surface profile, where the pavement has a standard foundation except between 15 and 20 metres, where the foundation is weaker. It can be seen that the initial profile shows no evidence of the weak part of the foundation; however after three time periods, each of 100000 vehicle passes, the weak foundation starts to become evident at the end of the second time period, and is clearly obvious at the end of the third time period. The weak foundation is indicated by the pavement showing additional deformation in one area compared to the parts of the pavement in the adjacent areas.

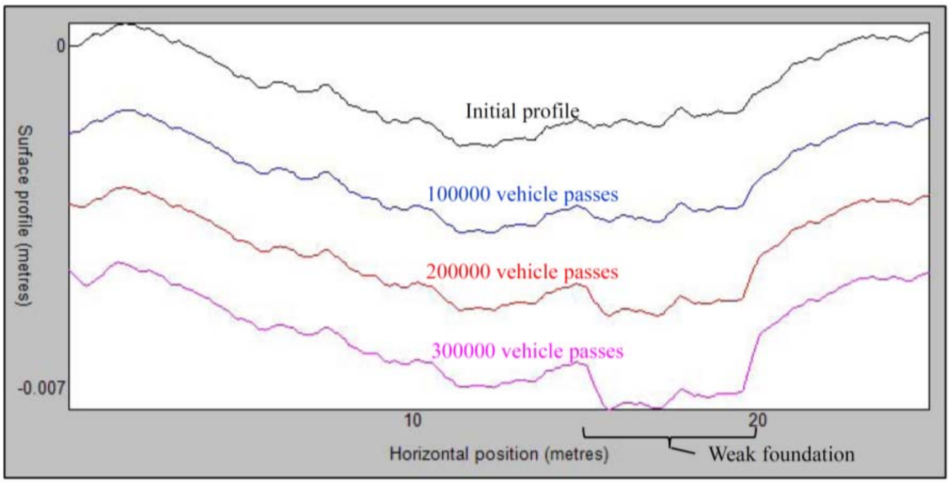

Figure 6 – Annotated screenshot showing the surface profile of a pavement with a non-uniform foundation.

Figure 7 shows the results obtained from the passage of a fleet of vehicles over a single sinusoidal bump in the pavement, of initial height 20 mm and length 0.6 m. It can be seen that the passage of vehicles over the bump causes permanent deformation to occur after the bump, as well as to the bump, due to the effects of the vehicle's oscillations.

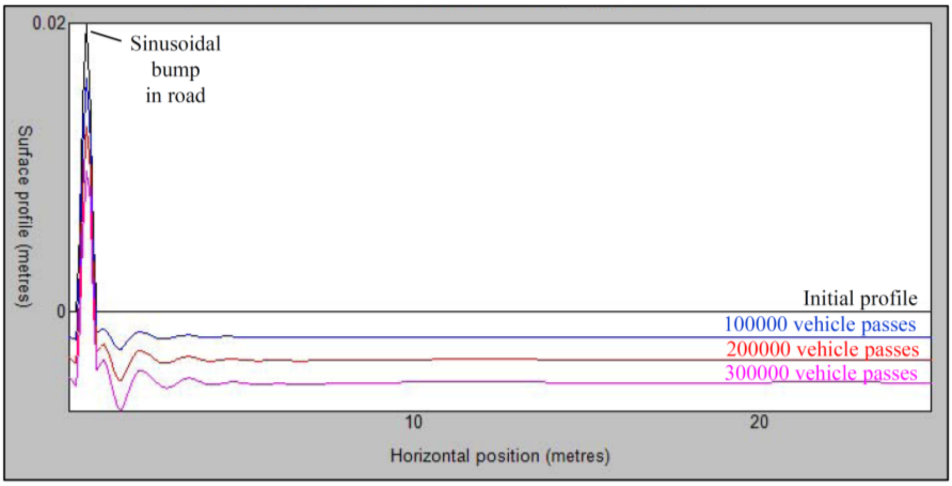

Figure 7 – Road profile deformation results for single sinusoidal bump in a road.

This deformation worsens with increasing numbers of vehicle passes.

4. Case Study

4.1 Introduction

Of the numerous aims for the newly devised software tool, one is to aid investigation of the effects of 'road-friendly' suspensions and Higher Mass Limits (HML) on Australia's roads.

Simulations were previously performed by Costanzi and Cebon (2007) to look at the effects of HML on the maintenance costs of spray-sealed roads in Australia. These simulations included dynamic vehicle simulations and a pavement deformation calculation, calibrated using experimental data for spray-sealed roads. The authors found that under HML, a fleet operating with 50% poorly-maintained hydraulic dampers increased pavement costs by 20.8% relative to a simulated fleet of leaf-spring vehicles as allowed under the previous General Mass Limits (GML) scheme.

4.2 Simulation Details

A simulation study was performed to investigate the effects of Higher Mass Limits (HML) and reduced vehicle damper function on full depth flexible pavement maintenance costs, over a 35 year period. The model was calibrated to Australian (New South Wales) conditions. The design pavement structure was a 300 mm thick 'full-depth' asphalt layer over a 200 mm granular base layer. Four different vehicle fleets, consisting of 6-axle tractor-semitrailers and 9-axle B-doubles, were simulated. Each vehicle fleet was simulated at either GML or HML. The axles were assumed in turn to be 100% leaf sprung, 100% air sprung with functioning hydraulic dampers, 100% air sprung with non-functional hydraulic dampers, and 100% air sprung with 50% of the hydraulic dampers deactivated. See details in Goodrum (2011).

4.3 Results

Figure 8(a) and 8(b) shows the progression of the road's International Roughness Index (IRI) with time, as a result of loading caused by vehicles at GML and HML. Note that decreased damper function led to progressively earlier resurfacing of the pavement. The lifetime until resurfacing was reduced by 10 years when the vehicle fleet had 50% malfunctioning hydraulic dampers. This amounts to an estimated increase in maintenance costs of $23k AUD/(km-year) at the time of writing.

Further details concerning this case study and related work can be found in Goodrum (2011) and in Goodrum and Cebon (2012a, 2012b and 2012c).

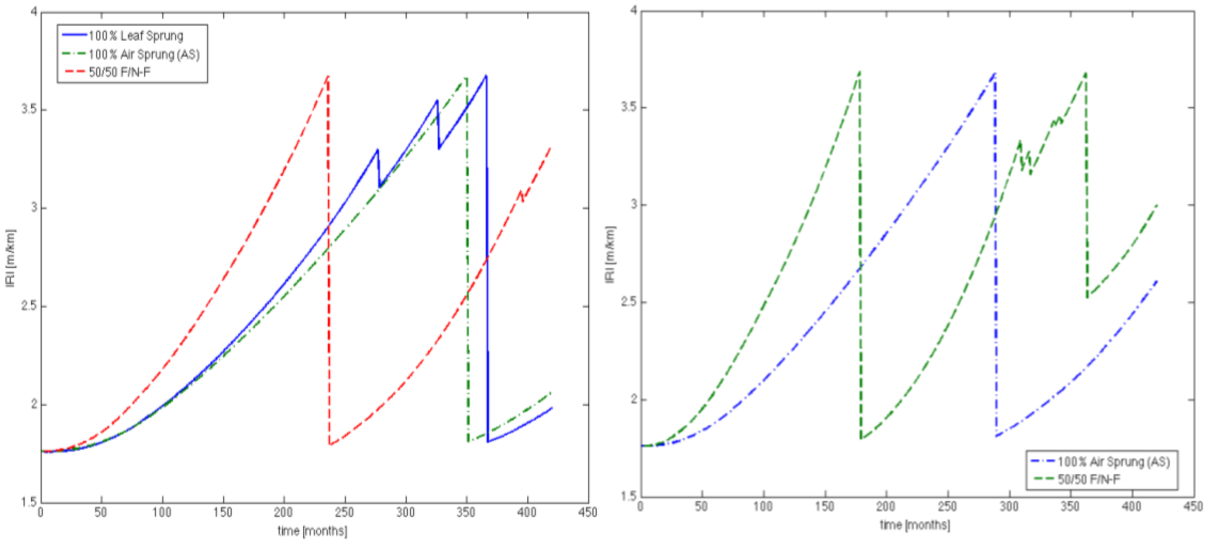

Figure 8 – Plots of IRI versus time for (a: left) GML and (b: right) HML conditions.

5. Conclusions

(i) A vehicle-pavement interaction software simulation tool has been introduced. The tool has a graphical user interface (GUI) to aid ease of use. The tool is modular in nature, allowing the 'plugging-in' of alternative calculation modules, with associated GUIs.

(ii) It is envisaged that there will be a range of users, from those who will use the package as distributed, to those who will write bespoke modules, but still take advantage of the existing framework. It is hoped that an emerging community of users will share the modules they develop.

(iii) Example simulations are presented showing the effects of weak road foundations and the damage caused to roads by the bounce motion of vehicles after a discrete bump in a road.

(iv) A case study is presented showing comparison between steel, air and defective air suspensions, under Higher Mass Limit (HML) and General Mass Limit (GML) regulations. The case study shows that road lifetime until resurfacing could be reduced by as much as 10 years if the air suspension vehicle fleet had 50% malfunctioning hydraulic dampers.

6. Future Work

Future work includes:

(i) Validation against Long Term Pavement Performance (LTPP) data (for more details concerning LTPP, see LTPP (2006 and 2009)).
(ii) Inclusion of modules for simulating rigid concrete and composite pavements.

7. Acknowledgements

The authors are grateful to the Advanced Safety and Driver Support for Essential Road Transport (ASSET-Road) project, the New South Wales Roads and Traffic Authority, the Nottingham Asphalt Research Consortium, and the Cambridge Vehicle Dynamics Consortium and its members for their continuing help and support with this project.

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