Investigating influences on the strain – axle load relationship in asphalt pavement using Finite Element Modelling

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ABSTRACT
Current pavement maintenance strategies are reliant on invasive measurements or visual inspection. Fibre-WIM sensors can improve this by measuring strain, which can be used to calculate axle loads. However, this process is not simple. Finite Element Modelling is used to study several circumstantial influences on the strain – axle load relationship. These factors are combined into a predicting function, which can be refined so that it can be used to calculate axle loads. This allows for more insight in pavement deterioration. Other than describing the results of the Finite Element Model, the implications for sustainable pavement maintenance are discussed.

Keywords
Fibre-WIM sensors, Finite Element Modelling, asphalt pavement, axle loads, strain

INTRODUCTION
In the pavement construction industry, maintenance strategies are not as effective as they could be; input for pavement maintenance strategies is based on incidental visual inspections and invasive on-site measurements [1]. These visual inspections only show defects, which means that pavement is already faulty when a defect is detected. This results in inefficient maintenance strategies, as preventative maintenance on a pavement is more efficient than breakdown maintenance [2]. Real-time non-invasive measurements are thus preferred over these invasive measurements. One useful measurement for determining the usage of pavement is real-time axle loads, as this knowledge is relevant for the wear a road experiences. These axle loads can be derived from strain measurements done by Fibre Weigh-in-motion sensors, which have the advantage of having a long lifespan, being accurate, non-responsive to electro-magnetic interference, having low operating costs, and being non-invasive [2]. These sensors can measure strain with good accuracy, but calculating the axle load of a vehicle with a given strain is not simple. This may lead to problems with inaccuracy. Since the relationship between strain and axle load is influenced by several factors, this paper studies the influence of pavement temperature, wheel velocity, wheel dimensions, wheel location relative to sensor and road, and pavement fatigue using the Finite Element Method (FEM).

THEORETICAL BACKGROUND
Fibre-WIM sensors can measure strain which can be used to calculate axle loads on pavement. This is possible because as the pavement experiences a load from a wheel, it is pushed downward and outward horizontally. The amount of horizontal strain is dependent on the stiffness of the pavement, which is determined by the asphalt mixture, temperature and pavement fatigue. Asphalt is a viscoelastic material, which means that it deforms partially elastic, partially plastic, and partially delayed elastic [3]. As viscous and delayed elastic deformation are proportional to the time that a load is applied, the time duration that a load is applied is relevant to asphalt pavement strain.

Influences on asphalt stiffness
A major factor in the amount of strain in pavement due to an axle load is pavement stiffness, also known as the modulus of elasticity (MoE) of the asphalt material [1]. This MoE has an inverse relation with strain. Temperature (T_a) affects the MoE of asphalt; the formula for the MoE (E_a) is given by:

$$\ln(E_a) = c_1 + c_2 * T_a + c_3 * {T_a}^2 + c_4 * {T_a}^3$$

Where $c_1 \dots c_4$ are regression coefficients that are experimentally determined for an asphalt mixture [4]. Time has an influence on the strain of asphalt pavement, and this influence is relevant when considering wheel velocity. This time-dependency can be eliminated by converting wheel velocity (V) and temperature (T_a) into a fictional temperature (T_{fict}) using the following formulas [4]:

$$T_{fict} = \frac{1}{\frac{1}{T_a + 273} - \frac{\log(f_{kar}/f)}{C}} - 273$$

$$\log(f_{eq}) = -0.6 * 0.5 * h_a + 0.94 * \log(V)$$

Where h_a is the thickness of the pavement in mm. This formula allows an asphalt pavement to be modelled elastically, which makes modelling with FEM easier. Pavement fatigue also affects pavement via its MoE; as an asphalt pavement is repeatedly loaded by vehicles, the bitumen that binds the aggregate in asphalt together gets stretched out, and the asphalt stretches out easier. This is expressed in a lower MoE for the asphalt.

Variance in strain measurements

Strain measurements on axle load assume a continuous plane of asphalt pavement, but this situation is not realistic in the case of a wheel passing on the edge of the asphalt pavement. In that case, strain is increased as the pavement is not constrained on the edge but free to deform without being held back by more pavement.

Not only can the amount of strain on pavement be influenced, the surface by which a wheel load is applied is also relevant for the amount of strain experienced. The width of a tire decreases the maximum strain on pavement, as the load is applied over a larger surface area. Conversely, tyre pressure increases maximum strain, since it decreases the contact area between the road and wheel [4]. Double wheels result in a strain profile that has two maximums compared to a single wheel configuration. As measured strain is not a single data point but a line of measurements over time, a statistic (such as maximum strain, minimum strain or total positive strain) of this strain that is not dependent on wheel dimension or shape, is most suited for determining the wheel load on pavement.

Lastly, as Fibre-WIM sensors do not measure strain in a continuous line but at a certain interval (8cm in the case of the Fibre-WIM sensors used in the study), the amount of measured strain can change depending on where relative to the closest sensors, a wheel passes over the pavement. If the location of peak strain is directly at a sensor, the maximum strain is higher than if it were between two sensors. This is because strain is not constant beneath the wheel, but has a maximum in the middle of the wheel. Not using the maximum measured strain but another statistic such as total positive strain can result in a less variable strain measurement.

RESEARCH METHOD

The selected influences on the strain – axle load relationship is investigated using FEM. In this method the asphalt pavement is modelled with a large amount of small geometrically simple elements, whose deformations are easily calculated. This method is often used in modelling construction elements [5]. The pavement model is 0.50m long, 1.75m (half a driving lane) wide and has the height of the surface, base and subbase layers of pavement. The wheel load is modelled with a frictionless rubber brick sliding over the pavement, see figure 1. The subgrade is not modelled, as it is outside of the scope of the research. The part of modelled pavement is from a highway located close to Rotterdam, the Netherlands. The validation measurements are taken from this location.

Model validation

The FEM model is validated using input parameters of a test bus driving over the Fibre-WIM sensors on the highway. The wheel load, speed, temperature and strain of this bus are used as input for the FEM model.

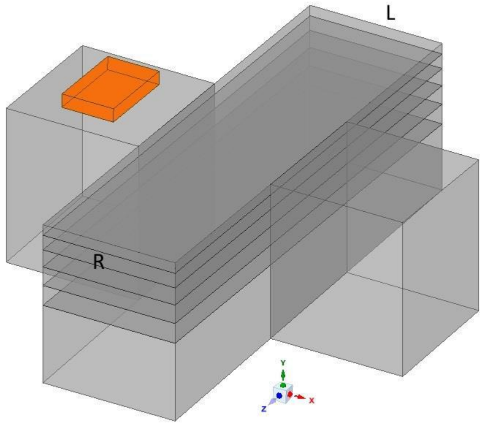

Figure 1 - overview of pavement model. Pavement in grey, wheel in orange.

A graphical representation of the result is shown in figure 2. Results of the modelled strain are compared to the validation tests and to a traditional strain calculation method called BISAR [6]. The results in table 1 show that while the course of strain can be modelled, the model needs to be adjusted in order to achieve accurate results.

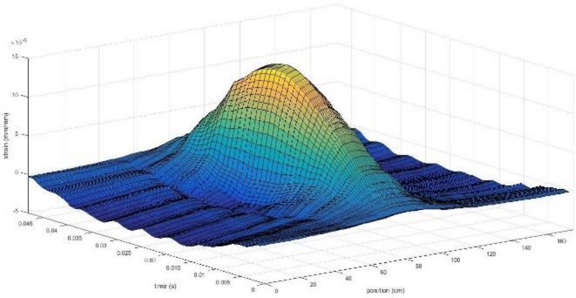

Figure 2 - strain profile over time for validation run

Table 1 - comparison of strain measurements

method	max	%	min	%	total	%
Fibre-WIM	8.2e-6	100	-7.6e-6	100	3.4e-3	100
FEM	1.47e-5	180	-4.1e-6	56	1.0e-2	294
BISAR	1.53e-5	187	-6.9e-6	91	-	-

The FEM model is used in the analysis of the selected influences on the strain – axle load relationship. The setup of the different analyses is listed in table 2.

Table 2 - Setup of analyses

Analysis	Constants	Variables
Temperature	Super single wheel, 30kN load, 75km/h	0, 8, 16, 20, 24, 32 & 40 °C pavement
Wheel location - sensor	100% of nominal maximum load, 75km/h, 20 °C	Single, double & super single wheel; distance between leftmost sensor and left wheel edge

Wheel location – road edge	Super single wheel, 30kN load, 75km/h, 20 °C	right edge of wheel 10, 20 & 30 cm from pavement edge
Wheel velocity	Super single wheel, 50kN load, 20 °C	5, 20, 40, 60, 80, 100, 120 km/h wheel velocity
Wheel dimensions	75km/h, 20 °C, axle load	Single, double, super single & super wide single wheel types; -25%, 0, +25% wheel width; -20%, 0, +20% tire pressure
Pavement fatigue	Super single wheel, 30kN load, 20 °C, 75km/h	+10, 0, -10, -20, -30, -40, -50, -60 % pavement stiffness

Using these parameters, the FEM model is run to determine the maximum, minimum average absolute strain and/or total strain, depending on the experiment.

RESULTS

Temperature, wheel velocity and pavement fatigue

The results of these tests all show a similar strain profile to the validation run. The results, summarized in table 3, follow the trend of lower MoE leading to higher strain.

Table 3 – summary for temperature, velocity and fatigue

°C	**max**	**%**
0	4.0e-6	7
20	9.6e-6	17
40	58.4e-6	100
Velocity (km/h)	**max**	**%**
5	1.09e-5	100
40	9.61e-6	88
80	9.58e-6	88
120	9.65e-6	88
Stiffness (%)	**max**	**%**
100	1.24e-5	100
80	1.55e-5	126
60	2.14e-5	173
40	3.30e-5	267

Wheel location and wheel dimensions

For the location of the wheel relative to sensors, the maximum difference of strain measurements for each wheel type is listed in table 4. Strain profiles in figure 3 from different wheel types show that double wheels have a different strain profile than single wheels, as they have two significantly lower peaks of maximum strain compared to the single wheel types.

Table 4 - maximum deviation of strain measurements in %

Wheel type	**Maximum (%)**	**Minimum (%)**	**Average absolute (%)**
Single	-13.9	-12.4	-2.0
Double	-15.4	-15.1	-6.4
Super Single	-2.5	-4.5	-4.2

As maximum strain for double wheels is almost half that of single wheels, a better strain measurement is required to find axle load. One measurement which partially eliminates the differences caused by wheel type is total strain, which is the sum of all positive strain caused by a wheel passing. Using this metric, the double, super single and super wide single all result in a similar amount of strain (with 1.4e-2, 1.5e-2 and 1.4e-2 respectively), with the single wheel resulting in 37% more strain at 1.95e-2 total.

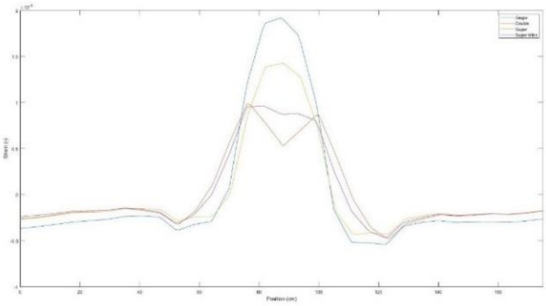

Figure 3 - strain profiles of different wheel types

A similar story is true for wheel width and tyre pressure. -25%/+25% tyre width results in +30%/-24% maximum strain, but in +3%/-18% total positive strain, making that the less width-dependent metric. A -20%/+20% change in tyre pressure results in a -4%/+1% change in maximum strain and a -1%/-5% total strain, indicating that tyre pressure is not significant in determining strain.

Unfortunately, the results from the tests of a wheel at pavement edge experiment are not conclusive. The strain profiles contain wave patterns and contain exclusively positive strain, indicating that the scenario is not modelled properly. As such, no significant findings could be drawn from this analysis.

ANALYSIS AND DISCUSSION

Results from the temperature, wheel velocity and pavement fatigue analyses are as expected; all three factors increase or decrease the MoE of asphalt, which has an inverse correlation with strain. If all three test results are shown in one graph, this correlation is confirmed, see figure 4. As a result, the effect of these influences can be combined when calculating their effect on the strain – axle load relationship as described in the theoretical background.

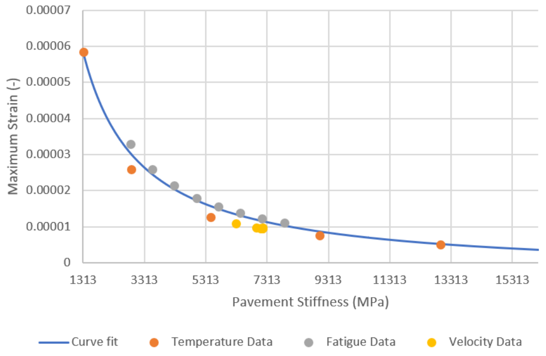

Figure 4 - temperature, velocity and fatigue tests

Wheel location and wheel dimensions both introduce uncertainty in the calculation of axle load. To reduce this uncertainty, different strain statistics were tried to reduce the variance in results. The statistic that was found to reduce variance the most is total positive strain, which is found by adding all positive strain measurements of one wheel passing. This metric leaves a -/+ 12.5% uncertainty due to wheel width and tyre pressure, a 3.2% uncertainty due to wheel location, and a 17% uncertainty due to wheel type. These uncertainties multiplied leave a 35% uncertainty, but this is assuming a maximum positive or negative deviancy from the average in all three categories. A better metric for the measured strain could significantly reduce the uncertainty in calculating strain.

Predicting function

The investigated influences can be divided into two categories; those that introduce uncertainty (wheel position and dimensions), and those that change the pavement stiffness (temperature, wheel velocity, pavement fatigue). These can be combined and be made into a predicting function of the general form:

$$F = C * TPS * E * (1 \pm U)$$

Where F is the axle load, C is a constant, TPS is the total positive strain, E is the final pavement stiffness, and U is the uncertainty due to wheel location and wheel type. The uncertainty would be a stochastic variable composed of the individual uncertainties as talked about earlier in the discussion.

Model validation and limits

The FEM model produces strain profiles that match in pattern with strain measurements from Fibre-WIM data, but the magnitude of the strain differs. The FEM model could be improved by incorporating viscoelastic behaviour for more accurate modelling and could be calibrated using test data. Currently this study is useful for identifying the nature of the selected influences, but a more accurate calibrated model is required before this research can be used to accurately calculate the load of vehicles. Additionally, for the predicting function to be able to give an axle load at a reasonable accuracy, the uncertainties caused by wheel size and shape must be reduced.

CONCLUSION

This study constructed a Finite Element Model to study the effects of pavement temperature, wheel velocity, wheel dimensions, wheel location relative to Fibre-WIM sensors and road, and pavement fatigue. This model can produce strain profiles that match existing strain measurements. Pavement temperature, wheel velocity and pavement fatigue all influence the pavements Modulus of Elasticity. Wheel position and dimensions introduce uncertainty in the calculation of axle loads. This uncertainty can be reduced by using total positive strain to calculate axle load, as it is less dependent on these factors.

These factors can be combined into a predicting function of the form $F = C * TPS * E * (1 \pm U)$, which can be used to calculate axle loads. This can improve knowledge of the usage and wear of asphalt pavements, which allows for better pavement maintenance strategies. In this way, this paper contributes to more sustainable infrastructure, by allowing for more effective infrastructure management.

ROLE OF THE STUDENT

The theoretical background, FEM building, processing of results, predicting function, writing of the report and formulation of the conclusion and discussion was done by the author.

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