Assessing Pavement Traffic-Induced Responses by Integrating Data from an Instrumented Test Section and Numerical Modeling

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Abstract

Since July 2023, a significant amount of in-situ pavement responses has been collected and analyzed from a new instrumented section built in the access road to the Edmonton Waste Management Center (EWMC), located in the Northeast of the city of Edmonton, Alberta, Canada. The data has been continuously recorded and stored locally, and afterwards processed. This research provides recent information regarding structural parameters, such as induced strains, which can directly relate to pavement performance. In addition, a Weigh-in-Motion (WIM) system was used to provide detailed insight about the traffic conditions. A dynamic modulus (DM) test was also conducted on asphalt samples collected during the construction of the instrumented test section. Based on the characteristics of the asphalt mix and the axle load information from the WIM system, induced strain values were calculated using a pavement analysis and design software (KENPAVE). The calculated values were then compared with the measured strain values from the sensors. Through this comparison, areas of convergence and divergence were identified, providing a comprehensive understanding of pavement traffic-induced responses as well as a foundation for refining data collection and analysis. One interesting finding was the reliability of the strain transducers, which proved to be satisfactory.

Keywords: Pavement performance; Instrumentation; Monitoring; Data analysis; Induced strain.

1. Introduction

Paved roads are among the most essential infrastructures to society. For instance, road transportation in Canada comprises more than 1.13 million kilometers of public road assets, facilitating the movement of passengers and freight across local, intercity, intra-provincial, and international scales.[1,2] In 2021, the Government of Canada reported a total of 26.2 million registered road motor vehicles, with approximately 91.9% being passenger automobiles, pickups, SUVs, and minivans, 4.7% being medium and heavy trucks, and the remaining 3.4% being other vehicle types such as buses, motorcycles, and mopeds. Furthermore, roughly 90% of goods and services in Canada are transported via trucks on Canadian roads.[1,3]

On one hand, these impressive numbers represent the in-land connectivity of the communities directly impacting their economy and promoting their growth. On the other hand, road maintenance procedures are crucial to ensure the safety and usability of the road network, alongside the constant need for new road pavement constructions.

Major categories of asphalt pavement distresses include fatigue cracking, rutting, thermal cracking, top-down cracking, and raveling/stripping.[4] These distresses can be classified into three types: structural (inability of the pavement to bear loads without further damage), functional (loss of skid resistance, structural capacity, or passenger comfort), and materials (disintegration or loss of material properties).[5] Causes for such problems can be numerous, but they are generally related to design, workmanship, soil and ground conditions, and drainage of inter-pavement and surface water.[6,7] In this regard, it is crucial to employ best practices throughout the planning, design, construction, and maintenance phases of road development to minimize the risk of premature deterioration and to allow for the road to achieve its intended service life.[8]

It is worth noting that traffic and environmental conditions are the most influential factors on pavement performance. In fact, Collop & Cebon concluded in their study that dynamic vehicle loads can markedly impact the long-term performance of flexible pavements.[9] Qiao et. al also established that climatic factors, particularly temperature and moisture, play crucial roles in the performance of flexible pavements, as they can modify the degradation of pavement materials and stiffness.[10] Furthermore, Molavi et. al stated that heavy truck transportation on roadways accelerates pavement deterioration and this damage is further aggravated by extreme weather conditions.[11] In regard to weather, the constant climate change, as concluded by Saleh and Hashemian,[12] is affecting transportation and pavement infrastructures, requiring adaptations in the pavement-related processes of design and maintenance. Therefore, a proper comprehension of these factors is of utmost importance in the process of monitoring, understanding, and improving pavement performance.

One powerful way to understand these factors is by utilizing pavement instrumentation, which involves embedding sensors in the asphalt pavement layers. This approach provides valuable insights into how a pavement behaves under varying traffic loads and environmental conditions, allowing for the refinement of pavement response models and improved pavement design methodologies.[13,14]

In fact, over the years, there has been a growing utilization of instrumentation technology to assess crucial pavement responses to traffic loads and to monitor pavement performance.[15-21] Sensors embedded in the pavement layers have proven effective for monitoring the physical condition of pavement structures by capturing their response to traffic loading and environmental parameters.[22-25] In addition to that, pavement instrumentation bridges the theoretical and practical aspects of pavement design and assists in developing prediction models for improving pavement performance.[26-28]

As previously stated, traffic conditions play a critical role in roadway deterioration, highlighting the importance of Weigh-in-Motion (WIM) systems. These systems, involving the installation of diverse sensors within the roadway, collect traffic-related information such as volumes, vehicle classifications, weights, and speeds.[29] Such information has proven to be of great support to environmental, safety as well as to research purposes.[30]

The data from such instrumentation can only be reliable if some practices are in place, such as proper calibration and installation in addition to good management of the data.[14,21] Therefore, the aim of this study is to identify areas of convergence and divergence by integrating and comparing traffic-induced responses from sensors in an instrumented test section located in Edmonton, Alberta, Canada, with a numerical model developed based on the traffic conditions at the same location.

2. Background

2.1 Pavement Instrumentation in Edmonton, Alberta

Considering the advantages and significance of pavement instrumentation, a new instrumented test section was built in Edmonton, Alberta, Canada, in July 2022. This section was constructed on the access road from Aurum Road to the Edmonton Waste Management Centre (EWMC) and Figure 1 shows its location.

Figure 1. New test section location

The test section was installed in a flexible pavement structure consisting of a 25-cm asphalt concrete layer, divided into a 9-cm wearing layer and a 16-cm binding layer. Below this, there's a 45-cm granular base course (GBC) atop the subgrade, which is natural soil. A previous study classified the soil as Well-Graded Gravel (GW) for the GBC layer and Clayey Sand (SC) for the subgrade layer, according to the Unified Soil Classification System (USCS).[31]

To monitor pavement performance under environmental and traffic conditions, 36 sensors were installed: 24 structural sensors to capture traffic loading responses and 12 environmental sensors. The structural sensors include 12 horizontal strain transducers, 6 vertical strain transducers, and 6 earth pressure cells. The environmental sensors include 6 soil temperature sensors and 6 soil moisture content sensors. Figures 2 and 3 illustrate the sensor locations and depths.

Figure 2. Pavement instrumentation layout

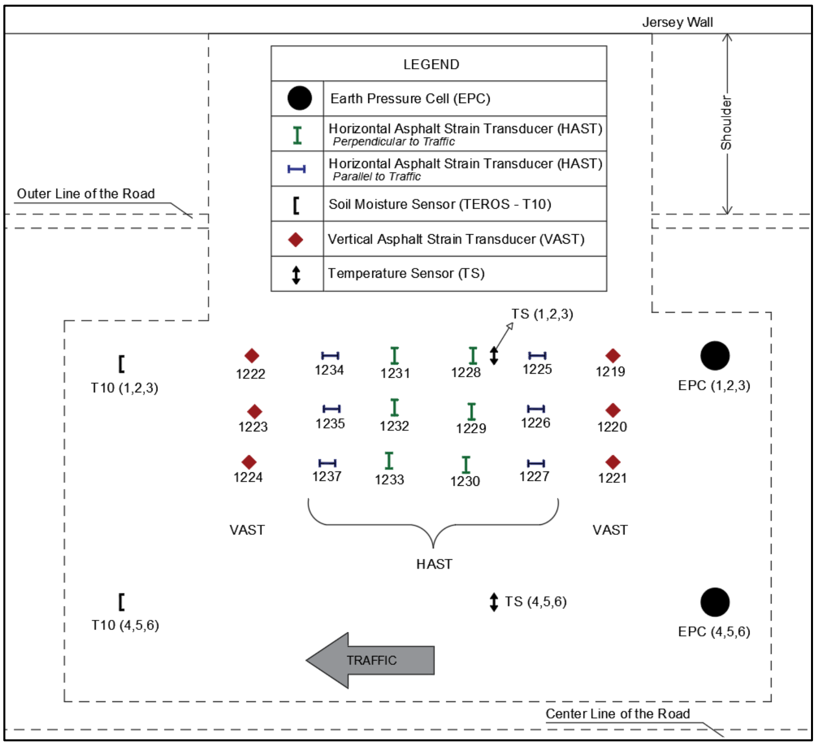
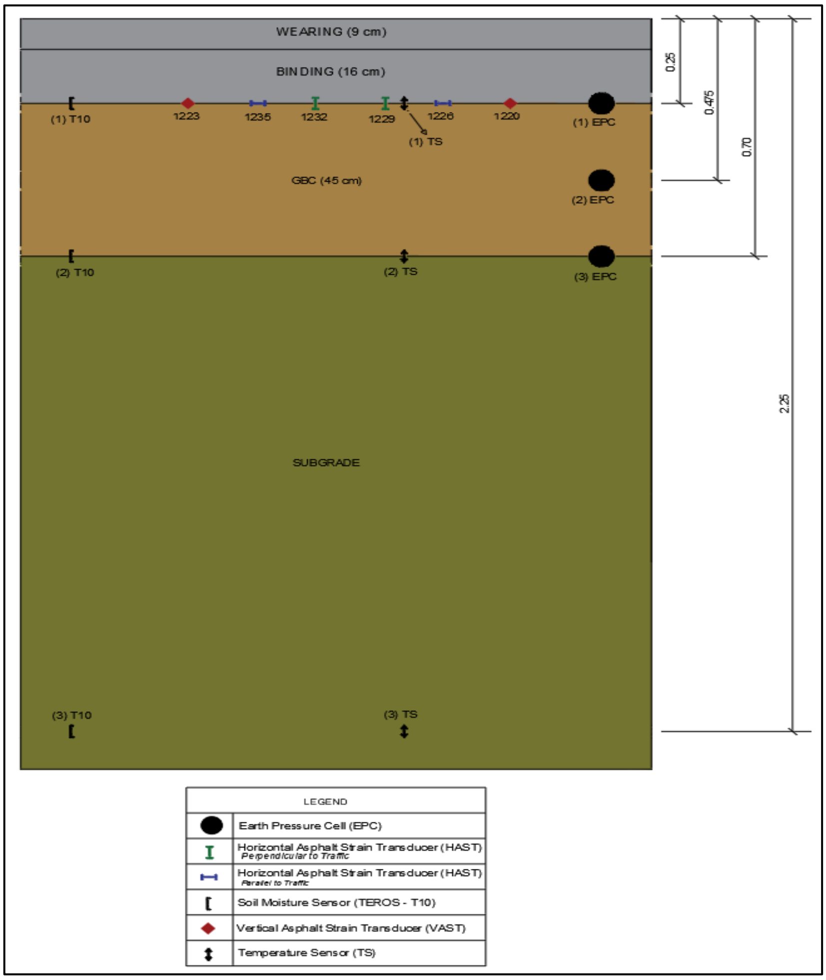


Figure 3. Cross section of the pavement structure



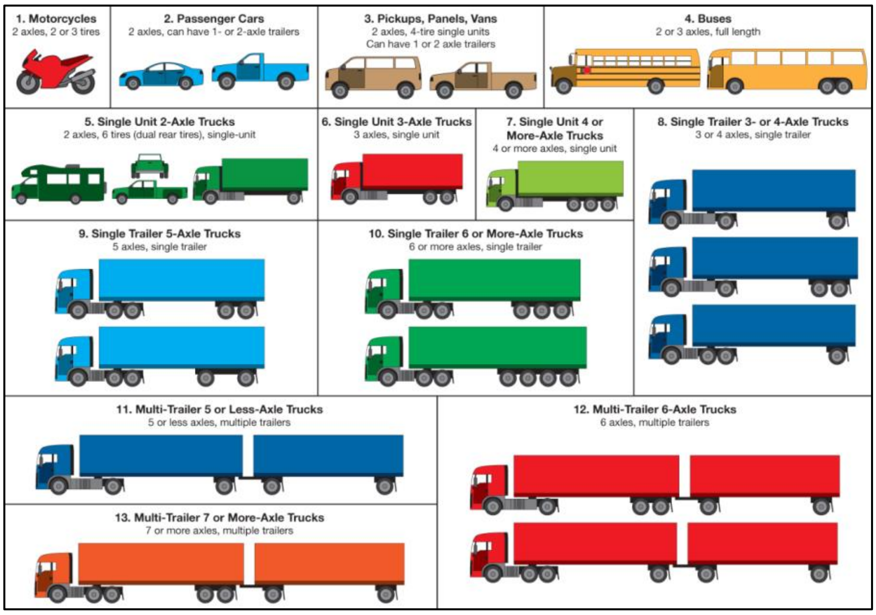
For the purpose of this study, the focus is on the vertical and horizontal strain transducers. As can be seen in Figure 3, they are commonly installed in the bottom of the asphalt layer, and they measure the vertical and horizontal strain values when a moving vehicle passes through.[32,33] Data from these sensors will be further presented from the month of July 2023 and the period between 12:00 to 18:00 o'clock.

2.2 WIM System in Edmonton, Alberta

The new instrumented test section along the EWMC access road includes a Weigh-In-Motion (WIM) system, which provides traffic information via sensors embedded in the asphalt layers. This low-speed WIM system, featuring capacitive, fiber optic, piezo-ceramic, piezo-polymer, and piezo-quartz sensors, was installed in June 2015 and last calibrated in January 2023. It records daily traffic data, including the exact time a vehicle passes, its speed, number of axles and their loads, total vehicle load, distance between axles, and vehicle class. This information has enhanced the understanding of local traffic conditions and improved data analysis from the test section.

The vehicle classes defined by this system follow the Federal Highway Administration (FHWA) guidelines, ranging from Class 1 to Class 13, as shown in Figure 4.[34]

Figure 4. FHWA vehicle category classification



In this study, daily WIM data between 12:00 and 18:00 o'clock for the month of July 2023 is analyzed to have the needed inputs for the numerical modeling program. The reason why this period is being under analysis is that data started to be constantly collected exactly in July 2023 and the period between 12:00 and 18:00 o'clock represents the one with the highest recorded traffic.

3. Objectives

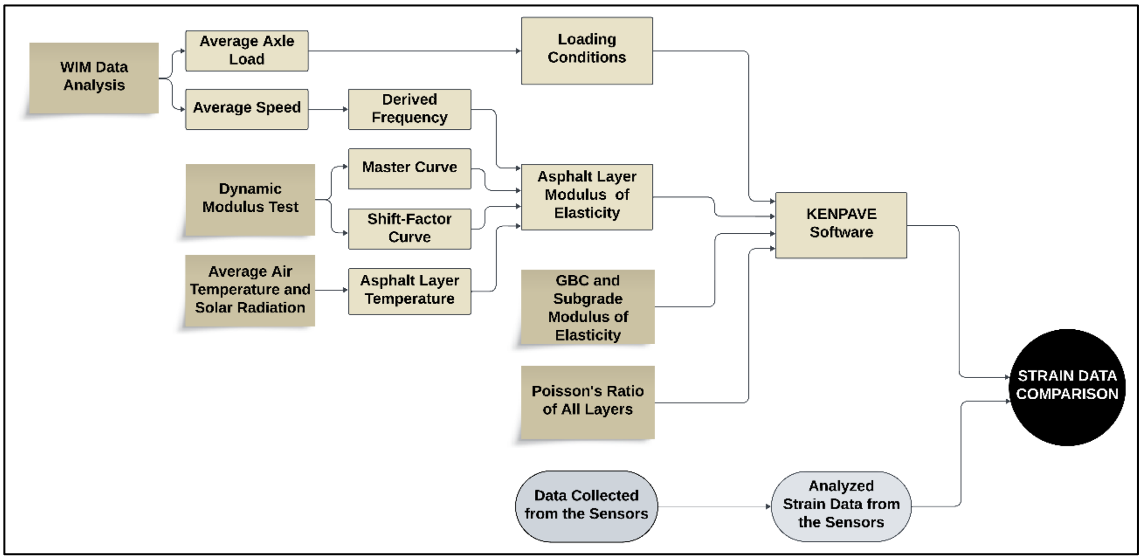
The main objective of this study is to provide a comprehensive understanding of traffic-induced pavement behaviour as well as a framework for data collection, refining and analysis. To do that, data collected from the presented instrumented test section was analyzed and compared to a numerical modelling analysis performed based on the traffic conditions gathered from the WIM system previously mentioned. The goal is to verify the recorded data by comparing it with the real traffic responses, identifying their similarities and differences for further improvement.

4. Methodology

4.1 Flowchart of the implemented methodology

The following sections present a series of information that had to be either retrieved, calculated, or analyzed, so the objective of this study could be achieved. Figure 5 illustrates the methodology flowchart of the study.

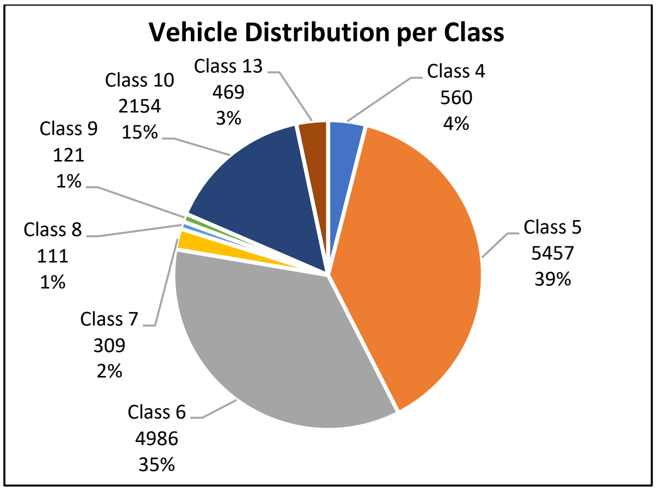
Figure 5. Flowchart with the methodology process



4.2 WIM data

Data was collected from the WIM system and further analyzed from July 2023 between 12:00 and 18:00 o'clock. In each month, a single file is compiled, containing all traffic data for the specified period. This file includes precise timestamps for vehicle movements on the road, facilitating easy selection of time periods for analysis. Moreover, considering that this is an electronic system based on installed sensors, interpretation of the file is required for excluding unwanted data. Given these considerations, a total of 14,167 vehicles passed over the new test section in Edmonton, having a daily average of 457 vehicles. Classes 5 and 6 together respond to almost 75% of the total, while Class 10 responds alone to 15% of the total. Figure 6 shows this distribution.

Figure 6. Number and percentage of vehicles per class

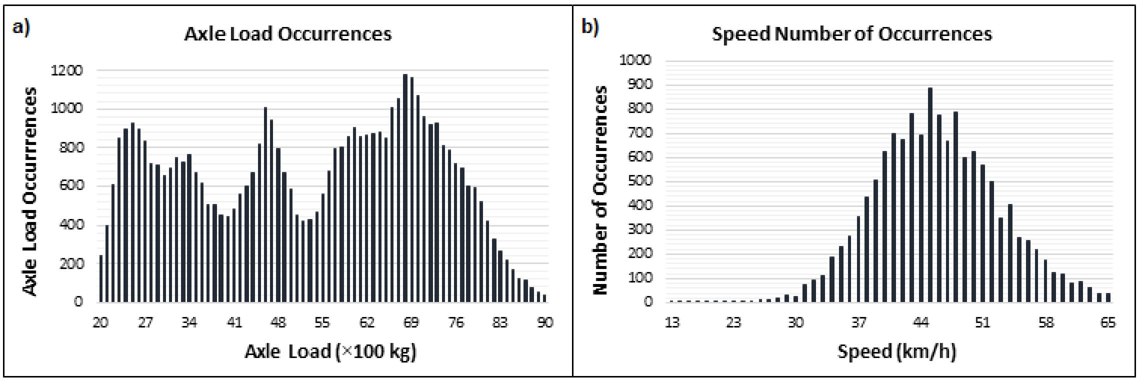


A total of 46,441 axles were registered, averaging 3.3 axles per vehicle. The most frequent axle load was 6,800 kg, with an average axle load of 5,370 kg. All axle loads were considered separately by the WIM system, presenting each axle (steering, tandem, single) independently. For simpler analysis and comparison with sensor data, average values were used.

Another important information is traffic speed because it is needed for determining the Modulus of Elasticity of the asphalt layer. For the same period and considering all the vehicles previously presented, the most frequent speed was found to be 45 km/h while the average speed was 46 km/h.

Figure 7 presents the distribution from Class 4 to Class 13 of the: a) Axle load; and b) Speed.

Figure 7. Class 4 – 13 Distribution: a) Axle load frequency; b) Speed



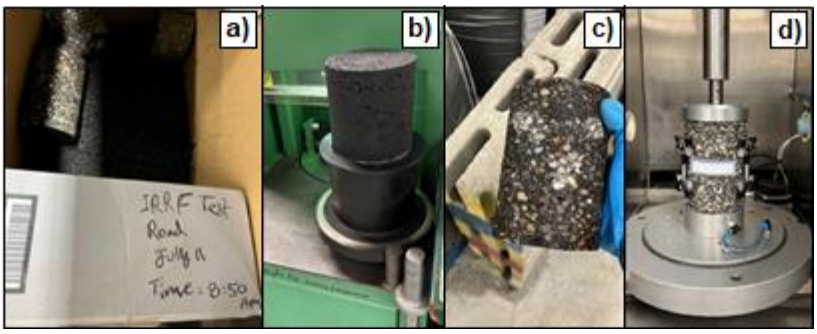
Based on this analysis, 5,400 kg for the average axle load and 50 km/h for speed were used in the KENPAVE Software. These averages were chosen to ensure consistency with the averaged strain data from the sensors.

4.3 Pavement Response Prediction

4.3.1 Material Inputs

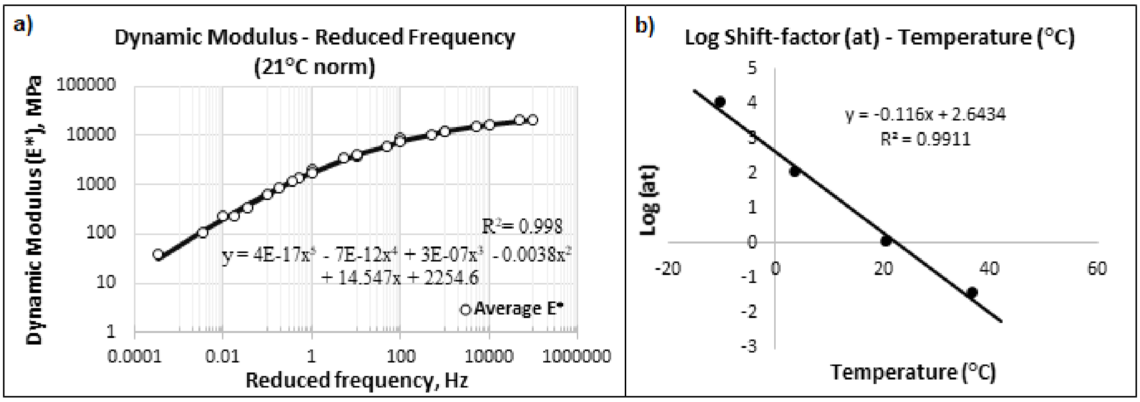
To determine the dynamic modulus of the asphalt layer, a Dynamic Modulus test was performed using an asphalt mix sample collected during the construction of the new test section. This sample came from the same batch used on top of the installed instruments. Three asphalt samples were prepared and tested at different temperatures (-4, 10, 21, and 37°C) and frequencies (10, 5, 1, 0.5, 0.1, 0.01 Hz). Figure 8 shows: a) the asphalt mix and cored sample from the construction site; b) the sample after compaction in the gyratory compactor; c) the sample after coring, cutting, and grinding; and d) the Dynamic Modulus Test setup.

Figure 8. a) Asphalt mix and cored sample from the construction site; b) Sample after compaction in the gyratory compactor; c) sample after coring, cutting and grinding; d) Dynamic Modulus Test setup



The successful completion of the test allowed the generation of a master curve considering time-temperature superposition principle for viscoelastic material, in addition to a shift factor curve. Figure 9 presents these two curves.

Figure 9. a) Dynamic modulus Master-Curve; b) Log shift-factor curve



The combination of these two curves gives the possibility of determining the Dynamic Modulus of an asphalt pavement under any temperature and vehicle speed.

The second step was to determine the asphalt layer temperature and, for that, the following equation from a previous study was needed:[35]

$$T_{\text{daily-average}} = 3.9832 + 1.1288(T_{\text{air}}) + 2.68\text{x}10^{-5}(\text{SR}) \quad (1)$$

Where:

$T_{\text{daily-average}}$ = daily average temperature of the asphalt layer (°C)

T_{air} = daily average temperature of air (°C)

SR = daily solar radiation (kJ/m^2)

As can be seen, the average air temperature and solar radiation are necessary for determining the average temperature of the asphalt layer. These values were obtained from the Oliver weather station located on the northeast side of Edmonton which is a few kilometers away from the new instrumented test section. Thus, considering the same period of July 2023 between 12:00 to 18:00 o'clock, the average air temperature and solar radiation were found to be 21.5°C and 1736.0 kJ/m^2, respectively.[36]

The third and last step was to find the correlated frequency from the speed of 50 km/h determined from the WIM data analysis (Figure 6). It is important to mention that, for laboratory testing, vehicle speeds are simulated as frequency. Based on this information and according to Kuna & Kelly, the speed of 50 km/h can be represented by a frequency of 2.5 Hz.[37]

In possession of all this information and with the use of excel solver, the elastic modulus of the asphalt layer was calculated to be 1,125,850 kPa. This value appeared reasonable considering that the applied asphalt mix, according to the Dynamic Modulus test results, exhibited lower strength. Additionally, the analysis was conducted in July, a hot month during which the asphalt concrete pavement tends to be less stiff.

As for the other layers, their elastic modulus values were retrieved from a previous study, which analyzed an old test section located in the same access road to the EWMC. In this study, the elastic modulus for the GBC and subgrade layers were back-calculated to be 215,000 kPa and 115,000 kPa, respectively, as a result of different environmental conditions.[38]

Another piece of information retrieved from this same study and required for the analysis was the Poisson's Ratio (PR) and it was found to be, as outlined in ASTM D5858, 0.35 for the asphalt layer, and 0.40 for both GBC and subgrade layers.[38]

4.3.2 Loading conditions

The loading conditions to be applied in the KENPAVE Software were determined by the average axle load found in the WIM data analysis – 5,400 kg. The inputs related to the load are the Contact Pressure (CP), the Contact Radius (CR) and space between the dual-tire wheels. The CR value can be determined by following the equation below:[39]

$$CR = \sqrt{\frac{\text{Tire load}}{\pi \times \text{Tire pressure}}} \quad (2)$$

A few assumptions were made for the analysis:

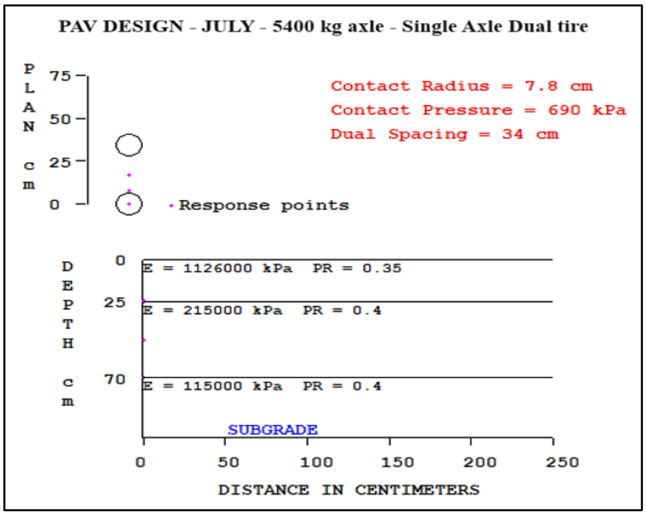
i. The axle configuration was considered to be a single-axle with dual-tire.
ii. The tire pressure was assumed to be 690 kPa (100 psi), given the fact that, for trucks, this value ranges from 590-760 kPa (85-110 psi).[39]
iii. The distance between the dual-tire wheels was assumed to be 34 cm, which is a relatively common number for trucks.

The contact radius could then be calculated, and it was found to be 7.8 cm.

4.4 Model Set Up

Having gathered all the necessary KENPAVE inputs, the program was ready for execution. The inputs mentioned earlier are depicted in Figure 10.

Figure 10. Inputs for KENPAVE design

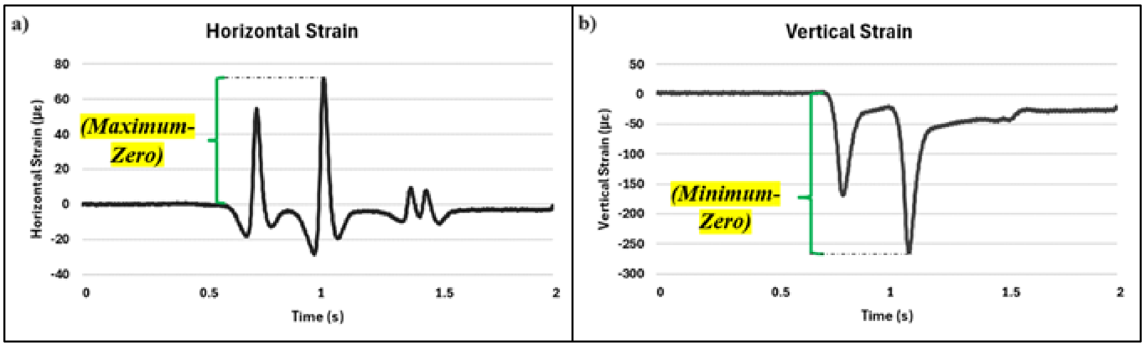


The main focus at this point was to find vertical and horizontal strain values that would represent the actual values, considering the fact that the inputs were determined based on traffic and environmental conditions that directly influence the test section under analysis.

4.5 Validation with in-situ responses

One important consideration that was found to be determinant to the success of this comparison was in the way in which each strain value from the sensors were analyzed. Figure 11 depicts a typical example of a horizontal strain (a) and a vertical strain (b) and how the analysis took place. For the horizontal strain transducers, the strain value was defined by the difference between the maximum and the zero values, while for the vertical strain transducers, the strain value was calculated by the difference between the minimum and the zero values.

Figure 11. Sample data from the sensors and validation:
(a) Horizontal Strain; (b) Vertical Strain



Considering the month of July from 2023 and the period between 12:00 and 18:00 o'clock, a total of 10,617 files were analyzed with an average of approximately 343 files per day.

5. Results and Discussion

After entering all the inputs and running the KENPAVE software, the maximum values for the horizontal and vertical strains were found to be 129 με and 115 με, respectively, and these results can be seen in Figure 12.

Figure 12. Strain results from the KENPAVE Software

PERIOD NO. 1 LOAD GROUP NO. 1

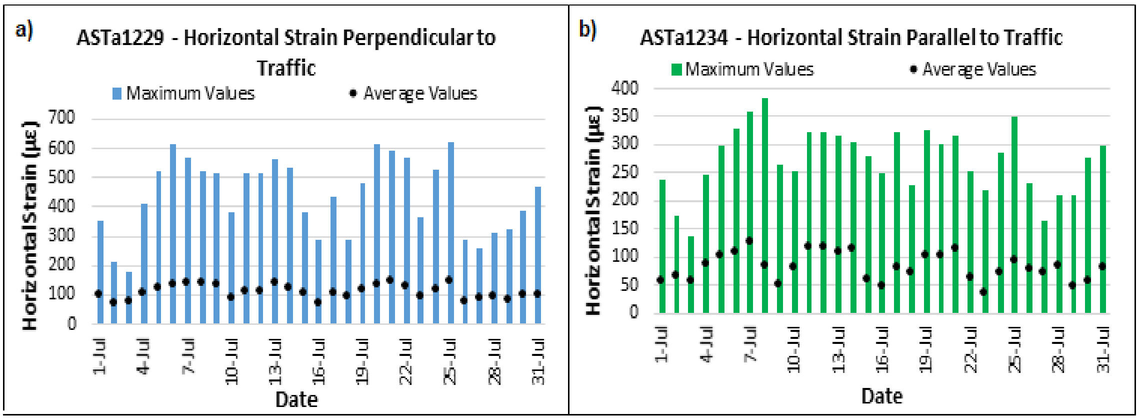
POINT NO.	VERTICAL COORDINATE	VERTICAL DISP.	VERTICAL STRESS (STRAIN)	MAJOR PRINCIPAL STRESS (STRAIN)	MINOR PRINCIPAL STRESS (STRAIN)	INTERMEDIATE P. STRESS (HORIZONTAL P. STRAIN)
1	25.00000	0.01703	54.195	54.546	-147.084	-113.984
	(STRAIN)		1.292E-04	1.296E-04	-1.122E-04	-1.122E-04
1	47.50000	0.01343	22.982	23.978	-2.617	-1.262
	(STRAIN)		1.123E-04	1.187E-04	-5.444E-05	-5.444E-05
1	70.01000	0.01132	12.545	12.849	-0.330	0.090
	(STRAIN)		1.089E-04	1.126E-04	-4.787E-05	-4.787E-05
2	25.00000	0.01749	53.080	53.082	-144.420	-94.471
	(STRAIN)		1.214E-04	1.214E-04	-1.154E-04	-1.154E-04
2	47.50000	0.01378	24.464	24.748	-2.736	-0.874
	(STRAIN)		1.200E-04	1.218E-04	-5.714E-05	-5.714E-05
2	70.01000	0.01153	13.136	13.228	-0.351	0.116
	(STRAIN)		1.147E-04	1.158E-04	-4.946E-05	-4.946E-05
3	25.00000	0.01757	49.193	49.193	-134.123	-67.267
	(STRAIN)		1.063E-04	1.063E-04	-1.135E-04	-1.135E-04
3	47.50000	0.01393	25.016	25.016	-2.781	-0.667
	(STRAIN)		1.228E-04	1.228E-04	-5.823E-05	-5.823E-05
3	70.01000	0.01163	13.387	13.387	-0.355	0.132
	(STRAIN)		1.172E-04	1.172E-04	-5.011E-05	-5.011E-05

It is worth reminding that, for getting all the required inputs, many average values were considered. Therefore, these presented results are a representation of the strains based on the average traffic and environmental conditions (air temperature and solar radiation) for the period under analysis.

Focusing on the horizontal strain transducers, based on their position during installation, the horizontal strain transducers are divided in perpendicular to traffic (blue box) and parallel to traffic (green boxes), as can be seen in Figure 2.

After collecting the data from July 2023, a thorough analysis was performed, and it was concluded that the sensors with the highest strain values were the ASTa1229 and ASTa1234. Given this conclusion, Figures 13 and 14 present the daily maximum values and the daily average values for these two sensors and for July 2023 between 12:00 and 18:00 o'clock.

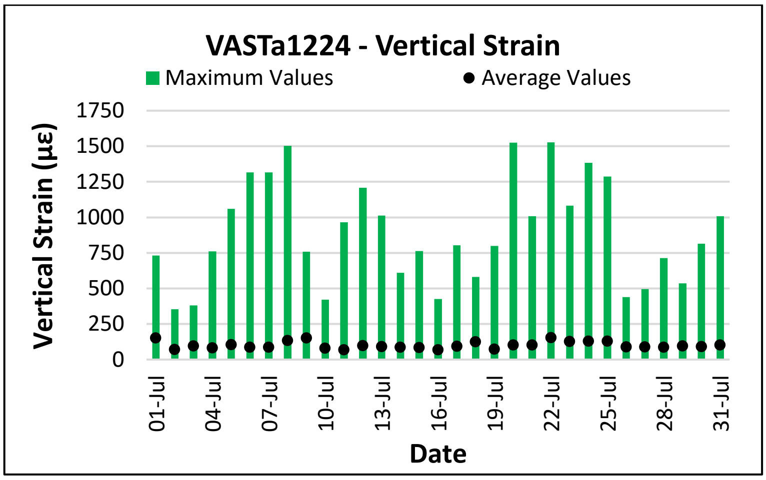
Figure 13. Daily maximum and daily average strains for: a) ASTa1229; b) ASTa1234



From Figure 13, it can be deduced that the highest average strain values are 147 με for the HAST perpendicular to traffic and 126 με for the one parallel to traffic. When compared with the value obtained from the KENPAVE software (115 με), differences of 32 με and 11 με are observed. However, it's important to note that this comparison involves daily values contrasted with a monthly value. To maintain consistency in the analysis, when the daily average results from the sensors are subsequently averaged on a monthly basis, their values decrease to 110 με and 82 με, respectively, which then fall below the maximum value determined by KENPAVE.

Focusing on the vertical strain transducers, as presented in Figure 2, six of these sensors were installed when the new test section was built. However, as of July 2023, only two of them were working, VASTa1220 and VASTa1224, and VASTa1220 was presenting faulty results. Therefore, the following analysis is focused on the VASTa1224 sensor. After thoroughly analyzing the generated data from July 2023 between 12:00 to 18:00 o'clock, the daily maximum values and daily average values could be determined for this sensor, and they are presented in Figure 14.

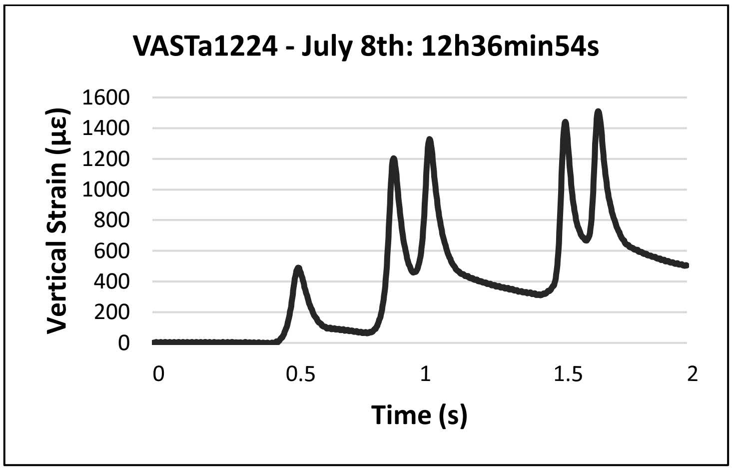
Figure 14. Daily maximum and daily average strains for VASTa1224



As presented in Figure 14, the highest value for the daily average values is 154 με. When comparing with the KENPAVE software maximum value (129 με), a difference of 25 με can be found. However, applying the average on the daily average values gives a result of 100 με, which presents to be smaller than the one calculated by KENPAVE.

Another interesting observation is related to the high values for the maximum vertical strains presented in Figure 14. After detailed analysis, some overlapping strains were identified. In other words, after the first axle passed, a wave was created. However, before the sensor could reset to zero, another axle from the same vehicle passed, adding more strain on top of the existing one. For better understanding, Figure 15 presents the highest cumulative vertical strain from July 18, which has the value of 1502 με. This will be an interesting topic for further analysis and discussion.

Figure 15. Sample individual file from VASTa1224



6. Conclusions and Future Work

In this study, a brief history of pavements and their importance to society were presented. Considering the pavement impact on economic growth, understanding its behavior plays a crucial role in contributing to this growth. In this context, using pavement instrumentation can be an effective method to monitor pavement performance and understand how it responds to both traffic and environmental conditions. The main objective of this study was to compare the measured strain values from pavement sensors with calculated values using a numerical model. It was found that the maximum horizontal and vertical strains from the numerical modeling were, respectively, 115 με and 129 με. Meanwhile, the results from the sensors, after determining the monthly average, were found to be 110 με and 82 με for the horizontal strains, and 100 με for the vertical strain. Based on the results obtained in this study, the following conclusions can be drawn:

- WIM system proved to be an important tool for pavement engineering, since they generate traffic-related information, which can be correlated with the data from traffic-induced sensors.
- Although the results presented to be satisfactory, a different statistical approach other than the average could achieve new responses and generate new possible verifications.
- Given the amount of data that was utilized and the high variation in the measured strain, it is unrealistic to expect the numbers from both measured and calculated strains to be the same.

Based on the large amount of data that has been constantly recorded from this new instrumented test section, and by integrating this data with the WIM motion system, there is an array of possibilities to work with in the future, and some of them are presented below:

- The procedures outlined in this study will be employed for the following months, with the aim of identifying differences between seasons.
- New statistical approaches will be attempted to yield fresh results and insights.
- In-depth analysis will be conducted to understand the high strain values captured by the vertical strain transducer.
- An analysis on stress values will also be performed to complement the investigation.

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