DEVELOPMENT OF A NOVEL WEIGHING DIGITAL SENSOR FOR FURTHER EVOLUTION OF WIM TECHNOLOGY

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Abstract

The paper describes the newly developed CAMEA WIMTRONIC digital sensor for high-speed weigh-in-motion (HS-WIM) applications, which enables the measurement of both gravitational forces (like current weighing sensors) and the monitoring of dynamic forces caused by vehicle vibrations due to road irregularities and sudden vehicle maneuvers such as braking, acceleration and swerving.

The new HS-WIM sensor also embeds a number of other sensors and performs digital processing and transmission of the measured data, which significantly simplifies and reduces the costs of installation by significantly reducing cabling and the number of additional sensors in the road. The WIM digital sensor architecture can be further extended to include additional complementary sensors and embedded processing for vehicle parameter calculation, compensation, calibration and validation of measured data, diagnostics, sensor wear level, etc.

The digital weighing sensor has a wide and robust design, while maintaining a low profile for minimal road interference, and a high and uniform sensitivity along its entire length, allowing accurate weighing across the entire lane width.

The new digital WIM sensor thus, together with advanced algorithms, offers a range of innovative functions such as monitoring of incorrectly inflated tires and vehicle maneuvers that cannot be provided by current analog weighing sensors.

Keywords: Digital WIM sensor, HS-WIM, Edge Processing, Embedded Digital Processing, Built-in Sensors, Combination of Sensing Technologies, PIM, Pressure-In-Motion, Tire Footprint, Road Wear, Measurement Validation

1. Introduction

Weigh-in-motion (WIM) is a process of measuring the dynamic forces exerted by tires of moving vehicles on sensors installed in the road, from which the weight carried by individual wheels, axles or axle groups is calculated and then used to calculate the total weight of the vehicle (Loo and Znidaric, 2019), (Jacob et al., 2002).

WIM systems can be divided into two basic categories - low-speed (LS-WIM) and high-speed (HS-WIM). LS-WIM systems are typically used to accurately weigh vehicles traveling at low speeds that are diverted from the traffic stream to specially designated locations off the main road. HS-WIM systems are typically used for weighing vehicles traveling at speeds higher than approximately 5 km/h, while also weighing vehicles traveling at high speeds, e.g., up to 130 km/h. The great advantage of HS-WIM systems is that they do not affect the speed or flow of traffic , as the weighing of vehicles takes place directly on the main road.

Although HS-WIM sensor technologies are quite mature, a number of features can be identified that are suitable for practical applications of modern WIM systems, but which are not provided by current sensor designs (Donțu et al., 2020). This paper discusses an innovative design of weighing sensors for HS-WIM applications that addresses a number of these issues, and in addition offers some additional features.

1.1. Interference with the Road Structure

The joint between the pavement and the sensor is mechanically stressed, especially in asphalt pavements, and this can cause cracks to form around the sensors, see Figure 1.

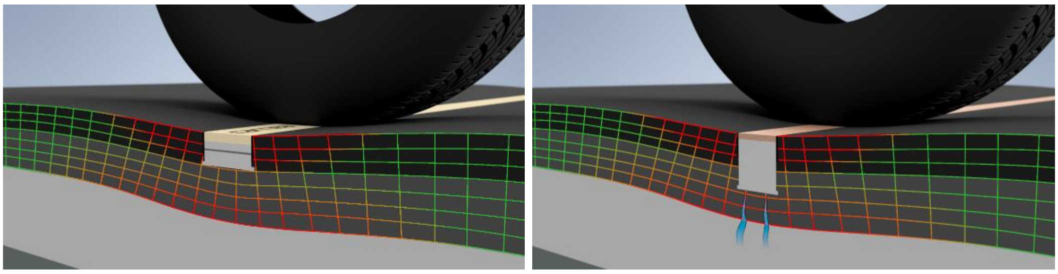

Figure 1 - The impact of WIM sensor height on potential damage and road lifespan

The installation slot depth is primarily determined by the height of the sensor body, which affects the level of stress and damage to the pavement, with a shallower slot being more suitable in terms of impact on the pavement.

1.2. Additional Sensors

To perform correctly, HS-WIM systems typically require not only weighing sensors but also other in-road sensing technologies such as vehicle detectors (typically inductive loops), lateral position and tire mounting sensors (typically piezo-polymer sensors installed in a tilted manner), temperature sensors, and others.

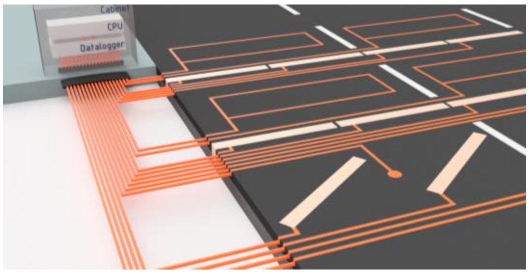

Figure 2 - A large number of cables required when using standard WIM sensors

Installing these additional technologies also significantly increases the number of pavement cuts required for the sensors themselves and their cabling. For example, up to 21 individual cables (4x inductive loops, 8x WIM sensors, 4x sensor ground cables, 4x position sensors, 1x temperature sensor) may be required for 2 lanes in a typical HS-WIM system with 2 rows of sensors. The number of cables and sensors potentially reduces the life of the road and makes the HS-WIM system more expensive and the installation more complex and time consuming.

1.3. Limited Number of Measured Quantities

Current WIM sensors typically measure only one quantity - the gravitational forces around the vehicle. The lack of direct integration of other sensing technologies not only requires the installation of additional sensors (see above), but also limits the accuracy of measuring these additional quantities.

For example, the tilted additional pressure sensors measure the position of the vehicle wheel. However, they do not measure directly at the HS-WIM sensor, but up to several meters away. Therefore, it is inherently inaccurate to measure and detect the position of vehicle wheels that are moving away from these sensors (off-scale). Similar problems resulting from the spatial dispersion of the measured quantities can be observed when measuring wheel acceleration, temperature (at the location of the thermometer, not the sensor) and other additional quantities.

Particularly for free-flow HS-WIM systems, measurement validation, i.e. the ability to flag invalid measurements that may have a potentially elevated error, is a key function in providing high quality and valuable outputs. For systems designed for applications such as direct enforcement or toll collection, any limitations in the ability to validate measurement results beyond those imposed by current sensor technologies are particularly critical.

1.4. Longitudinal Resolution

The majority of HS-WIM sensors only measure the sum of the loads applied to the sensor, and it is common for two WIM sensors to be installed across the lane. As a result, the WIM sensors of the HS-WIM system do not normally allow for the identification and distribution of loads in cases where more than one wheel is acting on one of the sensors at the same time. A combination of the relatively long length of the WIM sensors (up to 2 m), small vehicle width (up to 2.5 m), large wheel widths (more than 0.7 m for dual tires), and arbitrary lateral position of the vehicle usually results in the presence of multiple vehicle wheels on a single sensor.

Due to the low resolution, loads cannot be assigned to individual wheels and their position cannot be determined. This leads to complications in correcting the lateral sensitivity of the sensors. In some cases, the entire weight evaluation cannot be completed because the vehicles have an effect on several sensors at the same time.

1.5. Summary

Current HS-WIM requires a number of additional sensors which results in an increase in cabling, road interference and cost. This is due to the design and lack of embedded sensing elements for measuring more quantities. The spatial separation of these additional sensors from the WIM sensors also reduces the accuracy and usability of their outputs for validation and compensation of the measurement output. The analog signal, which with some exceptions is the sum of the responses of all the sensing elements within the WIM sensor, makes it impossible to address some of the vehicle passage cases that arise from the free-flow nature of HS-WIM system applications, and further limits the ability to validate, compensate, and in some cases complete the measurement results.

On the basis of the above, it can be concluded, that the "ideal" HS-WIM sensor should be:
1. As low as possible (low profile) to have minimum interference with the road structure.
2. Able to measure the position and width of each vehicle wheel individually.
3. Able to measure not only gravitational forces but also other quantities to reduce the number of additional sensors and their cabling.

2. Sensor Build

Based on a careful analysis of the limitations of current HS-WIM sensors and considering the needs of modern innovative and future HS-WIM applications, a design consisting of 2 rows of piezo-quartz sensing elements and electronics placed between 2 cover plates. The design was based on the study of a number of HS-WIM sensor designs, including the use of piezo-quartz sensors and integration of electronics (Sonderegger et al., 1990), (Calderara at al., 1993), separate measurement, digitization and transmission of measurement data from individual force sensing elements (Opitz et al., 2012), vehicle detectors (Rouse and Volna, 1993), or arrangement of force sensing elements in multiple rows (Sonderegger, 1998), (Libo et al., 2011), etc.

2.1. Force Sensing Elements and Their Layout

The sensing elements used in the new digital WIM sensor are piezo-quartz force transducers. This is due to the long experience in the field and the advantageous properties compared to other technologies. However, piezo-crystal elements made of other suitable materials such as langasite, langatate, gallium phosphate, etc. can also be used.

The sensor contains 2 rows of individually preloaded force sensing elements mounted in a hermetically sealed chamber consisting of a support and a cover plate. By using 2 rows of sensing elements, the sensor body has the advantage of being wider in the direction of vehicle travel (80 mm) than the most common HS-WIM sensors used today (up to 50 mm).

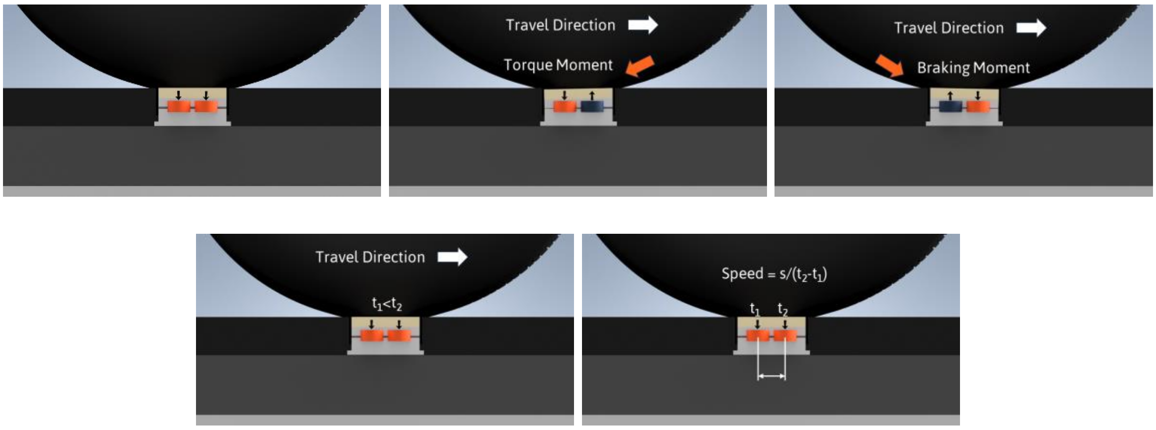

Figure 3 - 2 rows of sensors compared to a single row for standard WIM sensors allow measuring the effect of horizontal forces, determining the direction of travel and estimating the speed of the vehicle wheel

The 2 rows of sensing elements make it possible to measure not only the vertical gravitational forces exerted by the vehicle's tires, but also the effects of horizontal forces (braking, torque) that can affect the accuracy of the measurements, and these measurements are made while the wheel is on the sensor. It is also possible to determine the direction of the wheel and its speed. These additional measurements make it possible to validate and possibly refine the measurement of the weight of the wheel and therefore of the axle and the whole vehicle.

The larger sensor width, resulting from the use of 2 rows of sensing elements, also reduces the undesirable influence of road irregularities in the vicinity of the HS-WIM sensor and the tire pattern on the accuracy of vehicle weighing when a larger part of the tire is on the sensor then on the road.

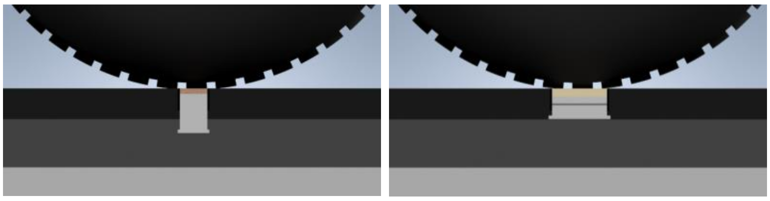

Figure 4 - The wider WIM sensor is less affected by tire tread and road irregularities

2.2. Build

A certain initial force - the so-called preload - must be applied to the piezo-quartz sensing elements placed in the body of the HS-WIM sensor to ensure that the sensing element is tightly clamped in order to function properly. Proper preload is a key factor in achieving high linearity, low hysteresis, resistance to bending moments, resistance to mechanical damage when applying dynamic effects caused by the wheels of weighed vehicles.

In the most common designs of piezo-quartz WIM sensors today, the preload is applied by the sensor body, formed by e.g., a closed profile of extruded aluminum. In order to achieve the required uniform preload across all piezo-quartz sensing elements, it is necessary to ensure very precise manufacturing tolerances, which is technologically (and therefore financially) demanding.

The design of the new HS-WIM sensor is also innovative in that it allows individual adjustment of the preload of each of the piezo crystal sensing elements located between the cover plates. This arrangement allows the sensor to be designed with minimal feature dispersion along its length, limiting the influence of manufacturing tolerances, ensuring consistent temperature dependence and the influence of material fatigue on the individual sensing and preload elements. In addition, an optimum preload is achieved, which has a positive effect not only on the reliability and lifetime of the sensor, but also on the uniform sensitivity and accuracy of the resulting HS-WIM sensor.

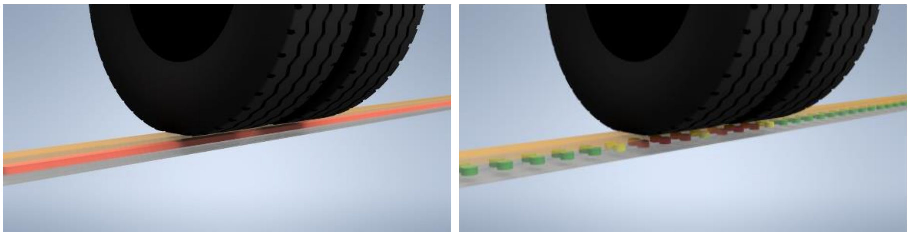

Figure 5 - Standard design and individually preloaded sensors placed in 2 rows

The chosen design also allows the use of relatively low cover plates. This results in a low sensor body height of only 33 mm (excluding the abrasive layer bonded to the top of the sensor). This low sensor height reduces interference with the pavement structure, thereby increasing the life of the pavement and the sensor itself. The initial height of the abrasive layer was chosen to be higher than the 10 mm commonly used in current sensors, although the total height achieved is still only 45 mm (comparing to up to 75 mm in some current sensor types). The higher height of the abrasive layer was chosen because it results in a longer lifetime in road ruts. The low cover plates also allow targeted force transfer to the sensing element, enabling precise localization of the applied forces and therefore the vehicle wheels on the sensor.

2.3. Embedded Signal Processing

Measurement electronics, digitizing circuits, computing unit, power supply circuits, communication, and network elements for transferring measured data to the HS-WIM system are placed in the sensor . Each piezo-crystal sensing element in the sensor body has its own channel of measurement electronics and is therefore processed separately. The separate processing of the individual sensing elements enables to determine the position and width of the individual vehicle wheels, the contact area of the tires, to process when multiple wheels are present on the sensor simultaneously and to compensate the sensitivity of each part of the sensor separately.

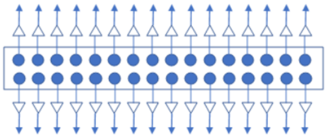

Figure 6 - Each piezo-crystal sensor in the sensor body has its own channel of measurement electronics

There are also additional sensing technologies in the sensor body for classification of weighed vehicles and measurement of the temperature of the road and/or the WIM sensor. In addition, digital signal processing (DSP) algorithms can be built into the sensor to calculate the wheel weights of the weighed vehicles, including any compensation, validation and diagnostic algorithms including calibration constants, wear counters, or cumulative loads.

Digital processing and transmission of measured data also has the advantage of noise resistance. The output data from the sensor is transmitted digitally for further use via a standard interface with integrated power supply (Ethernet POE or CAN), which allows multiple digital HS-WIM sensors to be connected to one communication bus. The sensor can then have 2 feeder cables, which allow the WIM sensors to be daisy chained, making the communication infrastructure even cheaper and simpler (e.g., only a single cable leads to a pair of sensors).

The integration of electronics and signal processing into the sensor body also significantly reduces cabling and thus minimizes the interference with the road structure when installing the digital WIM sensors. For example, , the amount of cabling of a typical 2-lane WIM system can be reduced from the 21 (see chapter 1.2) to 12 pieces (8x sensor, 4x sensor ground rows) or even to 8 or less pieces when using daisy chain wiring, see Figure 7.

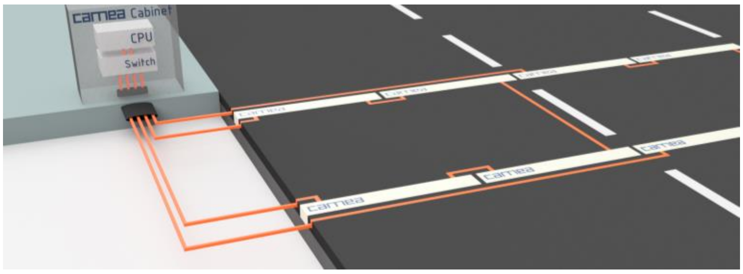

Figure 7 - Minimizing cabling and additional sensors when using the digital WIM sensor

3. Features of the New Digital Sensor Build

The new type of sensor is installed in a similar way to the current piezo-crystal HS-WIM sensors, where the sensor is glued into a slot in the road and its abrasive layer is ground level with the road surface.

Figure 8 - Sensor installation

3.1. Measuring Gravitational and Horizontal Forces

The individual piezo-quartz sensing elements measure the gravitational forces exerted by the vehicle wheels and, thanks to their 2 rows, the ratio of the responses of each row can be measured, providing information on both the vertical and horizontal components of the applied forces, see Figure 9. Therefore, it is possible to determine if the wheel is moving uniformly, accelerating or decelerating. For example, when braking, error dynamic forces superpose with the measured gravitational forces. This can affect the weighing accuracy. Thanks to the 2 rows of force sensing elements, these phenomena can be measured, allowing not only validation but also compensation of the measured values if necessary.

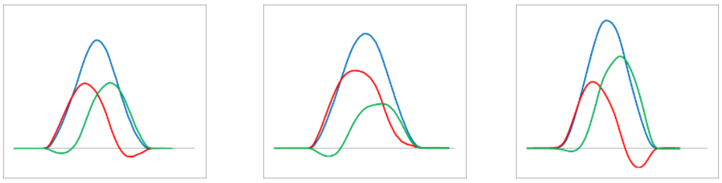

Figure 9 - Observed responses of the standard (blue) and presented sensors (red and green) for fluent driving, acceleration, and braking

3.2. Weighing Accuracy

In tests with a light twin-axle truck weighing 3,850 kg, the measured weights showed a standard deviation of 2.4 %. The values are given for 1 sensor and a light vehicle deliberately because light twin-axle vehicles often show a higher error due to increased chassis vibration. In the case of weighing heavy, fully loaded vehicles, the sensors will show even less variance in the measured values and therefore a lower weighing error. It makes sense to weigh fully loaded vehicles as the light vehicles are probably not overloaded. In general, it should also be noted that the value given is also largely determined by the quality of the road, the installation of the sensor and the dynamics of the vehicle. Significantly better values of repeatability and homogeneity of sensitivity have been achieved under laboratory conditions - these are within 1 %.

As already mentioned, to assess the sensor performance, field tests were performed to determine the standard deviation of the measured values. In practical WIM applications, multiple rows of sensors are used for vehicle weighing. This is partly because in order to determine the weight of the vehicles, it is necessary to know their speed, for which two or more rows of sensors are used. Furthermore, to reduce random errors (increase the accuracy of weighing), more measurements need to be performed. Therefore, two rows of sensors are usually installed in practice, or occasionally even more rows.

Let us assume that the WIM system has 4 sensors in two rows, where each row has always a left and a right sensor weighing the left and right side of the vehicle.
When weighing the left or right side of the vehicle, the results of the individual sensors are averaged, and the resulting standard deviation decreases with the square root of the number of measurements. When the whole vehicle is weighed, the weight of the left and right sides of the vehicle is added together and the resulting standard deviation is the combination of the standard deviations of the left and right sides of the vehicle.

This can be demonstrated with the example of a vehicle with a total weight of 3532 kg (i.e., 1766 kg on each side). If each sensor shows a normal distribution with a standard deviation of 42 kg (in 68 % of cases), then the standard deviation of the measurement of the mass of one side of the vehicle on the two sensors is 29.7 kg, which is 1.2 % of 3,532 kg (in 68 % of cases).

$$SD = \sqrt{2\sigma^2} = \sqrt{29.7^2 + 29.7^2} = 42.0\ kg \tag{1}$$

Sum of two independent random variables with a same variance

$$SD = \sqrt{\frac{\sigma^2}{n}} = \sqrt{\frac{42^2}{2}} = 29.7\ kg \tag{2}$$

Average of two independent random variables with a same variance

Assuming that in real operation the probability that the measurement will differ by two standard deviations needs to be 95%, then we get a so-called twice expanded standard deviation of the total mass measurement of 2*1.2% = 2.4%. This meets the requirements of accuracy class A(5) of COST 323, which requires a 2x expanded standard deviation of 5 % for 95 % of the measurement. This calculation is idealized and only determines the potential weighing accuracy that can be achieved with the new sensor. In practice, it must be taken into account that both random and systematic errors occur in the weighing of vehicles, which reduce the accuracy of the weighing.

3.3. Wheel Position and Detection of Multiple Tire Mountings

One of the requirements for the digital sensor functionality is to replace (in current HS-WIM systems) the additional tilted pressure sensors (e.g., piezo-polymer) which are used for measuring the vehicle position, track, tire width and detection of multiple tire mountings. It can be shown that the sensor design allows clear identification of multiple tire mountings and measurement of all tire widths, including tires in multiple mountings, see Figure 10.

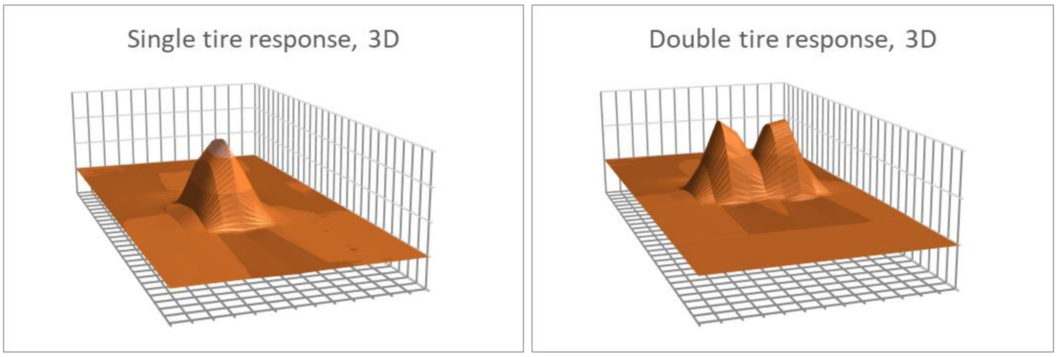

Figure 10 - Measured wheel responses with single and dual tires

To verify the required functionality, tests were carried out with a light two-axle truck with relatively narrow tires (195/70 R15). The measured values are deliberately given for narrow tires, which have a small footprint and therefore have a larger measurement error when measuring the footprint than would be the case for trucks with wider tires.

The results are shown in Table 1. The measurement algorithms and sensor design allowed the test to measure the width and position of the wheel with a standard deviation of up to 13 mm and an offset of up to 3 mm. This precise measurement allows, among other things, accurate calibration of the transverse sensitivity of the sensor, i.e., correction for road effects such as rutting, differences in road stiffness across the lane and others.

Table 1 - Tire width measurements

Reference	195 mm	195 mm	195 mm
	Wheel 1 Err.	**Wheel 2 Err.**	
	Single Tire	**Outer Tire**	**Inner Tire**
Average	3	2	3
	1.3 %	1.1 %	1.4 %
St. Dev. (68 % of results)	13	10	13
	6.6 %	5.2 %	6.8 %

3.4. Tire Inflation Pressure Measurement

The digital sensor also allows precise measurement of the load distribution over the width and length of the tire. This data in principle enables the measurement of tire inflation pressure.

Table 2 - Tire inflation pressure measurements

Reference	430 kPa	350 kPa	395 kPa
	Wheel 1 Err.	**Wheel 2 Err.**	
	Single Tire	**Outer Tire**	**Inner Tire**
Average	21	0	8
	4.8 %	0.0 %	2.0 %
St. Dev. (68 % of results)	13	5	11
	3.0 %	1.5 %	2.9 %

In tests using a light twin-axle truck (see above), a measurement error of up to 21±13 kPa (4.8±3.0 %) was achieved, see Table 2 (reference measured with a digital pressure gauge with an accuracy of 1 % FSO). The sensor and the measurement algorithms not only allow accurate tire pressure measurements, but also allow separate measurements even for wheels with multiple tire mountings.

3.5. 1111Cumulative Road Load

During the passing of vehicles, the road is stressed by the passage of wheels, which gradually leads to its wear, i.e., rutting, the formation of internal faults, cracks and subsequently potholes. One of the established methodologies for measuring pavement wear rates and estimating them for repair planning is the Equivalent Single-Axle Load (ESALs) calculation methodology (Cecil, 1972), and WIM systems can be used to measure them (ASTM, 2017).

A WIM system with a new type of digital WIM sensor can provide highly accurate data for measuring the level of road wear, enabling optimal maintenance planning and thus reducing the cost of operating and maintaining the road infrastructure. The digital WIM sensor, with its ability to accurately measure lateral position and tire inflation pressures, allows the cumulative counts, loads and pressures to be measured across the road profile, while the ESALS methodology works with a road or lane resolution. Thus, the data provided allows refinement of the road wear assessment beyond the ESALs estimate. The digital sensor therefore allows a detailed analysis of the loads and pressures in the lateral profile of the roadway, which opens up new possibilities for analyzing the load on roads and traffic infrastructure and planning their reconstruction, extension, and maintenance, see Figure 12.

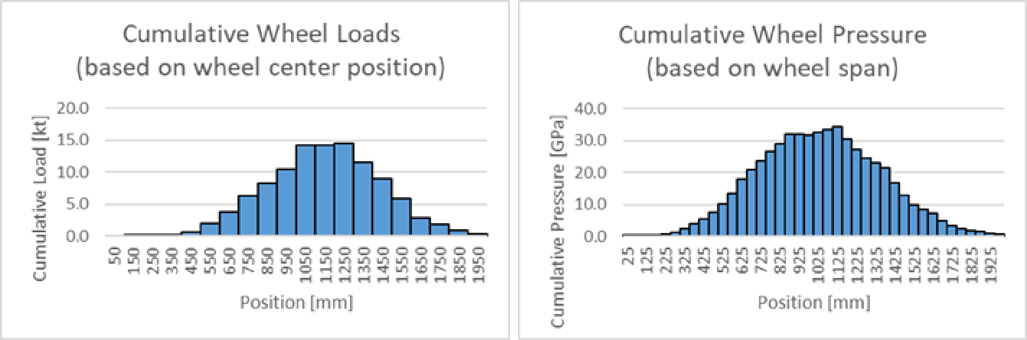

Figure 12 - Measured cumulative loads and pressures based on the lateral position of the wheel on the sensor

4. Conclusion

A new weighing sensor was designed, developed and tested with the following features: a low design height, a larger width, individually preloaded sensing elements arranged in 2 rows and embedded measurement and evaluation electronics, digitizing circuits, power supply circuits and communication elements. Algorithms have also been developed for processing data from this new type of weighing sensor. The sensor allows not only accurate weighing of vehicles, but additionally to detect various non-standard vehicle passage cases that need to be addressed in free-flow HS-WIM system applications. It also extends the possibilities of validation, compensation and completion of measurement results.

The sensor's lower height design reduces the interference with the road structure during installation, while the larger sensor width reduces the undesirable effect of road irregularities around the HS-WIM sensor and tire pattern on the weighing accuracy. The separate measurement of the response of the individual measuring elements and the integration of additional sensors and measuring electronics into the sensor body eliminates many of the problems experienced in current HS-WIM systems. There is no need to install additional sensors such as inductive loops, tilted sensors for measuring vehicle wheel position, temperature sensors. The elimination of these additional sensors and their wiring, along with the low design height of the sensor, further reduces the road interference. This extends its lifetime, reduces installation time and cost, reduces the cost of the system, and also reduces maintenance costs.

Tests have shown the new type of HS-WIM sensor to be very beneficial both in terms of its high accuracy of weight measurement and its ability to replace additional sensor technologies that currently complicate and increase the cost of the installation and also increase the purchase and maintenance cost of HS-WIM systems. In addition, the sensor provides new innovative features such as tire pressure measurement (PIM - Pressure-In-Motion or SIM - Stress-In-Motion), measurement of longitudinal forces acting on the sensor and determination of direction and speed of travel. Accurate measurement of lateral wheel position can extend current pavement wear diagnosis procedures by providing information on cumulative load and pressure in the lateral road section, thus opening the way for more accurate diagnosis and thus improving pavement maintenance and reducing the associated costs.

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