CETRA2020* 20-21 May 2021, Zagreb, Croatia
6th International Conferenceon Road and Rail Infrastructure

VEHICLE WHEEL LOAD ESTIMATION WITH FIBER OPTICAL CONTACT PATCH ELONGATION MEASUREMENT

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Abstract

Load estimation of wheels, especially for heavy vehicles, is of importance for several reasons. First safety imposes to respect loading limits for a given tire, but the variety of road infrastructures or bridges passed by a vehicle are defining constraints of larger scales as structure resistance or pavement durability. Moreover, multiple-wheels load estimation may be an efficient verification mean of the loading uniformity of goods inside a heavy vehicle.
All these reasons are justifying the interest for a continuous estimation of load for each wheel. In this context, this work aims at contributing to the development of an intelligent tire solution, able to estimate the loading applied on a wheel from the elongation measurement of the tire-to-road contact patch. As a first step of proof of concept, without regarding durability, this measurement has been done with a tire instrumented with a longitudinal, circumferential optical fiber. Measurement on a static test wheel has shown the relevance of the method to detect slight elongation of the contact patch, surrounded by compression of nearby tire areas. The Distributed Optic Fiber (DOF) measurement, widely used in the structural health monitoring domain (SHM), has been related to the force applied to the wheel, by a near linear relation, on the experienced domain of 70 mm to 110 mm for the contact length and 1.1 to 2.6 kN for the vertically applied force. As a result, demonstration is done that an intelligent tire could provide a relevant information on a given wheel load of a vehicle. The optimization of the experimental setup should lead to a robust system, usable continuously on heavy vehicles, to detect harmful loading displacements or to qualify adequacy between vehicle load and road infrastructure capacity.

Keywords: load estimation, force estimation, fiber optic, intelligent tire

1 Introduction

Knowledge of a vehicle loading is of importance for both road managers and vehicle users. Vehicle weighting and even weigh-in-motion techniques are therefore widely used and studied in this double aim. According to the cases, the loading evaluation could involve vehicle or infrastructure-based systems.
First of all, at the loading phase, the vehicle user may want to evaluate the load in order to be sure that the vehicle loading limit is respected or evaluate the quantity of raw goods sold or bought. Complementary, the infrastructure managers may want to evaluate the vehicle loads for a given road section or structure, for durability consideration or structural resistance.

DOI: https://doi.org/10.5592/CO/CETRA.2020.1121

Infrastructure-based vehicle weighting can be achieved by large scale systems, as instrumented bridges [1], with the use of concrete embedded strain transducers. In this case the B-WIM (bridge weigh-in-motion) was worked out successfully in order to evaluate ballast instability, since the bridge was hosting a railway, but the same approach is usable to monitor heavy vehicle traffic.
Weighting is useful to anticipate long-term fatigue of roads too. Rutting induced by loads applied to flexible pavement has been quantified with accelerated pavement testing facility (APTF) in [2]. Repeated loads on regular flexible pavement are then prone to generate rutting, and lead to structural rupture or vehicle aquaplaning in adverse weather conditions. Thus, vehicle loading control is an important parameter facing to the structure resistance.
Enforcement of overloaded commercial vehicles is an everyday application for weigh-in-motion. A sensitivity study has been realized in this aim [3], with piezo-ceramic and piezo-quartz sensors embedded in the pavement structure of a circular test track. Motivations were infrastructure premature deterioration, road safety and unfair competition between transport operators or modes. A precision of 10 % on axle loads has been reached, linked to metrological and trajectory parameters (dynamical loading effects are of importance too).
Road wear is another motivation to study loads of freight vehicles. In [4] it is suggested to set up infrastructure pricing to compensate the marginal cost of the road wear. Transport companies may accept higher road pricing for higher allowed axle loads and reduced transport cost, justified by higher road maintenance costs.
Load distribution at the contact patch can be achieved with a surface sensor. In [5] a multi-digit sensor has been used to measure the load and its spatial distribution (Fig. 1a and 1b). The advantage over embedded sensors is to avoid variation of road structural behavior, but there is a high constraint on wheel trajectory. Another infrastructure-related mean to measure dynamical loading has been developed and compared to a vehicle dynamometrical wheel. The Mevi system [6] provided high speed measurements, of a comparable precision with the Kistler wheel, but with the advantage to concern a large variety of vehicles. 3D forces are giving both vertical loading and rolling/braking forces (Fig. 2).

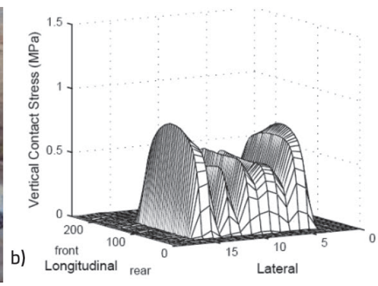


Figure 1 a) Set of instrumented tips; b) Distribution of contact pressures measured under a tire by this experimental assembly [5]

Figure 2 The Kistler wheel on the MEVI system [6]

Driving path and dynamical variations of forces are justifying the investigation of vehicle-based loading measurements. Such measurements could be deployed willingly by vehicle users for goods quantification or vehicle resistance, or be imposed by the infrastructure managers for pricing settlement.
Load estimation can be worked out by instrumented dampers and identification methodologies, as in [7] where low-cost sensor signals (two accelerometers for sprung/unsprung masses) are inputs for identification purpose with real-time observers, or even by direct wheel bearing instrumentation ([8], Fig. 3). Nevertheless by these methods the load estimation is subject to attenuation and vibratory shifts by joints and tire, and ideally measurement should be done as possibly close to the contact patch to avoid damping and resonance effects of intermediate system elements.

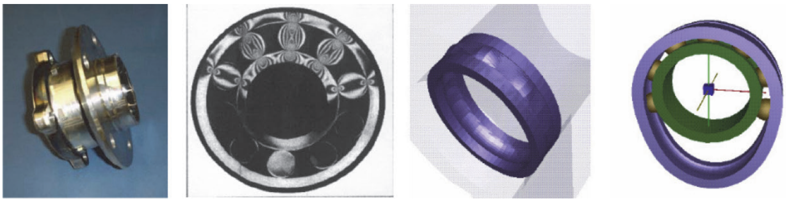


Figure 3 Dynamometer wheel bearing (SKF-TNO) [8]

At the immediate proximity of the contact patch, intelligent tire measurement solutions are involving embedded magnet and Hall effect [9] or saw sensors for tread element flexion monitoring [10] (respectively Fig. 4a and 4b).
In this context, the variation in length of the contact patch is studied in this work, as an indicator of the applied load on the wheel. Indeed, tires are composed of rubber, fibers, steel wires, and the tire belt is often modeled by an equivalent cord model [11]. Individual materials are leading to various elongation to tensile force ratios, with hysteresis loops [12] but due to a large steel wire volume fraction, the equivalent cord can be assimilated to a solid steel wire [12]. A linear fit of such a solid steel wire is given in Fig. 6. Outside the contact patch, the tire cord is subject to compression, and therefore inside the contact patch, the cord model is subject to elongation. Then, despite the fact that loading has been often evaluated with the tire vertical deformation [13], this work is centered on the elongation evaluation according to loading variations of the tire (fig 5a and 5b). The instrumentation is expected to be simpler and less dependent to the tire pressure. The estimation principle and experimental setup are described in the following.

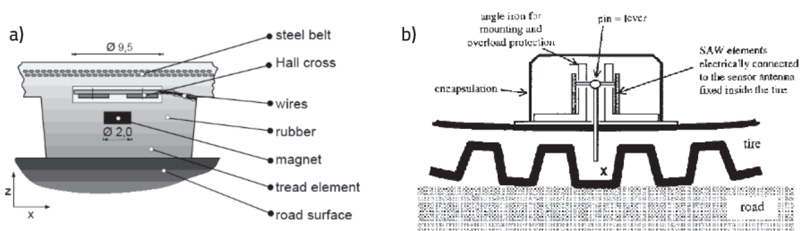


Figure 4 Instrumented tread block: a) Hall effect [9], b) SAW sensors [10]

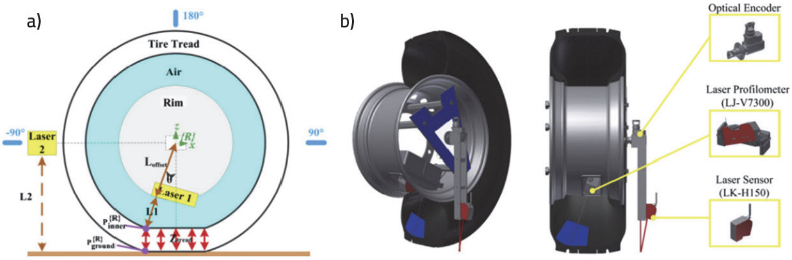
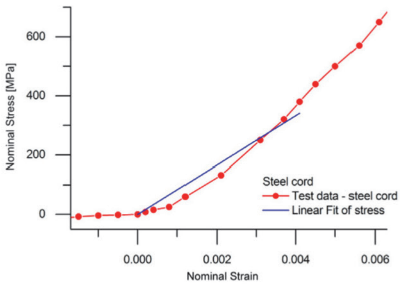


Figure 5 a) Tire deformation system; b) Prototype [13]



Linear parameters (y=ax+b) [MPa] and goodness of fit	
a	0
b	83209.40171
adjusted R^2	0.97543

Figure 6 Stress/strain linear fit (through 0/0); tire belt as a steel element [12]

2 Experimental setup

In the aim of wheel load evaluation, various loadings have been applied and the elongation of the belt in contact with the soil has been evaluated (Fig. 7). Indeed, as schematized on Fig. 8a and 8b, and while considering preceding works [11, 12], elongation of the equivalent steel cord should be in relation to the loading. This parameter has been chosen particularly for its presumable relevance, the measurement being very close to the tire-to-road contact patch. To do so, an optical fiber has been fixed inside the tire, with the help of a non-rigid epoxy-based glue, in the center of the tire belt (Fig. 7b and 7c). The loading is performed by means of a vertical press (Fig. 7a). The applied step-wise increasing force is recorded by a weighting sensor placed under the tire.

Stress is recorded all along the tire belt by means of a fiber optical method, described in the next section. Fiber sensor data are sampled at the frequency of 10 kHz. The tire loading is continuously measured and the steadiness of the temperature is monitored. The reference Rayleigh scatter frequency profile, used by the method, is established with an unloaded tire inflated at 2 bars.

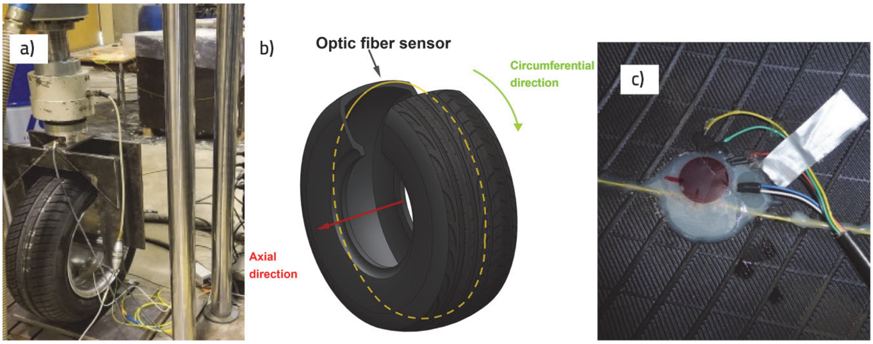


Figure 7 Instrumented tire placed in the testing frame (hydraulic loading system); b. Placement of the optical fiber in the tire; c. Detail of the rosette strain gauge beside the glued optical fiber (yellow).

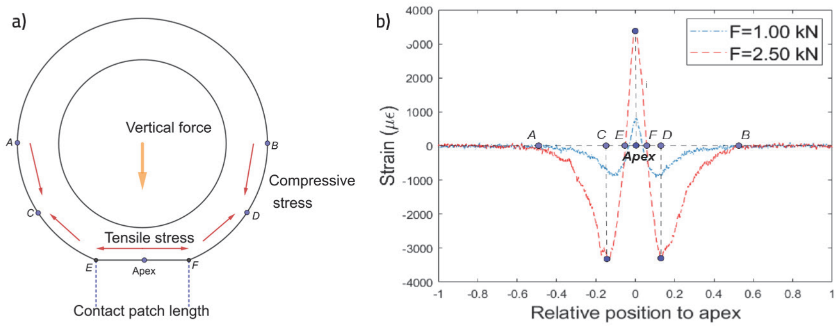


Figure 8 a. Compression and tensile stresses; b. Example of strain measured over the full belt, two loading cases (same reference points)

3 Fiber optical measurement principle

Depth of focus (DOF) Rayleigh sensing is widely used for structural health monitoring [14] and it is involving swept-wavelength interferometry [15]. The fiber index of refraction is locally altered by surrounding strain and temperature variations. Fluctuation of this index induce signal losses by backscattering, namely, the Rayleigh scattering phenomenon. Practically the local strain or temperature variations are determined by comparing the stressful scatter frequency profile to the stressless profile, or the reference profile. The spectrum frequency shift can be expressed in function of temperature and strain variations:

$$\Delta v / v = KT \cdot \Delta \mathrm{T} + K\varepsilon \cdot \Delta\varepsilon \tag{1}$$

with $\Delta v / v$ the frequency shift to the frequency v (Hz), Δ T and Δ ε respectively the temperature (°K) and the strain variations, KT and Kε proportional constants. At a constant temperature the strain can be directly computed.

The DOF method allows to locally evaluate the strain at each spatial pitch of the optical fiber, down to pitches of 0.65mm. Up to 1500 strain values can be recorded all along a 1 meter long fiber.

4 Results

Loadings have been applied to the center of the instrumented wheel with an electro-hydrostatic actuator. Four steps of increasing loading have been applied, each with a duration of 50 seconds (Fig. 9). The high loading speed of 0,14 kN/s generates peaking and relaxation values of the contact length at the establishment of each step (Fig. 9). This behavior is due to the loading speed and to the visco-elastic properties of the tire. It results in a small bounce followed by a steady section. In real-world situations, wheel loading could show rapid variations and identification of steady measurement samples is necessary.
Moreover, it can be seen on the third and fourth loading steps that these steps are divided into two "steady" sections for the applied force (ranges of 160-180-200 s for the third loading step and 210-220-270 s for the fourth loading step). This is an actuator issue, which is following a force target and occasionally switched between two close targets. New ongoing experiments would withdraw this issue by using another loading device.
Nonetheless, by using steady parts of inner contact length in the rolling direction and vertical force measurements presented in Fig. 9, representatives mean values can be established (Table 1.). The applied force can be expressed in function of the inner contact length by the mean of a simple linear regression:

$$F_v = a + b \cdot L_c \tag{2}$$

with F_v the applied vertical force (kN), L_c the length of contact (mm).
Computed regression coefficients are: a = 0.040 ; b = – 1.827.
The value of the associated coefficient of determination, r^2, is of 0.998.

There is a strong linear correlation between the applied force and the contatc patch length, measured by an optical fiber, as it has been already verified with a simplified model (Fig. 6, [12]). This correlation is obtained over a large variation of the applied force of 1:2.29 and a large variation of the contact length of 1:1.48. However new experiments are planned with a more progressive loading.

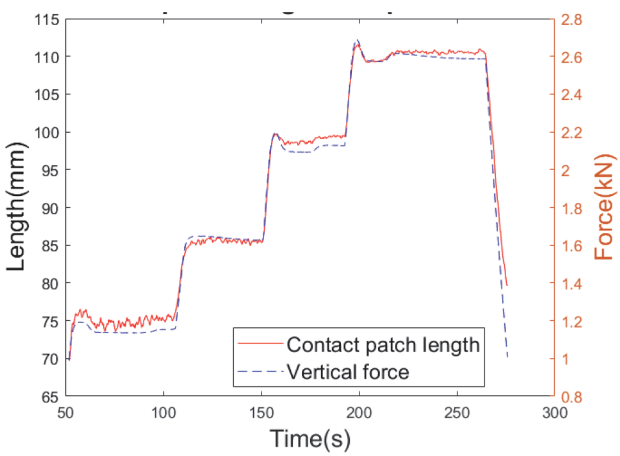


Figure 9 Correlation of the contact patch length to the wheel load

Table 1 Contact length and applied force (mean values).

Loading case	Mean value: Contact length [mm]	Mean value: Applied force [kN]
1	74.6	1.1367
2	85.6	1.6374
3	99.3	2.1200
4	110.5	2.5977

5 Conclusion

Measurement of wheel loading is of importance, to ensure the safe usage of tires or infrastructures. After having reviewed the existing methods both infrastructure-based and vehicle-embedded, this work demonstrates the possibility to use Distributed Optic Fiber (DOF) measurement for wheel loading evaluation.
This measurement has been done with a longitudinal, circumferential optical fiber, glued on the inner side of a tire belt. Measurements on a non-rotating test wheel have shown the relevance of the method to detect slight elongation of the contact patch, surrounded by compression of nearby tire areas. The measured elongation has been found to be related to the force applied to the wheel by a near linear relation, on the experienced domain of: 70mm to 110mm for the contact length and 1.1 to 2.6 kN for the vertically applied force.
Intelligent tire could then provide relevant information on a wheel load, and at the closest location to the tire-to-road patch, which minimizes intermediate materials as dampers or even tire sidewalls. The durability of the optical fiber inside a rolling tire is an issue, but a short fiber, of about 1cm, could be used without material fatigue and it is an ongoing work.

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