

In-tire load estimation for autonomous vehicle safe driving strategies

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Safe driving

Particularly without human supervision (autonomous vh), sensors are needed: cameras, lasers, lidar.

Vehicle weight measurement is important too (braking dynamics, stability in curves)

Autonomous vehicles

Number of passengers and luggages are not known, so the weight should be estimated at each stop of an autonomous vehicle.

Weight estimation systems

Roadside Weight in motion system exist but for an autonomous vehicle with indefinite routes an onboard system is preferable, in each vehicle.

This work

An experimental system is developed to estimate the load applied to a non-rolling wheel:

- The elongation of the tire to road contact patch is evaluated by a fiber optical sensor since it is reported to be in relation to the load (Garcia-Pozuelo 2019, Aguilar-Martinez 2015).
- The load is also estimated from the tire deflection by using a laser sensor.
- Pressure sensitive paper is used at the tire to road interface as a load comparison.

Limitations and perspectives

Experimental work focused on a non-rolling wheel, with an optical fiber glued inside the tire belt. An integration of the fiber in the tire structure should be more durable, for rolling tires. Nevertheless static measurements at each vehicle stop are sufficient to estimate load & impacts on vehicle safety.

Road systems

Weigh in motion systems (caltrans, kistler, captels,...) and force estimation with road sensors: Coiret 2008, De Beer 1996...

Onboard systems

Dampers (Van Raden 1967), suspensions (Tarter 1995), axles (O'Dea 1995), junctions (Fredrickson 2016).

This work

Onboard to be used at any traveling point ; in the tire to avoid the large diversity in vehicle suspensions and geometry. → Intelligent Tire research context.

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Passenger car tyre:

185/65R15, inflated to
2.1 bars.

Sidewall: 1 polyester ply,

tire belt: 1 polyester/2
steel/1 polyamide plies

Vertical force applied
from 2000 N to 5000 N,
by 500 N increments each
30 seconds. force cage
equipped with a loading
cell.

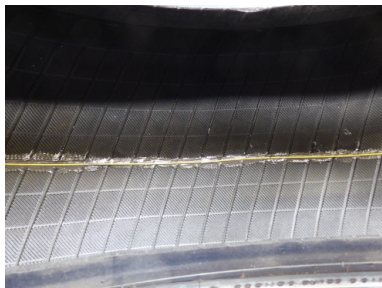
Three load variation
speeds of 50 N/s, 100
N/s and 500N/s:

L_{50} , L_{100} and L_{500} .



Measurements related to load evaluation:

Tire belt elongation over its circumference: optical fiber glued.
Allowed max. strain measurement of $10,000 \mu\epsilon$ (our experiment: $4000 \mu\epsilon$ max.) Distributed strain over the whole tire circumference at a sampling frequency of 10 Hz.



Tire deflection: laser sensor screwed on the rim ($0.2V/mm$).

Air pressure: sensor on the rim ($2.9V/bar$).

Load and its distribution: Pressure sensitive Fuji paper, bellow the tire.



Distributed Optical Fiber Sensors (DOFS) are based on reflectometry by involving swept-wavelength interferometry [Froggatt 1998];

Ability to monitor strain all over an element (→ Structural Health Monitoring [bassil 2019]).

The fiber index of refraction is locally altered by strain and temperature variations; thus the frequency shift can be expressed as:

$$\frac{\Delta\nu}{\nu} = K_T \Delta T + K_\epsilon \Delta\epsilon, \quad (2)$$

(ΔT , $\Delta\epsilon$ temperature and strain variations; K_T , K_ϵ constants)

Spatial resolution of our DOF sensor is of 0.65 mm, with 1500 strain values over 1 meter long fiber.

1 Introduction

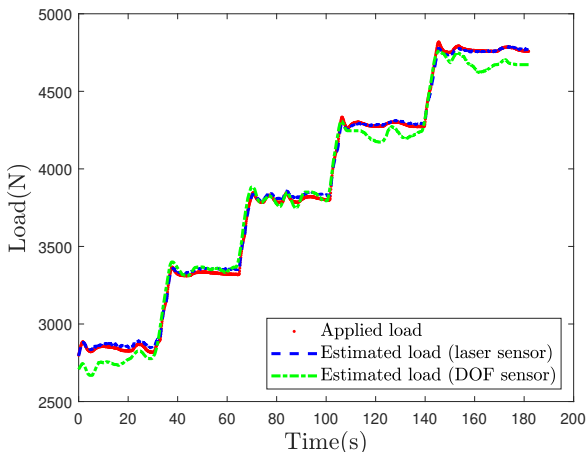
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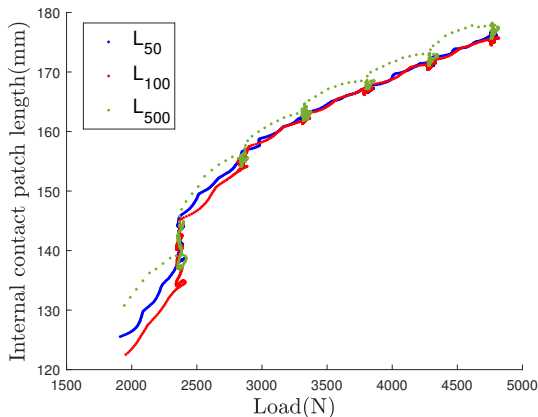
Load estimation from laser and DOF sensor

- Laser sensor: very good load estimation for the full loading range
- DOF sensor: good evaluation for the 3000 / 4400 N range, but error up to 5% outside this range.
- laser sensor remains dependent to a unique angular position (pointed vertically to the center of the contact patch)



Contact patch length estimation by DOF sensor

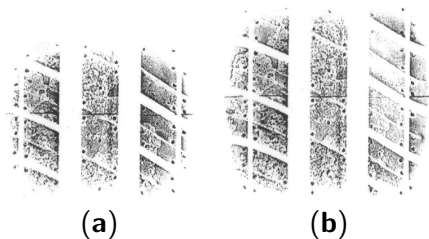
- 30s stationary step / each 500N
- 3 speed transition values L_{50} , L_{100} and L_{500}
- High speed transitions are showing non-linear variations, but with same stationary values as the low speed transition
- load/length relation is quite linear above 2500N. DOF sensor: mean of wheel load estimation, through internal contact patch length evaluation.



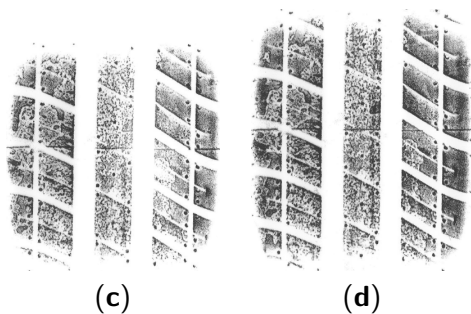
Tire footprint on Fuji pressure sensitive paper: vertical load of 2000 N **(a)** and 3000 N **(b)**.

Pictures are from a flatbed scanner, 600 dpi, and a 0.35 scale here on this presentation.

- tread pattern + dots due to rubber elements
- the longitudinal length is increasing more than the transverse width with load increase



At same scale, for vertical load of 4000 N (c) and 5000 N (d).



This table: paper footprint width, length in pixels and millimeter and DOF internal length

Wheel load (kN)	Width (<i>pixels</i>)	Length (<i>pixels</i>)	Pixel count	Length (<i>mm</i>)	DOF internal length (<i>mm</i>)
2	2672	2260	6,038,720	95.7	127
3	2996	2772	8,304,912	117.3	157
4	3096	3292	10,178,864	139.4	168
5	3188	3828	12,203,664	162.1	176

Pixel count is realized by means of a linux script on 8 bits converted footprint pictures (softwares: imagemagic, convert, histogram)

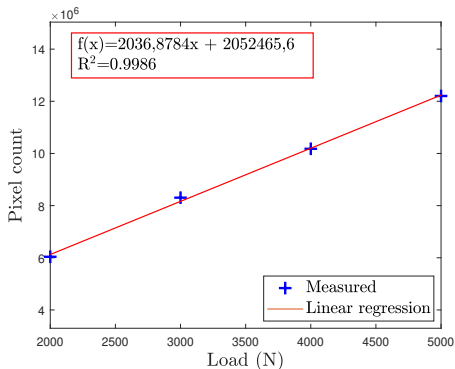
Pixel count is in direct relation to the loading

(R^2 regression coefficient 0.9986)

- load: integral of normal pressure over the contact patch area

- Each pixel correspond to the reach of the local activation pressure (local ink capsule break).

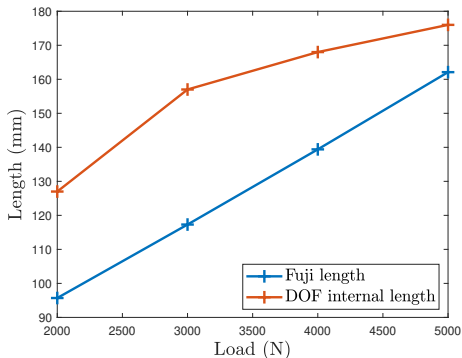
- The pixel count can be converted in contact patch surface, the equivalent surface with a pressure higher than the paper activation pressure: 10,822 14,883 18,241 and 21,870 mm^2 respectively for 2, 3, 4 and 5kN load cases.



contact patch length from DOF sensor and Fuji footprints / loading

Length are differing:

- DOF: internal contact patch length whereas Fuji paper is related to external tire footprint
- Fuji length is greater on tire sides, probably due to sidewalls loading; DOF sensor situated in the tire center line
- Contact with low pressure: no pixel, lower Fuji length



→ Fuji paper: good mean to evaluate the *loading* by surface estimation but length comparison to DOF is not relevant for structural reasons

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- Autonomous vehicles would take advantage of having a loading information, globally or for each wheel
- weight affects both braking dynamics and stability in curves. knowledge at least at each vehicle start (absence of driver)
- infrastructure-based sensors exist but tire related systems are preferable if the vehicles can start routes at indefinite points
- the elongation of the tire to road contact patch is estimated by means of an internal optical fiber sensor based on Rayleigh scattering interferometry
- a laser sensor situated inside the tire and sheets of pressure sensitive Fuji papers are used as comparison systems
- as a results for loads of 2.8 to 4.8 kN the optical sensor and the laser sensor are leading to load estimation error lower than 3%

- pressure sensitive Fuji paper is allowing an estimation of the total load but contact patch length are not comparable to DOF sensor, for structural reasons
- In perspective, for autonomous vehicles, the optical fiber solution can deliver a load estimation independently to the wheel angle position, at any vehicle start, without human intervention
- a more advanced development of this prototype could allow the continuous load estimation for a rolling vehicle but issues such as tire temperature elevation or tire rigidity alteration would have to be addressed
- another issue: resisting to rolling constraints in a full tire life. Manufacturers could use optical fiber embedded in the tire belt, associated to low-cost fiber interrogators.