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ROAD SAFETY ASSESSMENT IN CURVES BASED ON A ROAD EMBEDDED TIRE TO ROAD FRICTION SENSOR

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Abstract

Road safety relies mostly on available tire to road grip regarding to the forces required by a vehicle in a given dynamic situation. For example safety issues can occur when deceleration required forces exceeding the tire/road grip potential. Issues are much critical while traveling in a curve with a coupled longitudinal/transverse grip demand. Instrumented vehicles can be used in order to evaluate the available tire to road grip in rolling situations, but it remains linked to a dedicated vehicle and models have to be use to extrapolate these evaluations to various vehicles. The aim of this work is to propose a sensor embedded in the road infrastructure to evaluate the longitudinal and transverse grip demand of any traveling vehicle. A 6 axis sensor is embedded in a road test track, under a piece of the real road upper layer. Measurement are made at a acquisition rate of 2500 Hz and forces measuring ranges are of 2500 daN (vertical axis) and 750 daN (tangential). Measurements are compared to on-board measurement with a vehicle instrumented with dynamometric wheels. Three situations are experienced in a 100 meters curve: traveling at a given speed and traveling while accelerating or braking moderately, and for three vehicle speeds of 40, 60 and 80 km/h. Force evaluation from the two systems are differing of only 5 % for the vertical force and 10 % for the tangential forces. The differences are lower for the higher grip demands. For example moderate braking from 70 km/h in curve lead to 0.23 and 0.25 longitudinal friction coefficients (LFC) for road sensor and dynamometric wheel, and to 0.17 and 0.19 transversal friction coefficients (TFC). In perspectives, evaluations of an excessive grip demand could result in solutions as lowering the designed speed or improving the road surface layer.

Keywords: road infrastructure, energy moderation, ecodriving, speed policy

1 Introduction

Road safety relies on passive and active techniques, with respective relevance before and after an accident occurrence. Active safety devices as airbags are important but the passive safety is in the first line to avoid an accident and its consequences. Tire to road grip level is one of the most important factor of the road passive safety factors, since this grip represents the only mean to develop decelerating or steering forces.

For example safety issues can occur when deceleration required forces exceeding the tire/road grip potential. Issues are much critical while traveling in a curve with a coupled longitudinal/transverse grip demand. In [1] a large review is proposed to qualify the tire to road grip depending on surfaces conditions such as wetting state, pollutants and temperature, and depending on vehicle and driving conditions. [1] points out the combined importance of tires, which can be performance-labeled, and pavement classification.

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In [2] it is again stated that grip level is difficult to estimate under standard driving conditions. Therefore a lot of estimation methods can be distinguished such as sensor-based methods, non-parametric methods using generally black-box models and parametric methods including physical models. One of the most popular learning model is also presented, the Pacejka's model, combining likelihood and Monte Carlo Markov Chain.

From a driving task point of view, the knowledge of this grip level is of relevance to adapt the driving behavior, which could involve an experienced or inexperienced driver or even no driver at all in the case of the autonomous vehicles. It is an important information for the road manager in the process of road maintenance.

As a technical solution [3] developed an approach to estimate the grip level in real time with on-board sensors, with the aim to detect slip variation of 1 to 1000. This work shown the possibility to distinguish a wet roadway from a dry one, but without achieving a fine grip estimation.

In the research field instrumented vehicles can be used in order to evaluate the available tire to road grip in rolling situations. In [4] it is reminded that for the forces acting of the wheels should be estimated for the real operating conditions and not only for only the vehicle weight and load. In this study the wheel weight is considered as an important factor thus being unsprung masses and dynamometric wheels of the same weight as standard wheels are proposed in order to estimated the wheel load in given driving situations. Such wheels remains too expansive to be largely deployed on vehicles (Figure 1).

In [5] a strain-based intelligent tire is developed to estimate the situations of loss of control, by calculating the grip level. Authors are underlining that the limit of friction is not known and that it depends on road properties, wetting states, tire wear and so on. In this work an intelligent algorithm is proposed to estimate this limit of adherence, by the integration of the LuGre model. For that the transition between stick/slip and full slip is evaluated by the means of the force sensor. According to [5] the early detection of grip level by this type of intelligent tire could help the control systems to react against vehicle's loss of control. This approach is promising but the road conditions remains difficult to estimate by the on-board systems.

Figure 1 Dynamometrical wheel (source: kistler.com)

Force sensing bearings have been experimented to evaluated the grip in order to enhance the vehicle control systems [6] or to investigate the potential of estimation of vehicle sideslip [7] but these systems still lack of road conditions estimation in order to detect the maximum limit of the grip potential.

Road sensors approaches exists to estimate grip level, such as Stress-In-Motion system (SIM) developed since 1994 [8, 9] for capturing tri-axial tire to road interaction. It consist in a measuring pad with a transverse array of 21 sensing elements (Figure 2), but road texture and conditions are not taken into account.

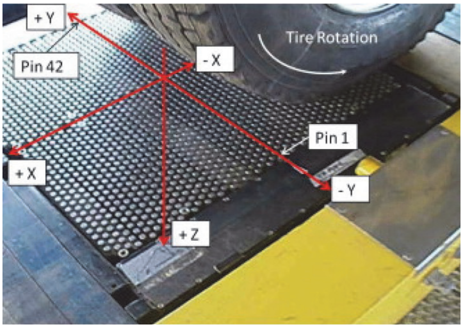

Figure 2 Stress-In-Motion (SIM) system (source: [9], fair use)

The aim of this work is to propose a sensor embedded in the road infrastructure to evaluate the longitudinal and transverse grip demand of any traveling vehicle. This sensor will not be more able to determine the grip limit of a given vehicle compared to on-board systems, but while measuring applied forces for all traveling vehicles it should allow the determination of a statistical grip limit.
This sensor consist on a 3D load cell place underneath a portion of the road surface. The knowledge of the actual grip demand for a whole traffic, and its evolution in time, and facing environmental conditions as wetting state and temperature will allow a statistical and dynamical determination of grip level. Thus a road benefiting of such a sensor could propose a dynamical speed enforcement, adapted to road wear, wetting state and seasonal temperature. Moreover it could be a decision making tool for road surface management and infrastructure works.

2 Experimental setup

A 6 axis sensor, forces and moments, is embedded in a road test track, under a piece of the real road upper layer (Figure 3). Measurement are made at a acquisition rate of 2500 Hz and forces measuring ranges are of 2500 daN (vertical axis) and 750 daN (tangential). Measurements are compared to on-board measurement with a vehicle instrumented with a dynamometric wheel. Three situations are experienced in a 100 meters curve (Figure 4): traveling at a given speed and traveling while accelerating or braking moderately, and for several vehicle speeds of about 40, 60 and 80 km/h.

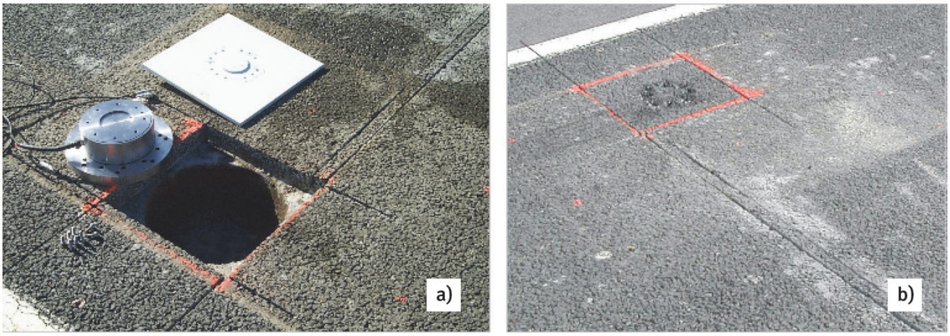

Figure 3 Road sensor: sensor detailed view (left), and final installation in the road pavement (right)

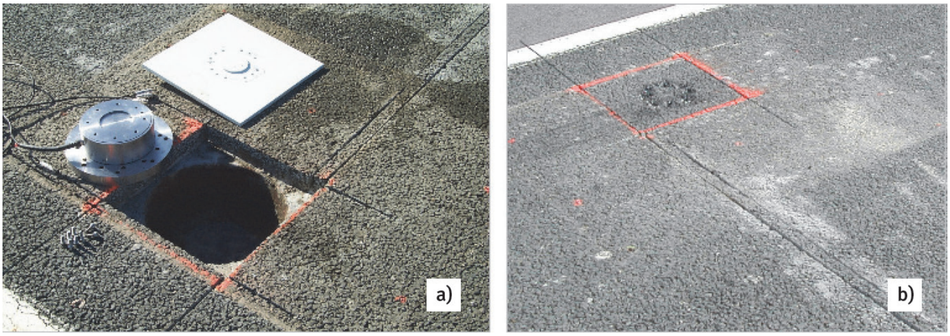

Figure 4 a) Sensor location in the curved test track; b) sensor under the vehicle instrumented wheel

3 Results from road sensor and instrumented vehicle

Forces and moments are recorded simultaneously by the road sensor and the dynamometric wheel. Several speeds are experienced, while driving at constant speed, or accelerating or braking moderately. The speed is determined by the means of an optical on-board system (correvit). In this section measurements from the two systems are compared in the perspective to use the road sensor alone as a long-term grip monitoring system on open roads.

3.1 Vehicle traveling at constant speed

The Figure 5 presents the forces and moments evaluated by the road sensor for the 40km/h speed case. The left rise and right lowering parts of each signal correspond to the entrance and leaving of the tire inside and outside the measuring area. Signals are selected within this area to establish mean values that are given in Table 1.

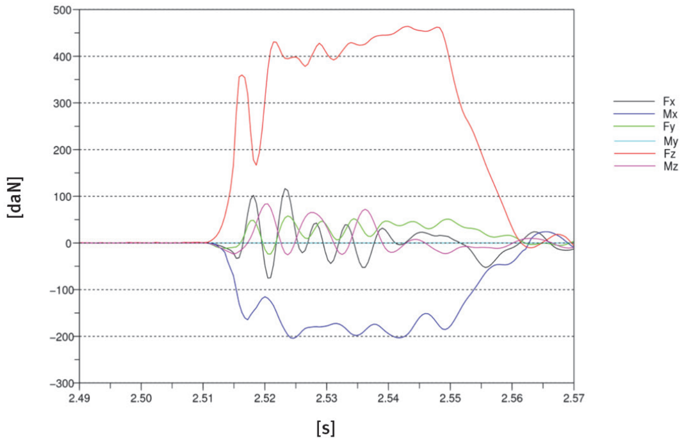

Figure 5 Road sensor measurements (Dan and N.m) in function of time (s); V40 speed case

Means values are indicating that the vertical force Fz is given similarly by the two systems, with a difference of about 5 %. Fx values are low for this constant speed case, especially for the 40 km/h speed for which systems are underestimating the probably higher value. Nevertheless Fx and Fy values are differing from 5, 7 and 15 % (Table 2), which is quite satisfying if considering that each system errors are added together.

Table 1 Measuring results; constant speed cases

Speed label	**Sensor**	**Vx**$_{opt}$	**Vy**$_{opt}$	**Fx** [daN]	**Fy** [daN]	**Fz** [daN]
V40	road			4	42	435
V40	wheel	41,6	-0,4	-1	35	460
V60	road			55	86	420
V60	wheel	59,7	-0,8	44	69	470
V80	road			93	194	490
V80	wheel	81,9	-2	98	227	526

Table 2 Force ratio between the wheel and road systems

Speed label	**D**$_{Fx}$	**D**$_{Fy}$	**D**$_{Fz}$
V40	125,00	16,67	-5,43
V60	20,00	19,77	-10,64
V80	-5,10	-14,54	-6,84

3.2 Vehicle traveling while accelerating moderately

With a slight acceleration, for two speed cases, the differential error is only about 3 and 6 % for Fz, and about 12 and 13 % for Fx and Fy at the 50km/h speed case. The low speed case of 30km/h is showing out large differential errors of more than 30 %. It should be remembered that the road system is dimensioned for 750kN and so this speed case is only using one tenth of the sensor full scale.

Table 3 Measuring results; acceleration cases

Speed label	**Sensor**	**Vx**$_{opt}$	**Vy**$_{opt}$	**Fx** [daN]	**Fy** [daN]	**Fz** [daN]
A30	road			47	40	423
A30	wheel	36	-0,2	30	25	437
A50	road			54	84	38
A50	wheel	53,8	-0,7	47	74	467

Table 4 Force ratio between the wheel and road systems

Speed label	**D**$_{Fx}$	**D**$_{Fy}$	**D**$_{Fz}$
A30	36,17	37,50	-3,20
A50	12,96	11,90	-6,21

3.3 Vehicle traveling while braking moderately

With a moderate braking maneuver, for two speed cases, the differential error is only about 4/5 % for Fz, and between 10/14 % for Fx and Fy at the 47 and 56km/h speed cases (Table 5 and 6). Intended test speed were of 60 and 70 km/h but by braking the vehicle reached the road sensor at sensible lower speeds. Road sensor signals are given in Figure 6 to show the negative braking Fx force and positive Fy transverse force.

Table 5 Measuring results; braking cases

Speed label	**Sensor**	**Vx_opt**	**Vy_opt**	**Fx** [daN]	**Fy** [daN]	**Fz** [daN]
B60	road			-120	50	475
B60	wheel	46,8	-0,7	-135	57	494
B70	road			-113	82	486
B70	wheel	55,6	-0,6	-126	95	513

Table 6 Absolute and relative differences; braking cases

Speed label	**D Fx**	**D Fy**	**D Fz**
B60	11,11	-12,28	-3,85
B70	10,32	-13,68	-5,26

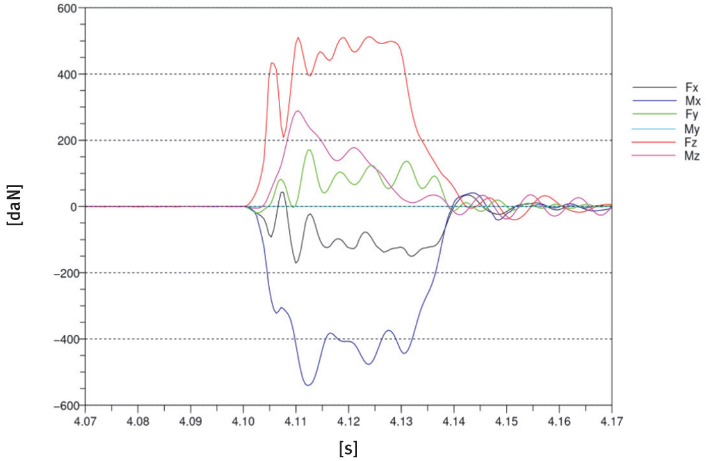

Figure 6 Road sensor measurements (daN and Nm) in function of time (s); B70 speed case

3.4 Tire to road grip estimation from the two measurement systems

Usually for road grip estimation the longitudinal and transverse coefficient CFL and CFT are considered. For the two braking cases these coefficient are computed and are given in Table 7. Road and wheel sensors are differing only about 10 %, for nonetheless low grip solicitations, since grip values are usually of 1 for dry conditions and 0.5 for wet conditions.

Such results are confirming that the road sensor is able to continuously measure the CFT and CFL mobilized by any vehicle traveling on it, on a given road. If the manager has the aim to rebuilt the road surface at a 0.3 CFL value for example, the road can be considered in good condition as long as CFL values over 0.5 are regularly recorded. Mean values of mobilized grip could be useful to estimate environmental impact as rain or low temperatures.

Table 7 longitudinal and transversal coefficients

Speed label	Sensor	CFL	CFT
B60	road	-0,25	0,11
	wheel	-0,27	0,12
B70	road	-0,23	0,17
	wheel	-0,25	0,19

4 Conclusion

Road safety is very sensitive to potential tire to road grip. The maximum grip level can be estimated by on-board systems or road systems but these systems are often very complex and are dedicated to research purposes. This work is about the use of a quite simple and robust system embedded in a road and able to estimate the grip demand of any vehicle. This road sensor is compared to a high-end dynamometric wheel and results are confirming a quite good correlation between the measurement from the two systems.
Indeed tangential forces differences are lower than 10 % to 15 % for moderate speeds and for rolling, accelerating or braking situations. Moreover measurement differences are lowering when speeds are increasing, so that differences should be very low for critical high speeds, since large forces are more in agreement with the sensors full scale. As a result longitudinal and transverse friction coefficient estimated from the two systems are rather close, in a 10 % confidence interval. In perspective a road embedded sensor could be use in a given road to record all vehicle grip demand and to statistically verify is the road is still able to offer a satisfying grip level. Environmental grip variations could be monitored too in order to take temporary management decisions as speed limitations.

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