

Concurrent evaluation of the tire/pavement contact torsor by means of both a dynamometer wheel and a road infrastructure-integrated system

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■ ABSTRACT

Knowledge of the forces exerted by vehicle wheels on a pavement facilitates the evaluation of control loss risk. More specifically, for experimental studies, such forces when measured can be correlated with tire skidding in order to consolidate the dynamic behavior analysis of a vehicle. Given the costly dynamometer wheels conventionally introduced for these studies, an alternative system has been developed at the LCPC Laboratory. Composed of an instrumented pavement section, this system enables measuring components of the contact torsor present between a tire and a pavement. Its validation will be performed in this article by means of comparing results derived from a vehicle equipped with a dynamometer wheel. Findings will be provided for situations of pure one-wheel turning situations, constant speed driving and emergency braking, under either dry or lubricated contact conditions. Even though such a system cannot yield precise values of forces over an entire trajectory, its inclusion in the pavement is still able to locally acquire the contact torsor, to a degree of precision that rivals the output of a dynamometer wheel. This holds true for any vehicle, even one that has not been instrumented. Use of this system on a road section could eventually authorize evaluation of the section in terms of forces mobilized by a heterogeneous group of vehicles. As for potential applications, it would be possible to complement the road speed observation data from existing network stations with measurements of skid resistance actually being mobilized by various road user categories, in the general aim of contributing to safety gains on road sections identified as especially dangerous.

Évaluation concurrentielle du torseur de contact pneumatique/chaussée au moyen d'une roue dynamométrique et d'un système intégré à l'infrastructure routière

■ RÉSUMÉ

La connaissance des efforts exercés par les roues d'un véhicule sur une chaussée facilite l'évaluation des risques de perte de contrôle. En particulier, pour des études expérimentales, de tels efforts mesurés peuvent être rapportés aux dérives des pneumatiques pour consolider l'analyse du comportement dynamique d'un véhicule. Face aux coûteuses roues dynamométriques traditionnellement employées pour cela, un système alternatif a été développé au LCPC. Constitué d'un élément de chaussée instrumenté, ce système permet la mesure des composantes du torseur de contact entre un pneumatique et une chaussée. Sa validation est ici établie par confrontation à un véhicule muni d'une roue dynamométrique. Des résultats sont présentés pour des situations de braquage pur d'une roue, de roulement à vitesse constante et de freinage d'urgence, en contact sec ou lubrifié. Bien qu'il ne donne pas accès à la connaissance des efforts tout au long d'une trajectoire, un tel système intégré à la chaussée permet d'acquérir localement le torseur de contact avec un ordre de précision semblable à celui d'une roue dynamométrique et ce pour tout véhicule, même dénué d'instrumentation. L'emploi de ce système sur une section routière pourrait autoriser l'évaluation de celle-ci vis-à-vis des sollicitations mobilisées par un ensemble varié de véhicules. En perspectives d'application, il serait possible de compléter les observatoires de vitesse existant sur le réseau routier par des mesures de l'adhérence réellement mobilisée par les divers usagers, dans le but général de contribuer au bilan de sécurité des voies répertoriées comme particulièrement dangereuses.

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INTRODUCTION

Road safety has improved considerably over the past several years, thanks in particular to a more repressive attitude towards unsafe driving behavior (i.e. automatic radar control of speeds). However, since 2007, this trend has run its course. While the benefits of control-penalty strategies cannot be disputed, the time has certainly come to introduce complementary approaches: the road operator can definitely further optimize the status and rules of infrastructure use, through improved knowledge of the relations existing between accident statistics and road characteristics. Against this backdrop, the work program set forth in this article is intended to develop and qualify experimental resources specific to studying vehicle *controllability*.

Controllability will be defined by the existence of controls applicable to a vehicle traveling along a viable trajectory (i.e. remaining within the traffic lane while maintaining a speed well adapted to both the flow of traffic and local restrictions). This controllability heavily depends on the contact forces mobilizable between tires and pavement. During experimental research, such forces may be measured either directly by means of dynamometer wheels fitted onto test vehicles (a costly approach) or indirectly via friction coefficients relative to a reference tire. The dynamometric wheel represents the preferred instrumentation for automakers seeking to validate the controllability of their prototypes. Yet this approach also introduces obstacles to studying a special pavement designed to accommodate an array of vehicle types, given the necessity of implementing various models of these — very expensive — dynamometer wheels. LCPC has thus developed an alternative system that enables measuring contact forces by means of a specific pavement component (the system is called by its French acronym MEVI, which stands for Infrastructure-based Measurement of Forces applied by a Vehicle). Installation of these devices on a number of road test sections would serve to authorize a controllability evaluation for multiple vehicle-pavement combinations.

As an initial validation step, output from the MEVI system was compared with onboard force estimations, via either a frontal braking procedure or interpretation of kinematic measurements [1,2]. System performance was also compared in [3] with homogeneity results from the French fleet of grip-testing vehicles during cross-referenced testing (equipment commonly used during road maintenance tasks).

Benefiting since that time from use of a dynamometer wheel, we are now given the opportunity to draw comparisons with the MEVI system. Both devices focus on evaluating the global contact torsor generated at the tire/pavement interface. While MEVI enables a near-direct measurement — owing to the introduction of transport laws — of the contact torsor, the dynamometer hub conducts the measurement only after filtering by the tire [4]. The viscoelastic behavior of the tire actually distorts the dynamometer hub measurement by generating delays and damping (experimentally speaking, these influences can nonetheless be limited by favoring quasi-stationary tire operating modes). Moreover, additional complex instrumentation would be required to establish the correspondence existing between benchmarks related respectively to the dynamometer hub and the contact zone (measurements of steering angle, vehicle body angle, deflection and slack, etc.).

Following a brief presentation of the state of the art on ways for measuring contact forces, the innovative MEVI system will be detailed. The next section will focus on system validation by providing a comparison with a dynamometer wheel, which serves as the reference system currently employed by automakers (see [fig. 1](#)).

CONTACT FORCE MEASUREMENT RESOURCES

A range of methods exists for evaluating the contact torsor transmitted between tire and pavement. We will be presenting hereafter a number of these methods, in distinguishing onboard systems from systems integrated into the infrastructure.

The majority of systems are confined to the global evaluation of the torsor transmitted at the tire/pavement interface. Though the actual distribution of forces at this interface is indeed quite distinct

figure 1
The Kistler wheel on the MEVI system



from the uniform loading model [5,6] (fig. 2), it is nonetheless difficult to experimentally obtain this distribution for high crossing speeds while incorporating pavement surfacing properties.

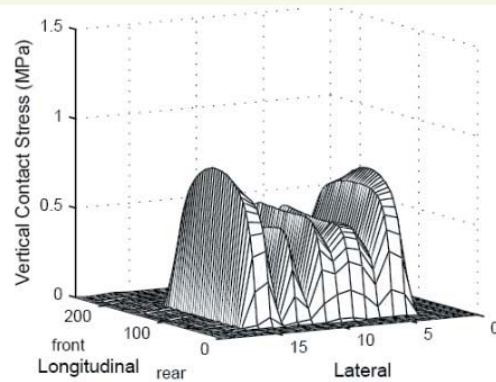


figure 2

extracted from [7]

a: Set of instrumented tips
b: Distribution of contact pressures measured under a tire by this experimental assembly

a | b

■ Onboard evaluations (from a test vehicle)

The so-called *kinetic balance* method offers a means for evaluating contact forces based on measurements of the difference in dynamic state of a vehicle in a braking situation between two points on its trajectory. The basic principle of the dynamic is utilized in order to estimate forces based on the average deceleration measured by proprioceptive sensors. The braking friction coefficient is given by:

$$\mu_x = \frac{\Delta V}{g \cdot \Delta t} \quad (1)$$

with ΔV being the difference between speeds at two points in time separated by interval Δt

This approach only yields an indication of longitudinal skid resistance averaged over time for all four wheels (or at best, for the two front axle wheels should a front braking procedure be employed). The braking friction coefficient, defined as the ratio F_x/F_z , is expressed in this case as:

$$\mu_x = \frac{F_x}{F_z} = \frac{L \cdot \left(\frac{V_2^2 - V_1^2}{2d} - \left(\alpha + \beta \cdot \left(\frac{V_1 + V_2}{2} \right)^2 \right) \right)}{L - x_g + h \cdot \frac{V_2^2 - V_1^2}{2d}} \quad (2)$$

where x_g is the longitudinal position of the center of gravity, L the vehicle's wheelbase, h the height of the center of gravity, α and β constants to be determined by means of free wheel deceleration tests, d the braking distance, V_1 and V_2 the speeds at the beginning and end of the given braking period, respectively.

The value of this method lies in its economic advantages: quick adaptation to a wide range of vehicles, relatively simple sensors (accelerometers or GPS/inertial/buscan hybrid system such as vbox3 produced by Racelogic™).

The dynamometric wheel rims enable directly measuring the torsor acting between wheel hub and rim runout (fig. 3). The technique applied [8] serves to measure the full contact torsor with a linearity of less than 0.5% (use of strain gauges; three-axis forces and moments). The fact that the design must be repeated for each vehicle, coupled with the high cost (on the order of 100,000 euros per wheel) limits this method to use by automakers in R&D studies or dedicated test vehicles. On a given trajectory, measurement may remain continuous up to a frequency of 500 Hz.

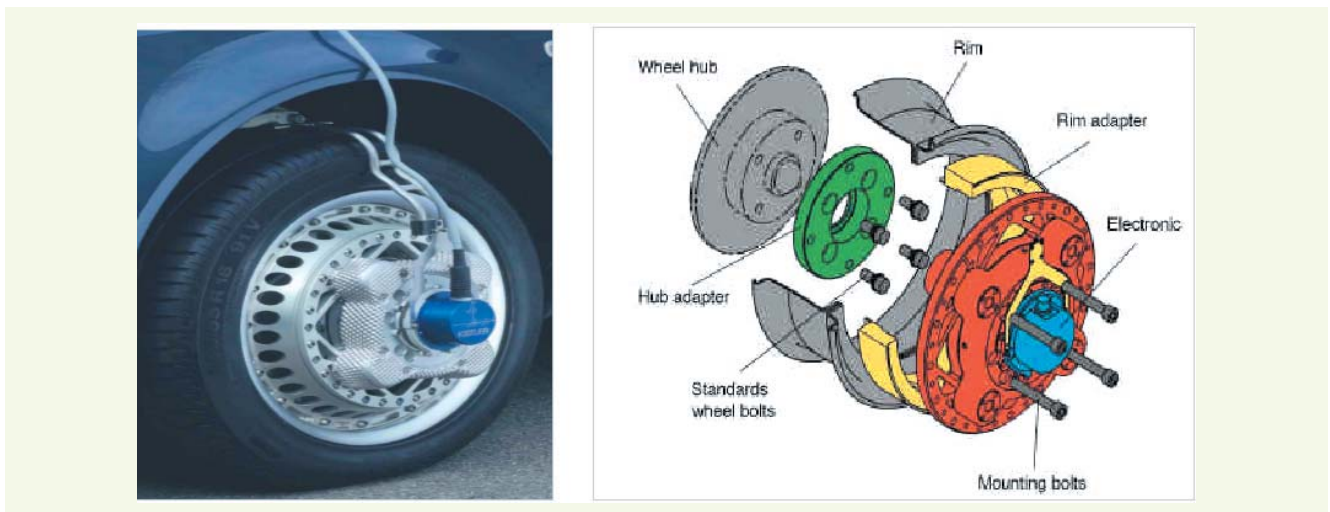


figure 3

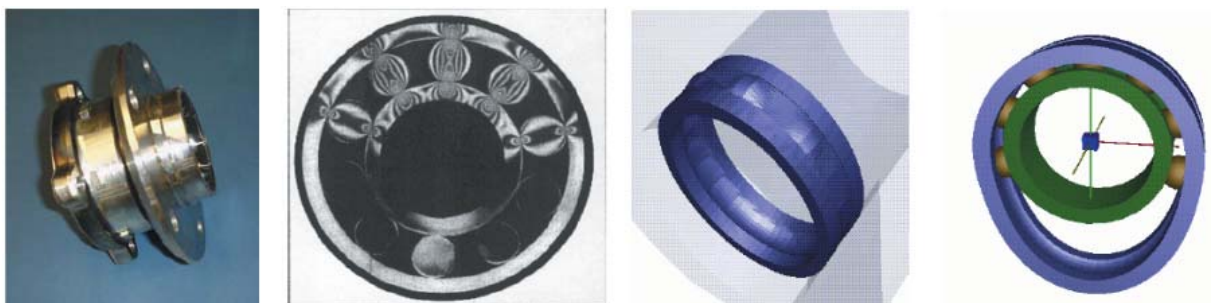
Dynamometric wheel rims [8]

a: Overview
b: Blow-up diagram

The development of dynamometer wheel bearings [9] (fig. 4) could lead to widespread use of dynamometer wheel measurements, thus making it possible to apply the method to passenger cars as well. This promising technique allows determining the forces acting between wheel axis and rim based on deformations of the outer bearing ring (three-dimensional forces, maximum error of 2%). Research has also been conducted on the topic of the *smart tire*: the instrumentation of a tread block has typically been performed to determine deformations and estimate the level of skid resistance actually mobilized [10,11] (fig. 5). One of the development goals of the smart tire is to provide ABS/ESP systems with an early indication of any skid resistance deterioration [12].

figure 4

Dynamometer wheel bearing (SKF-TNO) [9]



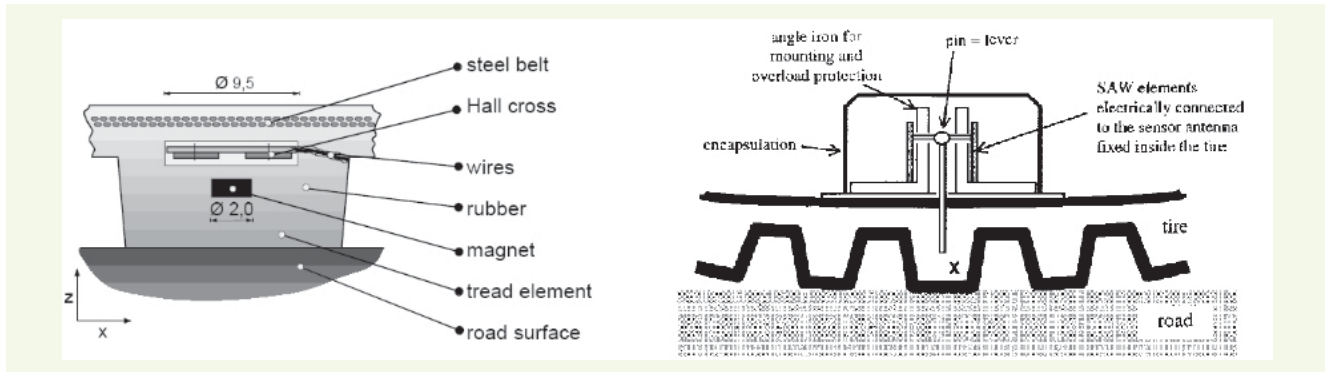


figure 5

Instrumented tread block

a: Hall effect [10]

b: SAW sensors [11]

a | b

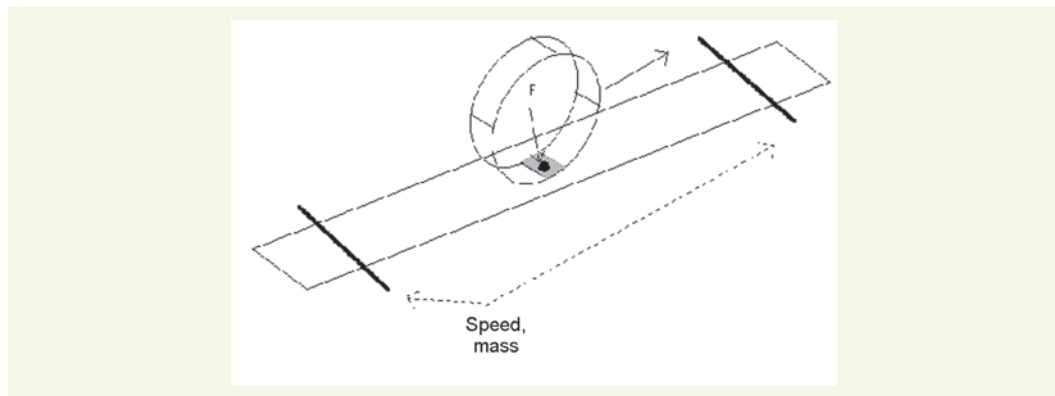
■ Evaluations related to road infrastructure

In a manner analogous to the onboard kinematic balance method, loops inserted into the road surfacing (SIREDO stations) or WIM (Weigh-in-motion) systems can yield access to dynamic parameters at several points along the trajectory of a vehicle: mass, speed (fig. 6). Optical kinemometers can also be advantageously introduced for deferred uses. The aerodynamic, or even hydrodynamic, forces are not identifiable and their effects may be assimilated with overall braking/acceleration performance. The scale selected remains that of the entire vehicle, with skid resistance averaged over all four tires on a road segment delimited by the specific evaluation positions.

figure 6

Overall kinematic balance

method



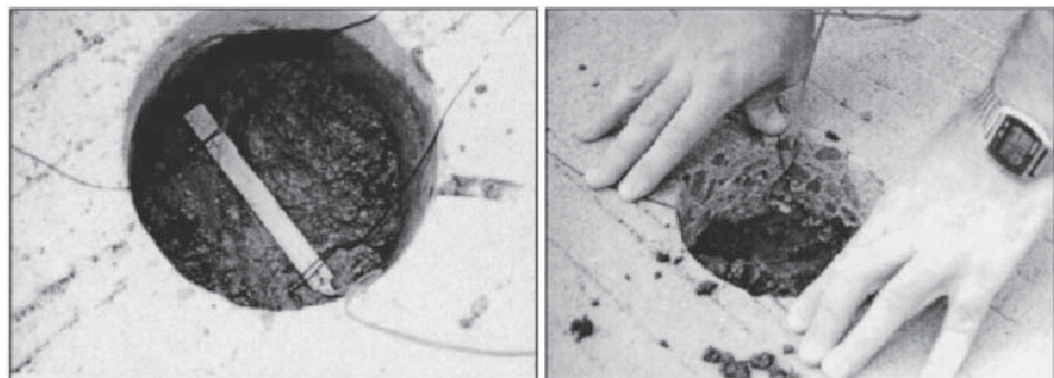
In order to evaluate the torsor applied by a given test vehicle tire, it is also feasible to use strain gauges embedded into the road surfacing [13] (fig. 7). The reduced measurement range requires a dense distribution of sensors over the target zone. The average equivalent mechanical modulus of the pavement must be determined, along with its sensitivity to temperature [14]. This sensitivity, in conjunction with the heterogeneous nature of road surfacing materials, serves to limit the possibil-

figure 7

Implementation of strain

gauges within a surfacing

[13]



ity of accurately measuring the force torses using this approach [15-17]. Lastly, systems based on *sensitive* plates (as shown in [fig. 2](#)) conceal the characteristics of road surfacing materials.

The limitations encountered with techniques available until now have led to examining feasibility and then proceeding with the method presented in the next section.

DEVELOPMENT OF AN INFRASTRUCTURE-BASED MEASUREMENT SYSTEM

■ Statement of development need

Given the complexity of the vehicle/pavement system, studies on controllability limits cannot rely solely upon numerical models and now require the experimental validation of forces being mobilized during emergency braking manoeuvres (longitudinal mode), curve handling (transverse mode) or combinations of both. To carry out such a validation step, a pavement-integrated and mobile measurement device is used to study numerous vehicles at different points along a given infrastructure. Within the framework of this measurement campaign, during which the roles of pavement and vehicle are of comparable significance, it is essential that the influence of surfacing materials not be overlooked. Moreover, the ability to estimate controllability limits imposes that high values of both speeds and contact forces can be tested experimentally.

In order to satisfy these needs, the decision was made to develop pavement instrumentation using a sensor of the *dynamometric balance* type that yields a measurement comparable to that derived by a dynamometric wheel rim, yet confined to a specific site (which proves to be an acceptable limitation for most tests, which are carried out within stationary dynamic states). Another advantage associated with the choice of a pavement-oriented instrumentation lies in the possibility of verifying the forces developed by the reference testing equipment (e.g. Adhera, grip-tester, Scrim). For this family of test equipment, the metrological discrepancies due to signal conditioning and sensors may be differentiated from variations under test conditions: wear on tires as well as bonding systems that serve to qualitatively modify the tread/ground contact. Metrological monitoring of these devices thus becomes streamlined.

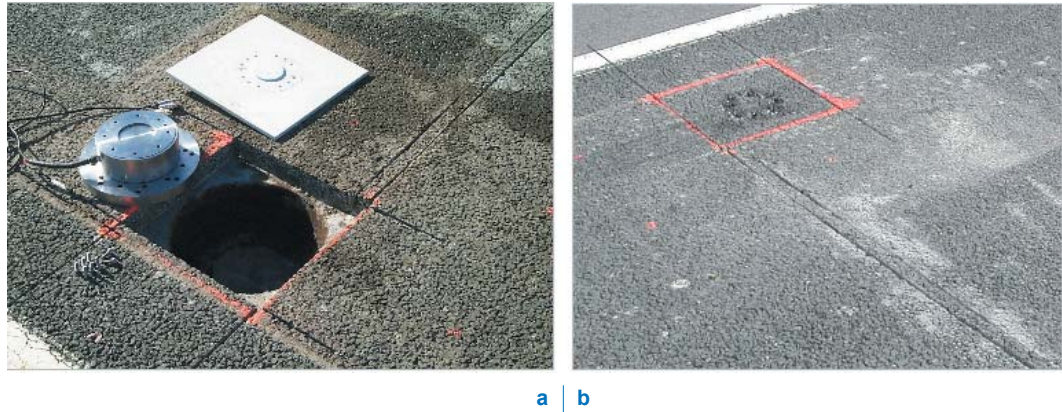
■ Experimental system

In order to obtain a measurement of the global torses of forces transmitted by a vehicle tire rolling on the pavement, we decided to instrument a pavement block detached from its environment.

From a practical standpoint, a square, 4-cm thick portion of the wearing course ([fig. 8](#)) was cut out and instrumented over its lower surface by a 6-channel measurement cell (three-dimensional forces and moments) and then repositioned within its original environment. Moments are evaluated at point O, located on the axis of revolution of the measurement cell and within the plane of its upper face. A clearance space was allocated around the cut piece of slab, such that its only connection with the remainder of the road structure runs through the measurement cell, regardless of the loading intensity. Slab dimensions were set so as to ensure complete tire/pavement contact for a long enough time for dynamic stabilization and sufficient data acquisition, while maintaining torses moments at levels acceptable for the measurement cell. A rapid acquisition chain (2.5 kHz) was utilized in association with a rigid test specimen.

A standard Peugeot 406 vehicle has been introduced for the entire series of tests. The tires on this vehicle, with a dimension of 195×65/15, show limited wear and have been inflated to a 2-bar excess pressure. The static adjustments associated with the vehicle bond to the ground are compliant with manufacturer prescriptions; for the set of measurements presented, their corresponding force levels will be included in the tare weights.

figure 8
Implementation of the
MEVI system on an LCPC
test track
a: six-component cell
b: final appearance, with
the slab repositioned



EXPERIMENTAL RESULTS

■ Pure steering static test: Initial verification

A static test has been conducted with the primary aim of comparing the dynamometer wheel system with MEVI. From the centered wheel position on MEVI, vehicle steering control is shifted as much as possible first to the right, then to the left also to the extreme point and ultimately drawn back to the center while locking the specific wheel rotation using the service brake. MEVI offset is adjusted by extracting a prerecorded sample from the signals in the absence of a wheel. Offset of the dynamometer wheel is adjusted according to a two-stage process, i.e. wheel off-loaded and during free rolling.

The torsor measured by MEVI for this test (fig. 9) displays the following characteristics:

- The moment Mz_{mevi} is representative of the progression of applied steering control (with a scale ratio imposed due to power steering). Its constant-level saturation on each major steering control phase is tied to the fact that contact is made by sliding and without rolling for most of the contact surface (i.e. a constant Coulomb friction value in sliding).
- The resultant \overline{Fy}_{mevi} is the lateral contact force of the tire on the pavement; it is due to the elastokinematics of the vehicle's front axle. Behavioral details of this resultant will be studied in greater depth by means of more thorough experimentation, in accounting for benchmark variations. An amplitude variation on the order of 70 daN is nonetheless likely; positive and negative forces of the same level of intensity should have been expected however for both right and left steering movements; in practice, this asymmetry is undoubtedly correlated with a permanent or context-specific force (geometry of the vehicle's axle system, pavement cross-slope).
- A resultant \overline{Fx}_{mevi} appears for high steering angles (near the point of blocking); it is correlated with the resultant Fy due to the locked wheel condition when spinning. A test conducted by leaving the wheel free to rotate, with the vehicle held in place by the back parking brake, has shown that this resultant no longer appears. Such behavior can certainly be tied to the tire's mechanical response, and in particular to sidewall stiffness in torsion.
- The resultant \overline{Fz}_{mevi} slightly increases during turning towards the right and decreases when turning left. This finding seems to be caused by the crosstalk between the Mz and Fz measurement channels. The influence of Mz on Fz lies on the order of 1% of the full Fz scale, i.e. 25 daN, which corresponds with the observed variation.

The same variables measured with the dynamometer wheel are depicted in fig. 10. The following can be noted:

- The moment Mz_{dymw} is strictly opposite to the moment measured by MEVI (as a result of the coordinate directions established by convention). This specific type of manoeuvre involves the most directly comparable magnitude between the two systems.

- The load $\overline{Fz_{dynw}}$ is comparable to the load measured by MEVI, with the same 15 daN difference corresponding to the wheel weight minus the deadweight of the dynamometric wheel hub ($Fz_{mevi} > Fz_{dynw}$).
- The forces $\overline{Fx_{dynw}}$ and $\overline{Fy_{dynw}}$ exhibit, in an initial approximation, variations comparable to those affecting the forces measured using MEVI. It would be necessary however to apply the benchmark modification laws to perform a comparison during sharp turns.

Let's close this section by commenting that both systems display moments Mx of homothetic curves, yet with substantially different amplitudes. A comparison of these moments imposes knowledge of the exact point of contact and the lever arms, as well as coordinate changes in the dynamometer wheel in order to determine the transport laws to be applied ($Mx_{dynw} \approx Fy_{dynw} \cdot R_{wheel}$ and $Mx_{mevi} \approx Fz_{mevi} \cdot d_{center} + Fy_{mevi} \cdot h_{mevi}$). This experiment, initially intended to draw a simple metrological comparison, will undoubtedly need to be repeated using different tires and for different tire inflation levels in order to characterize the tire/pavement contact in greater detail. A pressure-

figure 9

MEVI torsor, with the main brake blocked, a dry ground, centered tire; sequence of center steering/right swerve/left swerve/return to the center

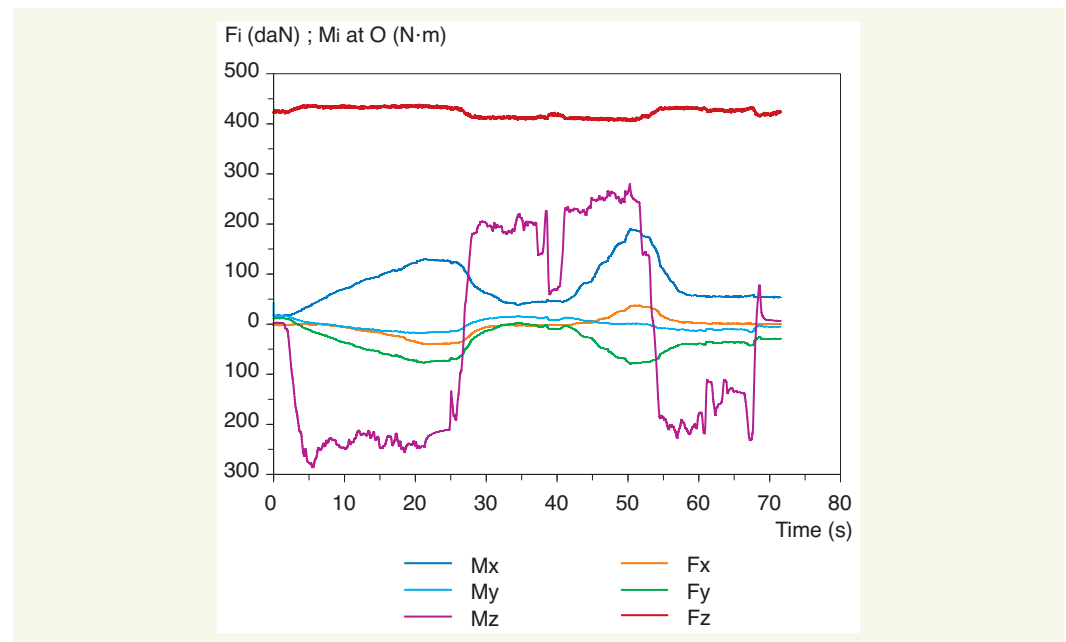
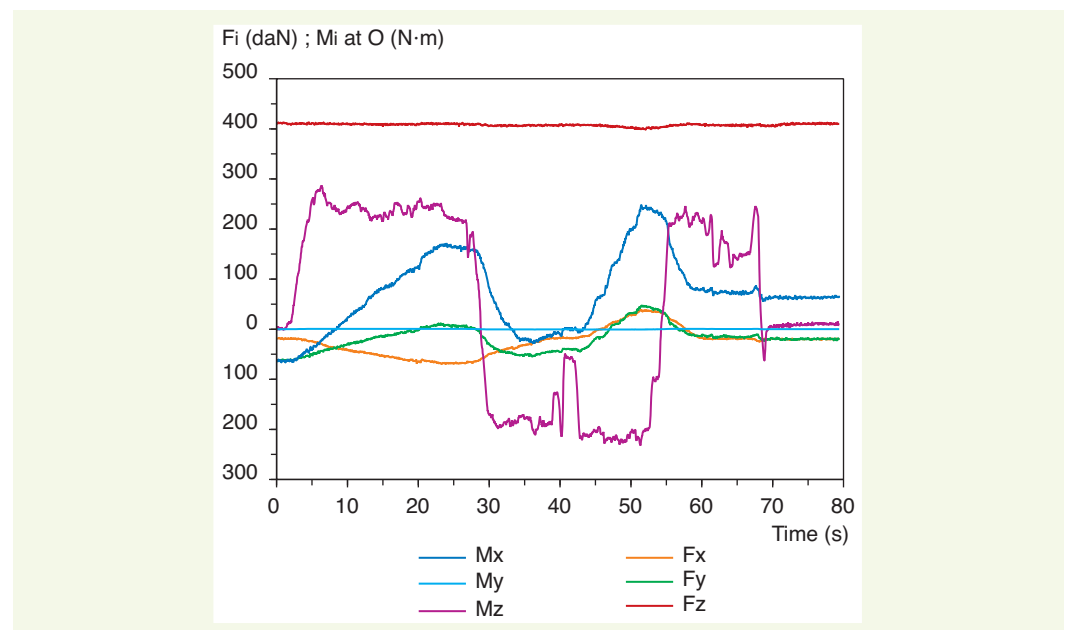


figure 10

Dynamometer wheel torsor, with the main brake blocked, a dry ground, centered tire; sequence of center steering/right swerve/left swerve/return to the center



sensitive rug would also be useful in determining the distribution of stresses within the contact area (which is still not a sufficient condition however for respecting actual contact characteristics).

On the whole, it is therefore noted that if offset adjustments have been well chosen, measurement results would offer a strong level of agreement for this special near-static situation.

■ Constant-speed rolling situation

Figure 11 shows the contact torsor variations measured by MEVI over a period that encompasses the length of time required for the vehicle's right front wheel to cross the MEVI central longitudinal axis. The test depicted corresponds to a vehicle crossing speed of $10 \text{ km} \cdot \text{h}^{-1}$. Tests were conducted for constant travel speeds varying from 10 to $110 \text{ km} \cdot \text{h}^{-1}$ by increments of $20 \text{ km} \cdot \text{h}^{-1}$, through control over engine power regulation.

› Low-speed rolling

For a wheel rolling at $10 \text{ km} \cdot \text{h}^{-1}$ (MEVI measurement in **fig. 11**), the vertical load F_z is measured under a stable regime and in a similar way by both the MEVI and dynamometer wheel systems, with the difference of 15 daN ascribable to the mass of the tire (and a portion of the wheel rim).

The tensile force F_x read from the dynamometer wheel measurement equals approximately 30 daN. The average of this force is evaluated at 25 daN by the MEVI system, in examining the full tire support period (one-tenth of a second). The dynamometer wheel yields a lateral force F_y equal to 30 daN, yet according to MEVI this value is much less (around 10 daN). The difference is admittedly sizable, yet still less than the maximum linearity/hysteresis/crosstalk system errors (for this situation, 22 and 11 daN for the dynamometer wheel and MEVI, respectively, in considering a low crosstalk level of 0.5% since a moderate loading F_z has been applied). Moreover, this difference can in part be ascribed to the appearance of a vehicle body angle capable of altering the F_y measurement on the dynamometer wheel, whereas the MEVI measurement is not being influenced by any front axle angles.

The small value of moment $M_{x_{\text{mevi}}}$ indicates good lateral centering of the tire on the asphalt-coated measurement plate. Within a rectilinear trajectory, the contribution of the lateral force to moment M_x may be neglected; skewed tire centering can thus be estimated at a level of:

$$d_{\text{center}} \approx \frac{M_x}{F_z} \approx \frac{50}{4500} \approx 0,01 \text{ m.}$$

› High-speed measurement trends

For higher test speeds, between 30 and $110 \text{ km} \cdot \text{h}^{-1}$, the tensile force $\overline{F_{x_{\text{mevi}}}}$ rises to reach a value of 50 daN, with no apparent variation on $\overline{F_{x_{\text{dynw}}}}$, which remains stable at the 30 daN value. The variation of approximately 20 daN revealed by MEVI is of the same order of magnitude as the half-difference of the increase in aerodynamic force being applied on the vehicle (17.5 daN for each drive wheel). This increase can in fact be estimated as an initial approximation by Equation (3), which for practical reasons neglects the aerodynamic stirring of the wheel, tire rolling resistances, residual brake frictions, etc.

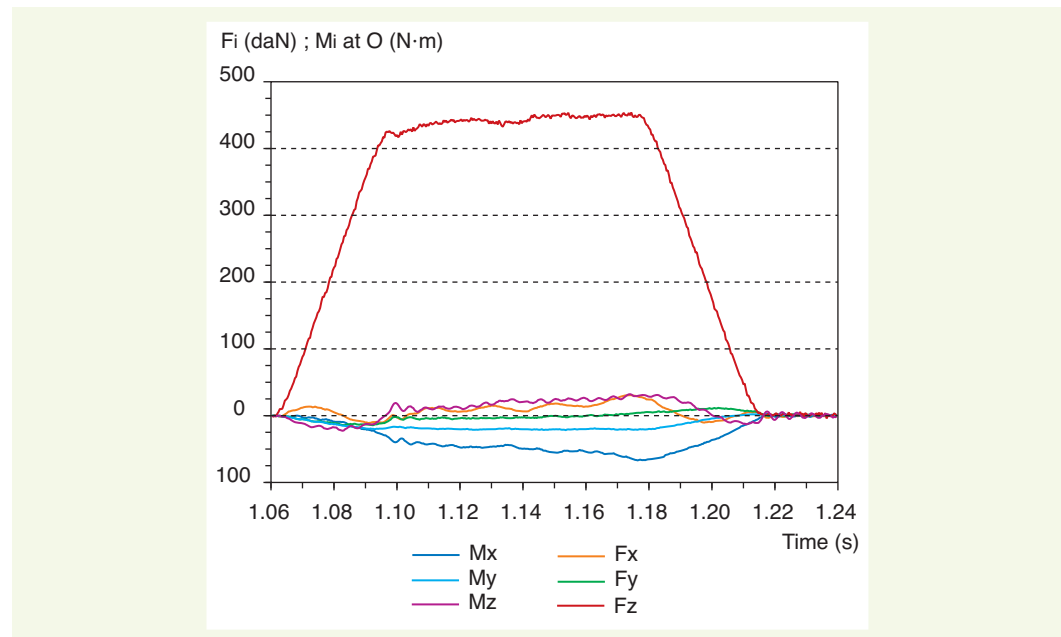
$$\Delta \overline{F}_{\text{aero}} = \frac{1}{2} \rho \cdot S C_x \cdot (V_{110}^2 - V_{30}^2) \approx 33 \text{ daN} \quad (3)$$

with: $S C_x = 0.63 \text{ m}^2$

$\rho = 1.2 \text{ kg} \cdot \text{m}^{-3}$

The inability to identify the increase in this aerodynamic force when using the dynamometer wheel may be explained by the small variation found with respect to the breadth of measurement range $\overline{F_{x_{\text{dynw}}}}$ (1,500 daN). Verification testing is underway with a redundant instrumentation set-up (torquemeters attached to transmission shafts).

figure 11
MEVI torsor at a constant speed of $10 \text{ km} \cdot \text{h}^{-1}$



Emergency braking on a wet road surface, without the ABS feature

› Identification of system-measured data

Figs. 12 and 13 display the forces acquired by both MEVI and the dynamometer wheel during an emergency braking manoeuvre held on a wet road surface and starting at an initial speed of $70 \text{ km} \cdot \text{h}^{-1}$. The vehicle's ABS system was deactivated in order to avoid eventual braking oscillations. The wavelength of such oscillations is in essence too great to enable MEVI to acquire complete periods. For subsequent potential applications, the use of longer MEVI slabs could be anticipated.

The MEVI system produces a short-duration signal sampled at high frequency (2,500 Hz), i.e. twice the eigenfrequency of the measurement modulus. The useful signal corresponding to the complete tire/pavement contact, which lasts approximately 1 ms, is framed by the phases of tire contact initiation and tire separation from the measurement pavement block.

figure 12
MEVI torsor, braking without ABS on wet surfacing, with an initial speed of $70 \text{ km} \cdot \text{h}^{-1}$

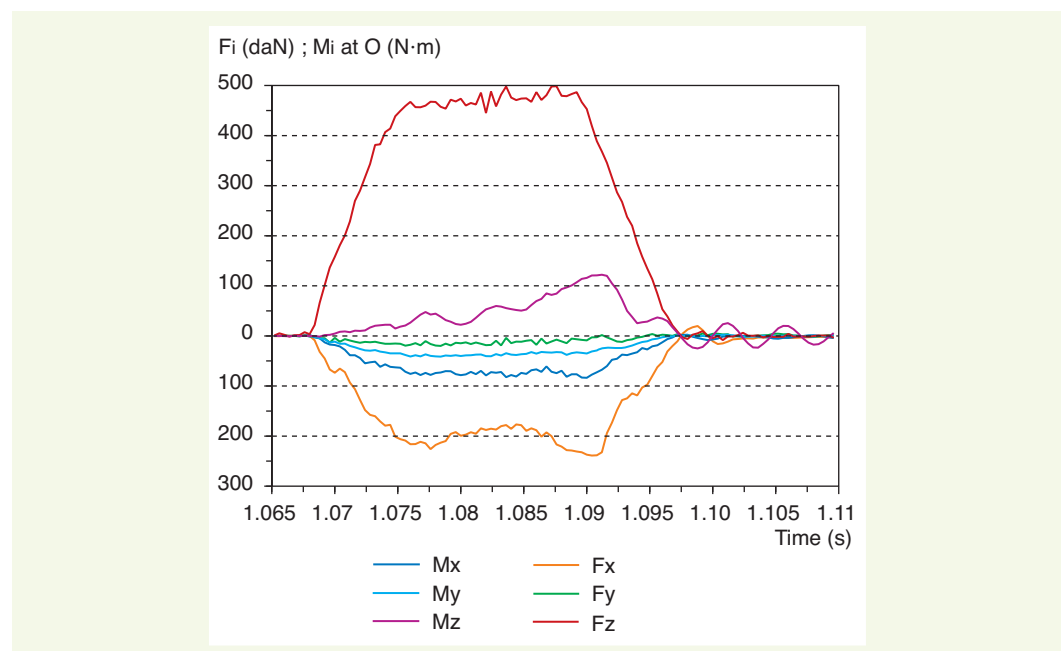
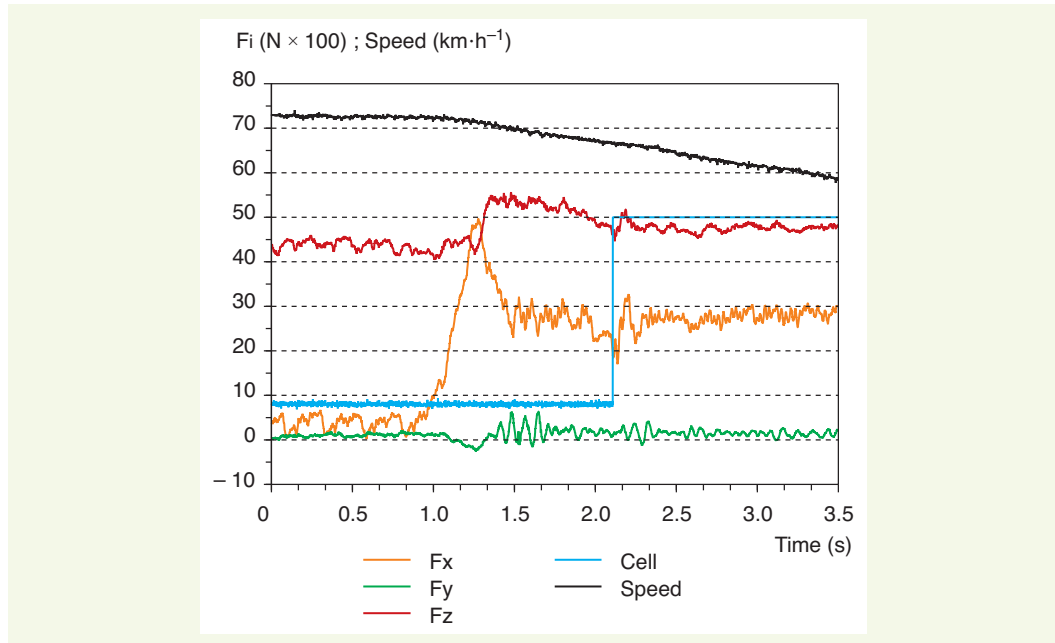


figure 13
Overall evolution in the
dynamometer wheel torsor;
braking without ABS on
wet surfacing



Conversely, the dynamometer wheel produces a signal covering the whole test at a frequency of just 100 Hz. Qualitatively speaking, this measurement allows recognizing the various test phases: moving towards the constant speed of $73 \text{ km} \cdot \text{h}^{-1}$ ($t < 1 \text{ s}$ on [fig. 13](#)), emergency braking without ABS as of $t = 1 \text{ s}$, crossing of MEVI at $t = 2.1 \text{ s}$.

The braking friction coefficient moves within two-tenths of a second through a maximum near 1, before stabilizing at a lower level equal to 0.5. These coefficients, conventionally identified by μ_{max} and μ_{bloq} , characterize the optimum and degraded braking modes, which correspond respectively to the ABS system operating objective and to a wheel locked in rotation, exhibiting only pure sliding with respect to the pavement.

More specifically, this test enables verifying that a stationary braking mode does in fact occur for over a half-second before the vehicle actually reaches the MEVI slab.

Another emergency braking test was conducted starting at a speed of $30 \text{ km} \cdot \text{h}^{-1}$.

In order to facilitate comparison of the two systems, data stemming from the dynamometer wheel are displayed as a function of the longitudinal position x , relative to the center of the MEVI slab ([figs. 14](#) and [15](#) for speeds of 70 and $30 \text{ km} \cdot \text{h}^{-1}$, respectively).

› Comparison of measured torsors

For the test with an initial speed of $70 \text{ km} \cdot \text{h}^{-1}$, the forces equal: $Fz_{\text{mevi}} = 470 \text{ daN}$; $Fx_{\text{mevi}} = 220 \text{ daN}$; $Fz_{\text{dynw}} + M_{\text{tire}} = 485 \text{ daN}$; $Fx_{\text{dynw}} = 200 \text{ daN}$.

For the test with an initial speed of $30 \text{ km} \cdot \text{h}^{-1}$, these force values equal: $Fz_{\text{mevi}} = 500 \text{ daN}$; $Fx_{\text{mevi}} = 300 \text{ daN}$; $Fz_{\text{dynw}} + M_{\text{tire}} = 480 \text{ daN}$; $Fx_{\text{dynw}} = 350 \text{ daN}$.

In an introductory assessment, the two systems agree when finding better friction at $30 \text{ km} \cdot \text{h}^{-1}$ than at $70 \text{ km} \cdot \text{h}^{-1}$, most likely due to the fact that the tire is rolling at a lower temperature at the lower speed.

Uncertainties specific to the forces amount to 20 daN for the dynamometer wheel and then 25 and 8 daN, respectively, for the Fz and Fx forces derived from MEVI. Linearity and hysteresis uncertainties have also been incorporated. Strictly speaking, the crosstalk uncertainty would need to be added, yet this value is only known for maximum calibration.

figure 14
Close-up of the dynamometer wheel torsor around the MEVI device with an initial speed of $70 \text{ km} \cdot \text{h}^{-1}$

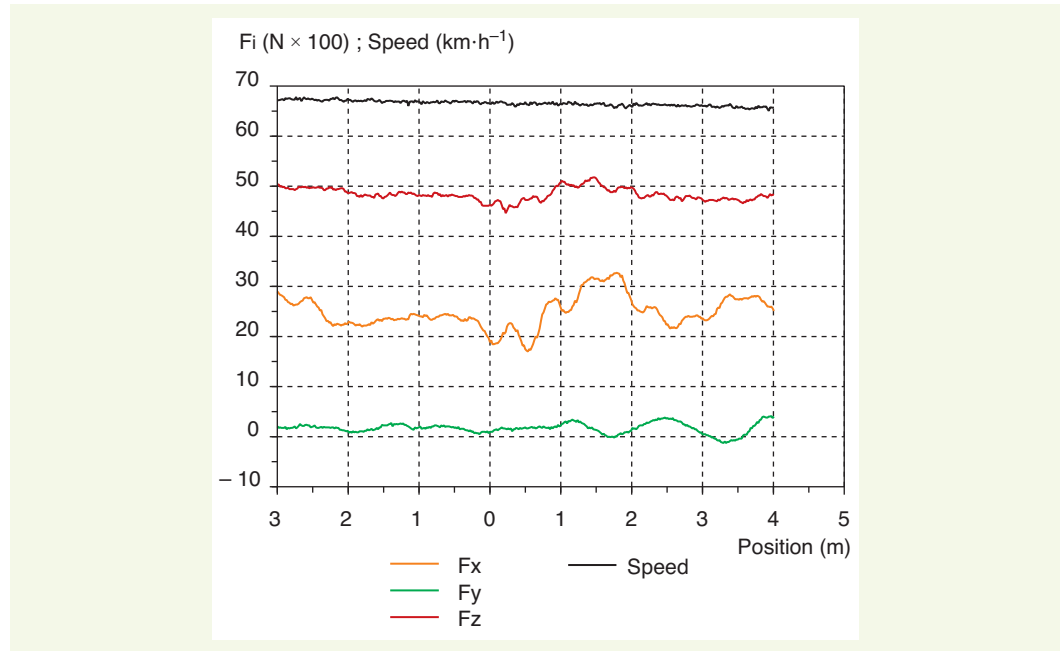
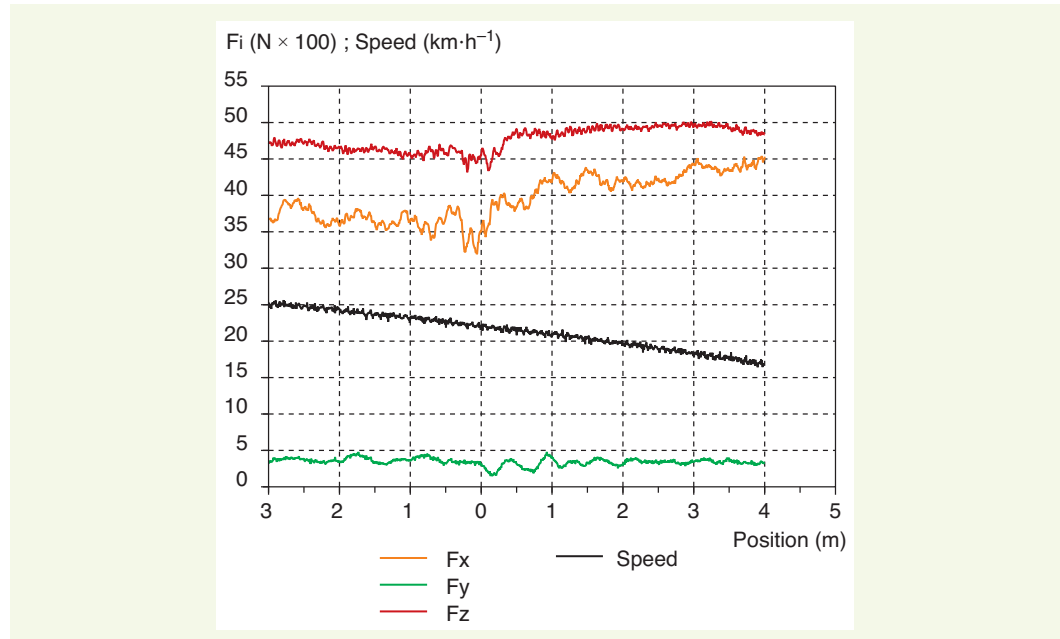


figure 15
Close-up of the dynamometer wheel torsor around the MEVI device with an initial speed of $30 \text{ km} \cdot \text{h}^{-1}$



For both tests, the deviation between vertical forces Fz_{mevi} and Fz_{dynw} , increased by the tire mass, remains less than 20 daN (i.e. below the sum of all uncertainties).

The deviation on braking forces remains acceptable for the test at $70 \text{ km} \cdot \text{h}^{-1}$, while it exceeds metrological uncertainties for the low-speed test (deviation of 50 daN for a 28-daN uncertainty). Nonetheless, the resultant Fx_{dynw} shows a high level of variability around the instant of wheel contact centered over the MEVI slab (fig. 15); the uncertainty over this point in time thus induces high uncertainty on Fx_{dynw} (temporal sensitivity bias).

CONCLUSION

The preliminary tests presented in this study have been intended to validate the MEVI system in comparison with the onboard force measurements conducted by the reference system composed of the dynamometer wheel. The primary advantage associated with the MEVI system relates to the possibility of including, at lower cost, many vehicles using a section of road infrastructure targeted for qualification.

Static tests subjected to various loadings have reinforced the notion of an equivalent level of precision between MEVI and a dynamometer wheel. In a torsion test (steering), the moment M_z and applied vertical force measured by both systems yield identical results.

During tests carried out at different constant speeds, the MEVI system has revealed an increase in tensile forces with aerodynamic resistance, yet no such increase was found with the dynamometer wheel. This unexpected outcome will be verified, although it may merely be the consequence of crosstalk, which is substantial in the two systems and results from a low level of longitudinal forces with respect to the vertical loadings.

In emergency braking mode without ABS capacity on wet ground, braking forces may exhibit a deviation that exceeds the metrological uncertainties if sizable variations in the contact torsor are present around the common measurement site (i.e. the MEVI slab).

Beyond these few differences, the dynamometer wheel and MEVI type systems output comparable order-of-magnitude measurements with highly similar precision. The MEVI system can thus be considered as entirely valid. In addition to a cost eight times less, the MEVI system offers the advantage of being independent of the test vehicle and relatively easy to move. This system can therefore be used to measure forces applied on the pavement by any vehicle traveling over a given section of roadway. Information on the forces being mobilized can then be added to the – classical – knowledge of average speeds traveled to contribute to the safety assessment of a particularly dangerous lane.

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