Evaluating viscoelasticity

Detailing a new, non-invasive and portable instrument to characterize the viscoelastic properties of tires

by Francesco Carputo, Flavio Farroni, Andrea Genovese, Antonio Maiorano, Aleksandr Sakhnevych and Francesco Timpone, Vehicle Dynamics Research Group, Department of Industrial Engineering, University of Naples Federico II, Italy

Vehicle dynamics is heavily influenced by the phenomena occurring in the interface between tire and road. Many of these phenomena – such as grip performance, rolling resistance and wear – are largely dependent on the viscoelastic properties of the tire tread compound.[1,2] Gaining knowledge of these viscoelastic properties in a non-destructive way is a key factor for several applications, from development of polymers for innovative compounds to vehicle performance and road safety, and is gaining the attention of industries and academics from different sectors.[3,4]

This paper details a new tool for the viscoelastic characterization of tires. The proposed methodology is non-destructive and non-invasive and, thanks to a compact layout, enables the characterization in situ.

The VESevo (Viscoelasticity Evaluation System Evolved) is a patented technology[5] developed by the Vehicle Dynamics Research Group of the Department of Industrial Engineering at the University of Naples Federico II. The principal aim of this device is the evaluation of the viscoelastic properties of tire tread compounds via a non-destructive testing procedure.

The device, in its prototype configuration, was developed with a pistol-shaped handle with the main purpose of guaranteeing ergonomics and stability, as shown in Figure 1a.

The inner structure of the VESevo is based on a steel rod with a semi-spherical indenter. Via a trigger, the rod is brought up to a proper release height. After that, by means of a semi-automatic system that enables high repeatability, the rod is let free to bounce on the tread surface, sliding through a suitable zero-friction guide so that the damping phenomena during rod motion can be negated.

The motion of the rod is measured by an optical laser sensor at high resolution and frequency. Simultaneously, the tread surface temperature is measured for each test, thanks to a compact IR sensor.

To record and manage the VESevo signals, an acquisition unit, shown in Figure 1b, supports the device. This unit is plugged into a laptop to acquire and analyze the signals in real time during the test sessions, thanks to a proprietary, user-friendly GUI, shown in Figure 2.

With this interface, it is possible to check the temperature at which every measurement is carried out on the tread and the quality of the bounce displacements.

For explanatory purposes, a displacement raw signal of the rod during a single test is shown in Figure 2. The first phase of the motion corresponds to the impact of the sensor rod on the tire tread surfaces and the first indentation. During the second phase, the rod reaches the maximum point of the curve after the first indentation, and other bounces can then be identified depending on the material's properties and its temperature. The last phase consists of the established continuous contact between rod and surface at the end of transient dynamics.

Viscoelasticity analysis

The displacement signals of the rod can be acquired in a wide temperature range to identify the glass transition temperature of the tread compound and characterize the full viscoelastic master curves in terms of storage modulus and loss factor, corresponding to a reference frequency. The tire tread is defined as a viscoelastic material and is usually based on styrene-

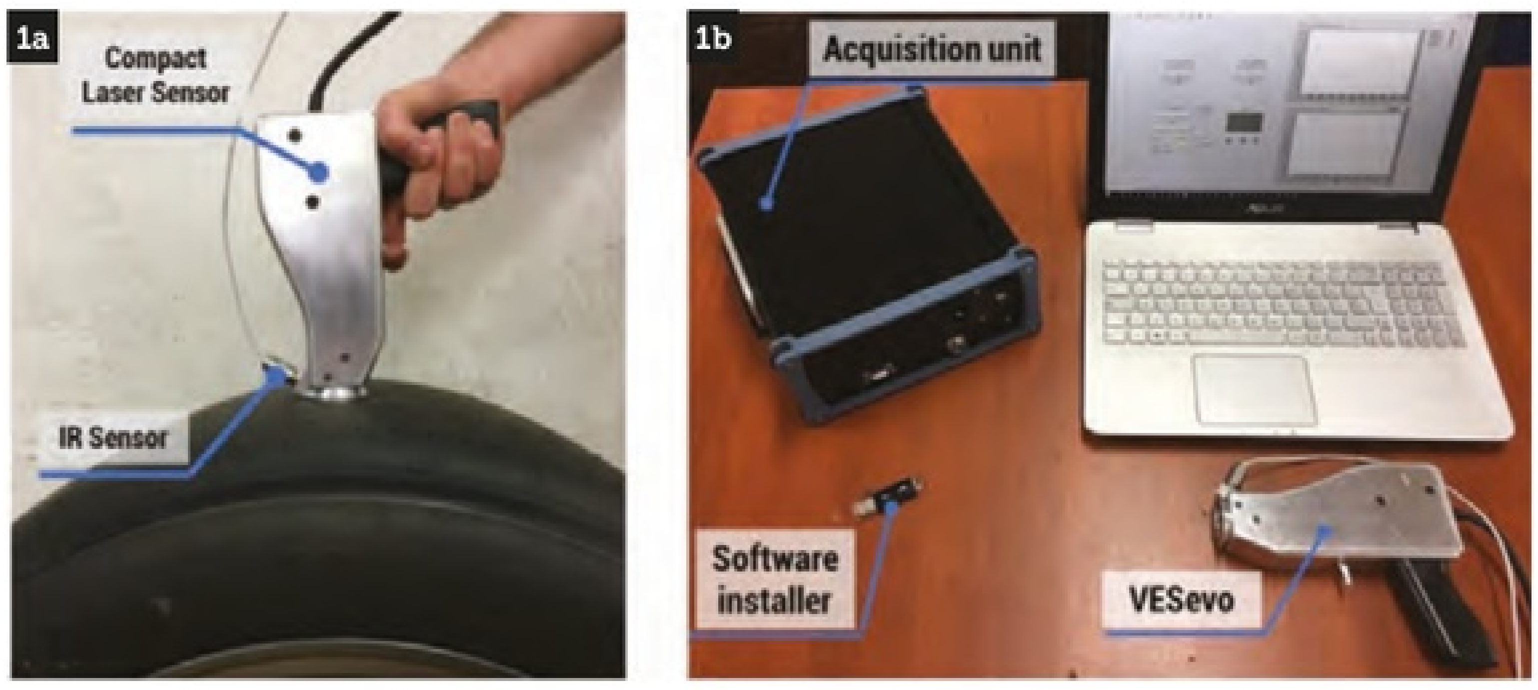


Figure 1a: VESevo device on the tire

Figure 1b: Device together with the acquisition unit

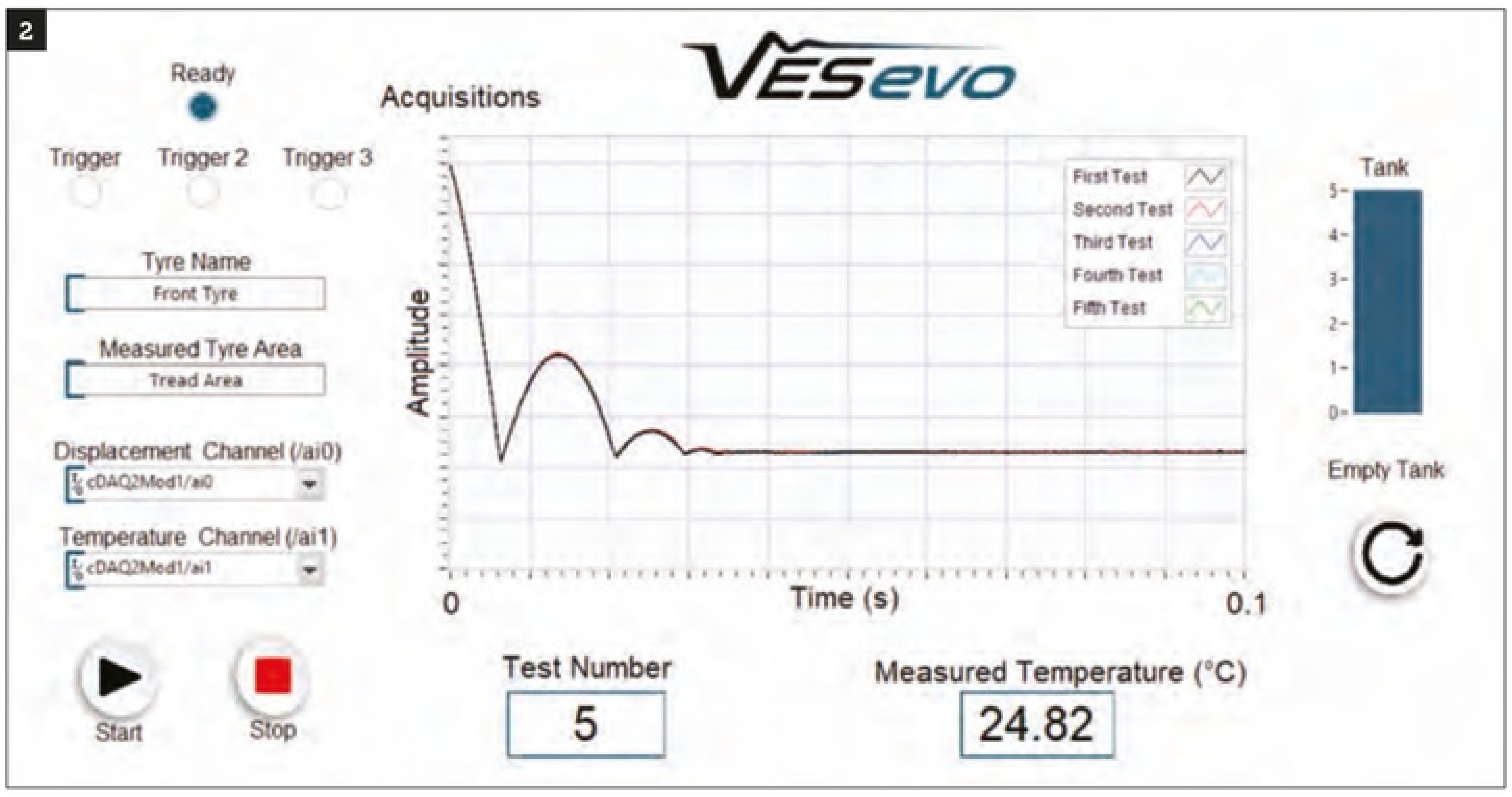


Figure 2: Displacement raw signal of the rod on the tread surface at 24°C

butadiene rubber (SBR) compounded with silica, carbon black, oils and other fillers during the manufacturing process. A viscoelastic material behaves halfway between a purely elastic solid and a purely viscous one. This means a phase angle between 0° and 90° occurs, comparing the stress and strain toward the time, and the constitutive relationship is based on a complex dynamic modulus E^*. The corresponding real part, called storage modulus E_1, is a measure of the elasticity of the material linked to the ability to store energy during a solicitation cycle; the imaginary part, loss modulus E_2, is associated with the aptitude of the compound to dissipate energy during a solicitation cycle as heat. The ratio of the loss modulus to storage modulus defines the loss factor, tan(δ), which is a fundamental tire tread property for the performance analysis and grip estimation. The properties mentioned depend on both solicitation frequency and compound temperature; this means the time-temperature superposition is satisfied for this kind of material and this principle is described by the William-Landel-Ferry relationship.

A typical VESevo test session is based on the following phases:

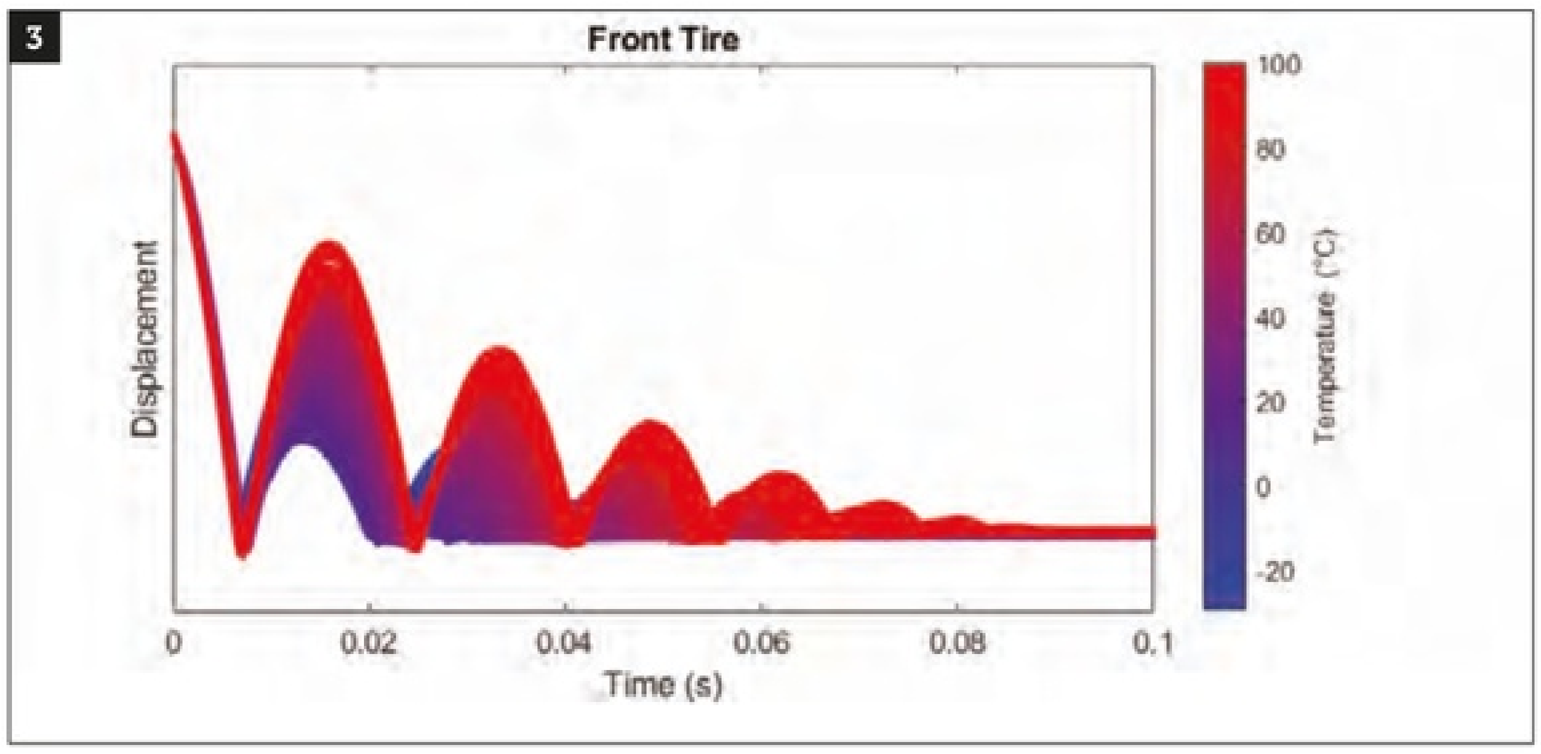
- Performing experiments at ambient temperature on the tread area of interest;
- Cooling down the tire at least -30°C through a climatic cell or a freezing spray, then carrying out the VESevo measurements on the tread until the ambient temperature is reached;
- Heating the tire to 80-100°C (or higher, if necessary) through use of a thermal blanket or a professional heating gun, then starting the VESevo experiments until the ambient temperature is reached again.

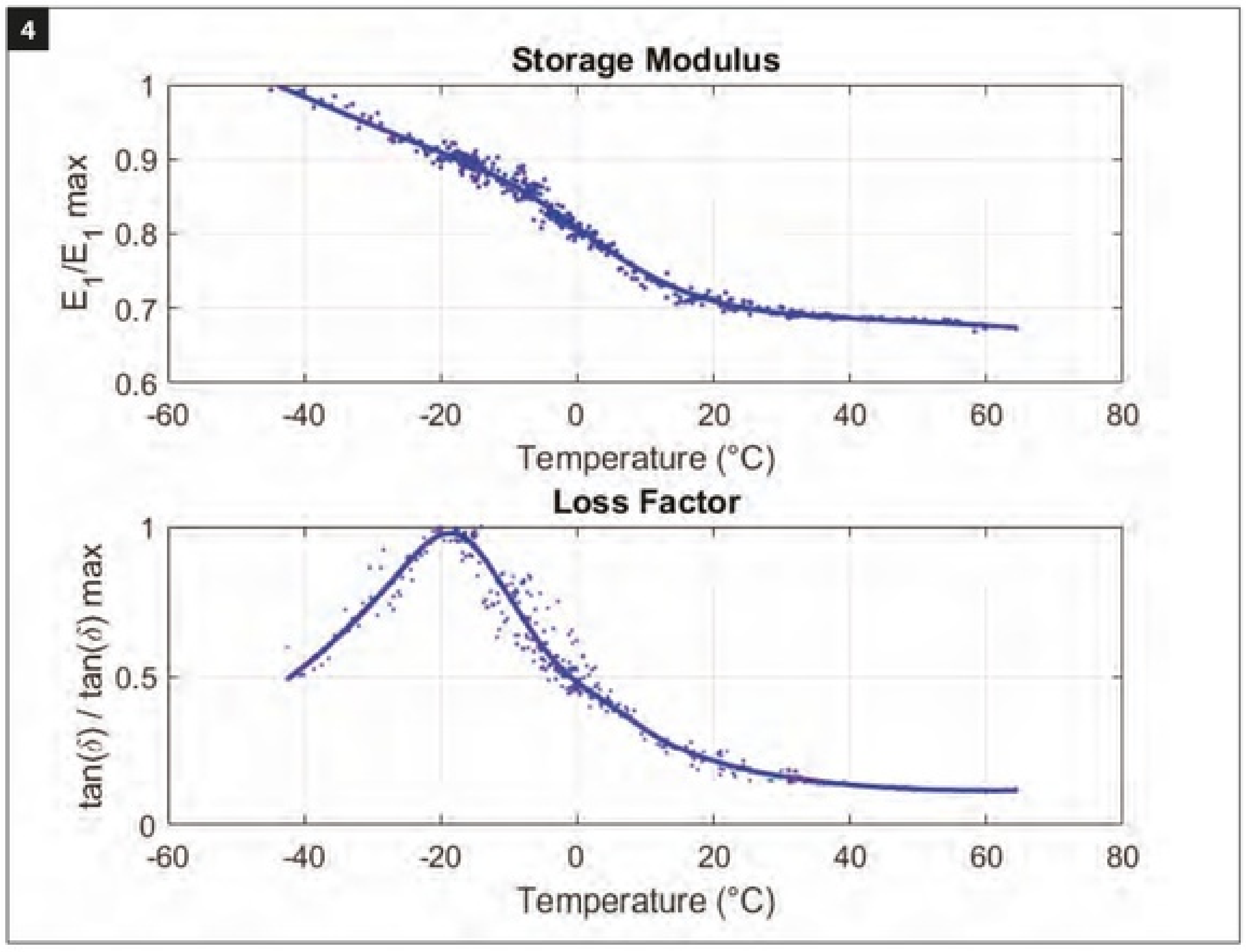
The displacement curves of the VESevo rod on a tire tread at different temperatures are shown in Figure 3. Observing the shape of the

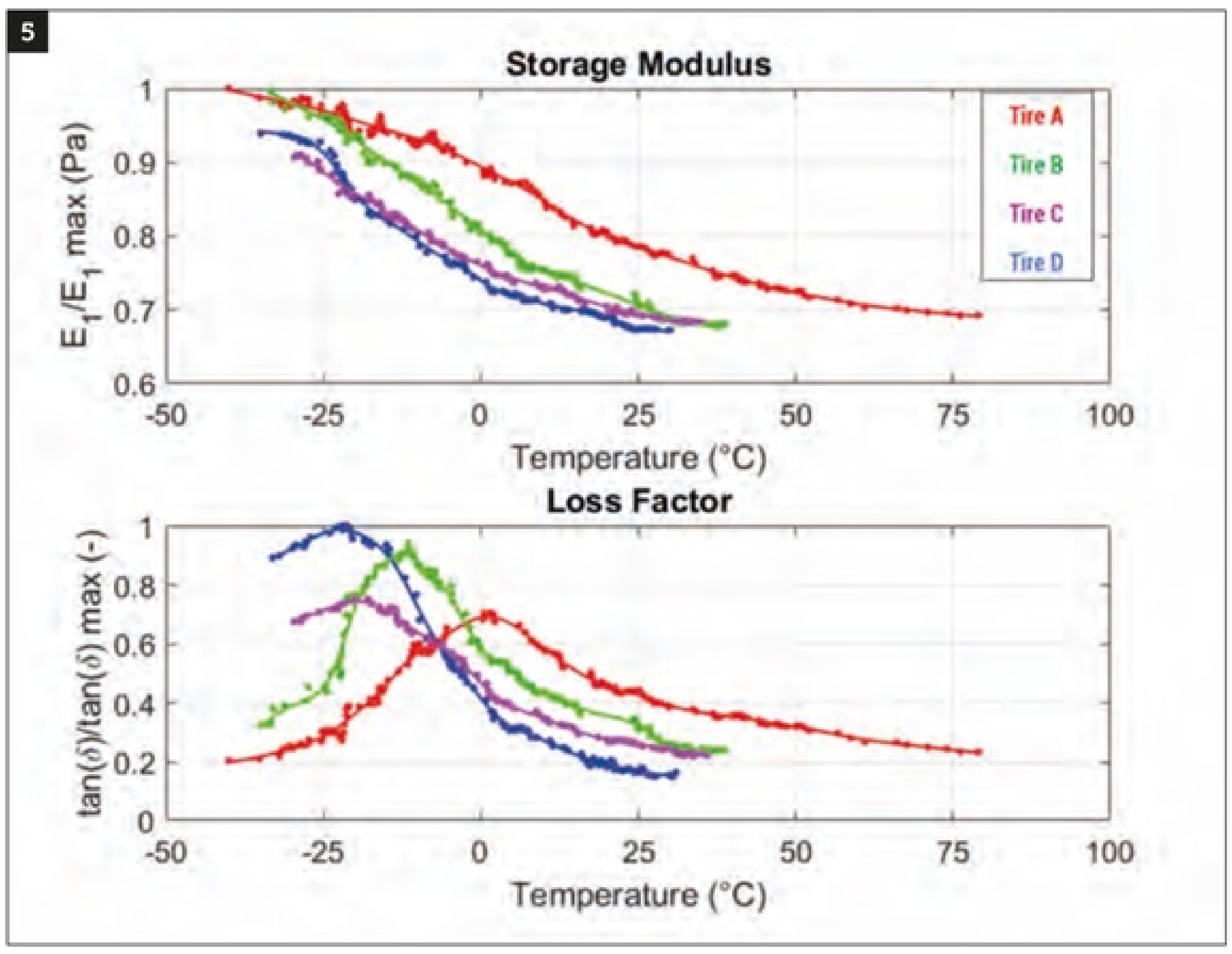
Figure 3: Acquired curves at different tire temperatures

Figure 4: VESevo master curves at 1Hz for a tire tread compound

Figure 5: VESevo master curves for different tire tread compounds







acquired displacement curves of the indenter toward the temperature, it is clear that the response of the material is largely dependent on its temperature, and the proposed methodology is able to highlight this phenomenon. Focusing on the transient phase, it is possible to observe that, starting from 40°C until 100°C, the rebound phase is longer, and several bounces occur in 0.1 seconds.[6]

This means that at increasing temperature, the compound behaves as pure rubber and a low dissipation of the potential energy of the rod is observed. On the other hand, by reducing the temperature from 40°C to -20°C, the transient phase is shorter and low bounces occur: the compound returns the highest energy dissipation measured in terms of rod displacement and this means that the material moves to a glassy behavior. From a qualitative point of view, it is interesting to point out here that the duration of the indentation phase increases with the temperature in accordance with the observation that, at the low-temperature range, the behavior of the compound is similar to a glassy one – whereas, at high range, it is analogous to rubbery. The quantitative study of the indentation phase is detailed in the next paragraphs. Finally, is it worth noting that, as concerns the drop phase, it is independent of the temperature as this phase does not involve the material under investigation but is only characterized by the rod-spring mechanism.

The VESevo post-processing algorithm is capable of analyzing each displacement curve at the corresponding temperature and of extrapolating the features that are most correlated to the viscoelastic behavior of the tire tread compound. In particular, the storage and loss moduli can be defined as a function of the following magnitudes:

$$E_1 = f(A_c, T, K_c) \quad [1]$$
$$E_2 = f(A_c, \omega, T, S_c) \quad [2]$$

where, A_c is the effective contact area between the semi-spherical indenter and the compound, ω is the solicitation frequency linked to the single VESevo test, T is the compound temperature and K_c and S_c are the equivalent contact stiffness and damping coefficient, which can match with the tire tread ones being the VESevo spring stiffness and rod guide damping negligible. The loss factor, tan(δ), is determined as the ratio of E_2 and E_1; therefore, it depends on the same magnitudes in equations [1] and [2]. The typical viscoelastic master curves at 1Hz of a tire tread compound are shown in Figure 4.

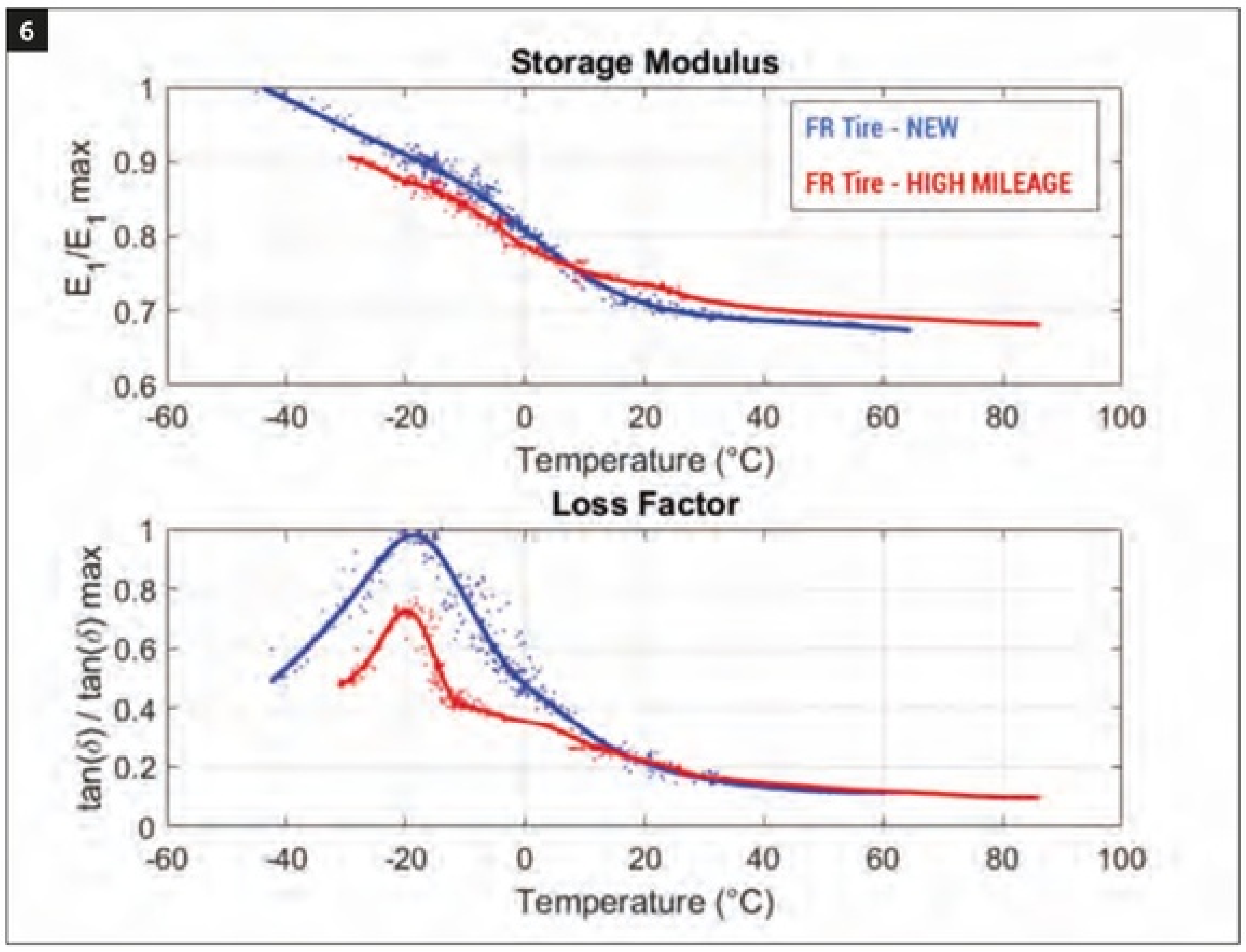


Figure 6: Wear/degradation effects on FR tire properties

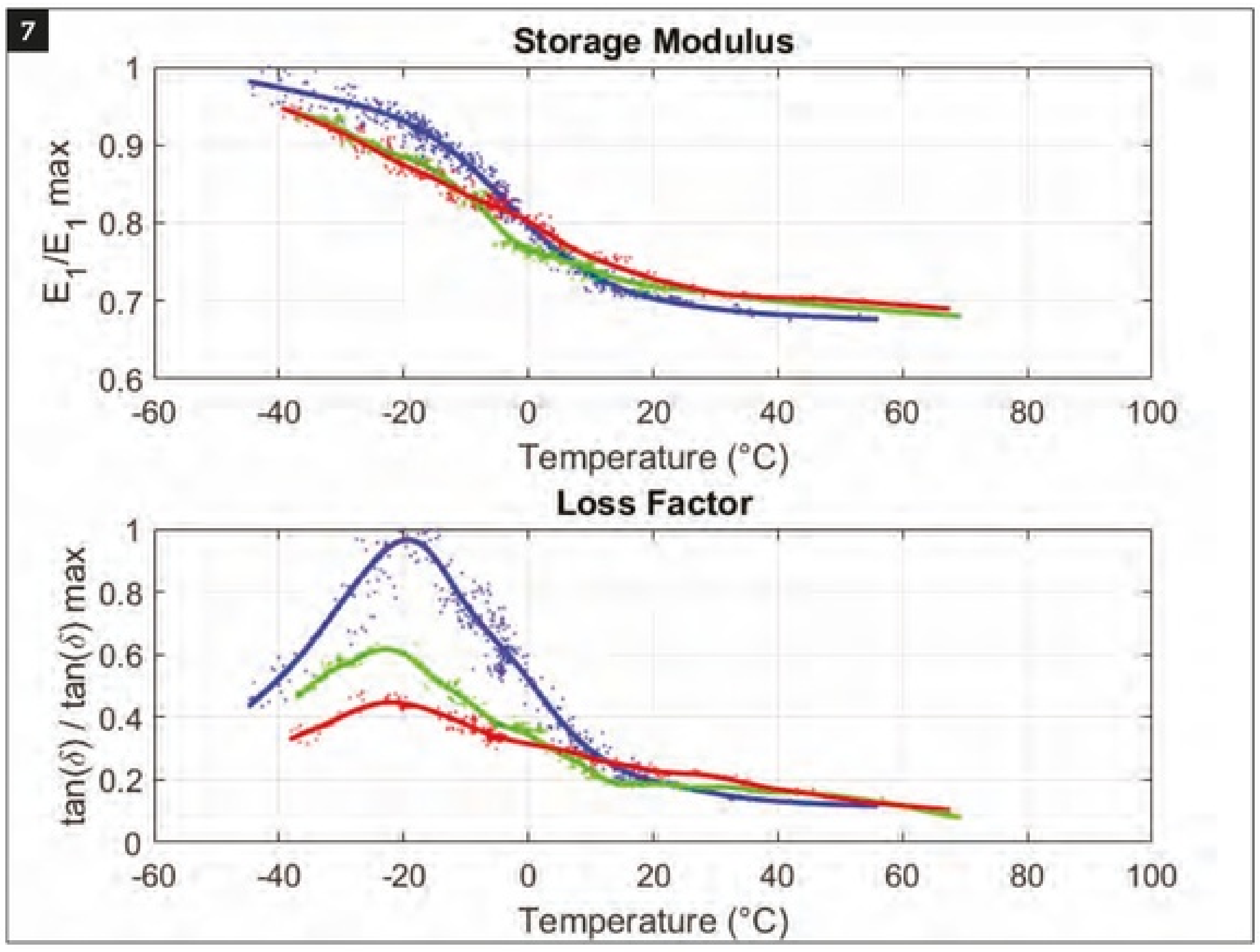


Figure 7: Wear/degradation effects on RR tire properties

Results

One of the main advantages of the VESevo is the ability to run tests an unlimited number of times. This opens up broad application scenarios such as the change in properties of a tire during its life, or after a thermal cycle or, furthermore, investigation of the effects of aging, wear or monitoring quality in production.

A fundamental capability of the VESevo technology is the ability to identify and characterize different tire tread specifications without affecting the tire integrity, as shown in Figure 5, which reports the results of VESevo measurements for four tire tread compounds. The testing procedure and the data processing algorithm outlined in the previous sections are able to identify differences among the specifications, enabling the building of a compounds database to gather data useful for feeding into correlative analysis and physical friction models.

Then, the analysis of tire modifications over the progressive mileage is also presented, in order to carry out a study on tread performance degradation due to wear phenomena. A non-destructive and smart track testing procedure is useful for obtaining data for the optimization of the vehicle setup or for predicting the limit adherence at different tire statuses. In Figures

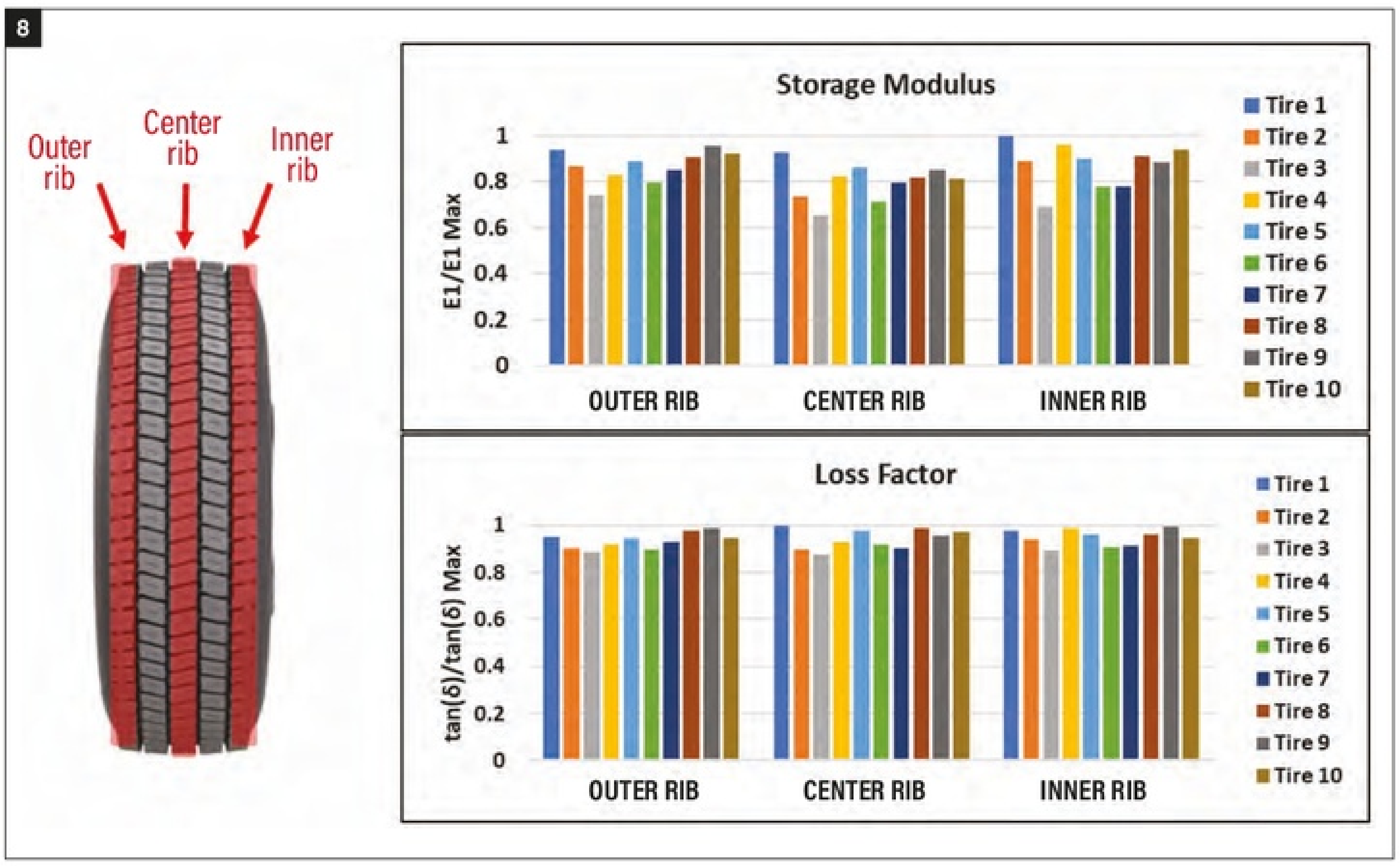


Figure 8: Tire series analysis through the VESevo (normalized data)

6 and 7, the results of VESevo measurements on the front and rear tires (indicated as FR, front right, and RR, rear right) illustrated in Figure 4, related to such analysis, are displayed. The results are normalized with respect to the maxima values of E_1 and tan(δ) of the front tire.

Analyzing the fit curves of VESevo data, a relevant reduction of the loss factor peak values can be identified for both front and rear tires together with slight variations of the glass transition temperature. On the other hand, the slope of the storage modulus changes and, at high temperatures, exhibits values greater than the ones in the new conditions. The highlighted phenomena, highly depending on the amount of energy absorbed by the tires during the run distances, can have a significant effect on vehicle balance in case of wide differences between the two axles (as in the high mileage case in Figures 6 and 7, acting more deeply at the rear than at the front in the tested run).

The VESevo can be also employed in the analysis of viscoelastic properties uniformity among different tires of the same production series, thanks to its ability to retain the tires' integrity after the test. As a result, tire manufacturers using the device are able to save money and time in testing the quality of many products, replacing the common testing procedures requiring DMA machines and specific rolling benches. In Figure 8, 10 tires of the same truck family have been characterized by the VESevo at ambient temperatures to compare the storage modulus and loss factor in the highlighted tread areas. Analyzing the bar plots, it is noticeable that Tire 3 exhibits the lowest values of E_1 and tan(δ) among the tested specifications, which may be due to issues in the vulcanization procedure during the manufacturing process. These kinds of results have been achieved thanks to the VESevo smart testing procedure, which is merely the starting point for further activities regarding the adoption of the illustrated methodology in the plastic materials industry and the quality monitoring processes.

Conclusions

A portable device that enables a non-destructive procedure for viscoelastic properties characterization of tire tread compounds has been described. The proposed technology makes it possible to test physical properties directly on tires and can be performed in various environmental condition and during/after various kinds of runs. Moreover, the VESevo can be used to create a compounds database, reporting the differences among the thermal working ranges and their adhesive/hysteretic friction attitudes. The presented results confirm the capability of the VESevo to highlight the degradation of a compound due to the mileage and the differences that can occur on different ribs of a tire due to inhomogeneities in the vulcanization and manufacturing process. **tire**

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