ANALYSIS OF THE INFLUENCE OF DIFFERENT FACTORS ON THE ROLLING RESISTANCE OF RETREADED TIRES: CONTRIBUTION TO CO_2 EMISSIONS

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ABSTRACT

The reduction of fuel consumption of vehicles is one of the priority objectives in addressing the reduction of CO_2. Current EC regulations stipulate minimum requirements for new tires in relation to their low rolling resistance coefficient (RRC) and rolling noise. Nevertheless, these requirements do not apply at present to retreaded tires, which represent today 40% of the consumption of truck and commercial vehicles. The influence of different parameters on the RR obtained after retreading is studied. First, an attempt has been made to eliminate the influence of the condition of the starting casing, studying separately the influence of factors associated with the retread process and the materials used therein. To achieve this goal, RRC tests were carried out on new tires, on the casings of the same tires after being scraped, and finally after being retreaded using different formulations and processes. The results show that retreading significantly increases RRC, but the influence of the casing manufacturer is very important; a tire retreaded using a first-class casing can present an RRC lower than an equivalent low-cost new tire. On the other hand, the dynamic properties of the material added in the new tread are important, but the difference encountered between retreaded tires using different retreading materials and processes remains less than 5%. To study the influence of the aging of the materials, used tires were also tested before and after retreading. In view of the results, the aging condition of the casing seems not to have a clear effect on the RRC of the used tire. Indeed, the effect seems to be beneficial for the passenger car and detrimental for the truck samples studied. Those effects are smoothed during retreading, and the casing condition is not presented as a main factor of the RRC of the retreaded tire. It is worth noting that the study was carried out on a small sample of tires of two specific dimensions: a small passenger car tire (185/65 R15) and a European standard size for long-distance trucks (315/70 R22.5). Although the results and conclusions are very interesting, they should be taken with caution when extrapolated to other types of tires. [doi:10.5254/rct.19.81483]

INTRODUCTION

MOTIVATION AND OBJECTIVES

In the context of measures to optimize energy and reduce CO_2 emissions, the reduction of fuel consumption of both passenger and freight vehicles is one of the priority objectives.[1] In the case of freight vehicles, in addition to the environmental argument, cost reduction is also very important, which is particularly interesting for the road transport sector, in which very tight profitability has been achieved in recent times.

One of the factors with a great influence on fuel consumption is the rolling resistance of the tires. In this sense, regulation (EC) No. 661/2009 provides that new tires manufactured from November 2012 must meet minimum requirements in relation to low rolling resistance and rolling noise.[2] It is estimated that the reduction in vehicle fuel consumption associated with the reduction of rolling resistance raised by the regulation could exceed in some cases 15%.

Regulation (EC) No. 661/2009 does not apply at present to retreaded tires,[2] which currently represent 40% of the consumption of commercial vehicle tires. Nevertheless, the preliminary considerations in the document itself state that the Commission should carry out an evaluation of this business sector and evaluate the adjustment of the regulatory regime for this type of tire. Thus, new rules regarding rolling resistance of recycled tires might be expected to appear in the coming years. However, beyond its future compulsion, reduction in the rolling resistance of recycled tires is presented as a necessity. In the near future, verification of good environmental and energy performance of these tires will become a fundamental argument to maintain their current wide presence in the market.

The objective of this work is to advance the knowledge of the behavior of retreaded tires in relation to their rolling resistance and to analyze the influence of different parameters on this behavior. The variety of types, dimensions, and constructive processes of the tires is very wide, as are the factors that can affect the rolling resistance coefficient (RRC). First, this study addresses the influence of the state of repair and aging of the carcass of used tires and the type and quantity of material added in the new tread during the retreading. Second, the proportion of the RRC attributable to the casing and the tread, in both new and retreaded tires, will be quantified. Third, a comparative analysis will be done of the values obtained and the values demanded by the regulations for standardization[2] and labeling[3] of new tires. The RRC of new and retreaded tires will be compared, and the influence of using retreaded tires on a vehicle's fuel consumption and on CO_2 emissions will be assessed. Finally, the tests will be repeated for other speeds common for passenger cars and trucks, and the results obtained will be compared with the previous results for these speeds.

STATE OF THE ART AND PRECEDENTS

With respect to the rolling resistance of new tires, the phenomenon and the parameters of influence on the RRC have already been extensively studied, especially by tire manufacturers.[4–10]

A factor of fundamental influence is the material used in the tire design. The development of new materials and compounds to obtain a low RRC has already been extensively studied.[11–13]

Futamura[14] studied the rolling resistance through the energy loss due to dynamic viscoelastic properties of the materials. He introduced the concept of the "deformation index," obtained from the mechanical properties of the materials, to estimate the energy loss. This concept was recently reviewed and extended by Futamura and Goldstein,[15] comparing the results with the energy losses obtained from finite elements analysis (FEA). The deformation index is proposed as a tool for developing new compounds and materials for tires, intended to reach good properties of rolling resistance, dry traction, and wet traction.

Using the deformation index and FEA analysis, the authors identified the contribution to rolling resistance of each component of the tire, such as the tread, subtread, sidewall, body plycoats, steel belt coats, inner liner, and others. In view of the results, it can be inferred that the contribution of the tread is about 50%, in front of the 50% contribution of the rest of components. On the other hand, looking at the interaction between materials, the authors found that "when the stiffness of one tire component is changed, the cyclic energy dissipation of other components may also be influenced." That interaction was included in the deformation index definition, leading to a very good correlation with FEA results.

Another main factor affecting rolling resistance is tire inflation. On one hand, Cohn[16] concluded than an underinflated tire could increase the rolling resistance by up to 13%, but the pressure increase above the recommended values had a lower influence, in that it could reduce the RRC by only 5%. On the other hand, Bachman[17] concluded that the relationship between inflation pressure and RRC is almost linear, and a variation of 5% in tire inflation pressure induces a variation of 1.1% in the RRC. Taking into account a typical fuel economy return factor of 5:1 (a 5% change in rolling resistance produces a 1% change in fuel economy),[18] a nonnegligible effect of tire inflation in CO_2 emissions can easily be deduced. These conclusions on tire inflation effects can be extrapolated to the RRC tests and should be taken into account for pretest conditioning and warm-up.

Nevertheless, not many publications in relation to tread rolling resistance of used tires have been found. It is relevant to mention the work of J. R. Luchini et al.,[19] who compared the RRC of a sample of new tires with another of used tires during 95 000 km and observed that significant differences existed between them. We can draw two interesting conclusions from this study. The first is that, generally in both cases, rolling resistance decreases with the thickness of the tread as it is gradually eliminated. The second is that, at the same thickness of the remaining tread, the aging effect on the casing can be favorable or unfavorable, depending on the case.

Regarding the rolling resistance of retreaded tires, not much relevant literature has been found. The two most salient and up-to-date publications that discuss the RRC of retreaded tires are the final report of the RETYRE project[20] and the report of a study by the European Tyre and Rim Technical Organisation (ETRTO).[21] The RETYRE[20] project tries first to identify the influence of the casing on the RRC, in an attempt to isolate it, to focus later on the influence of the parameters of the retreading process. Accordingly, the first stage of the study set out to measure the RRC of used tires with a known history (dimensions, age, mileage, and prior use) and the same for retreaded tires. In the end, for reasons that are not relevant, it was not possible to complete the test plan, and as a result, only a coarse estimation of the RRC percentage attributable to the casing was published, between 50 and 60%.

In their quest to analyze the impact of different factors deriving from the retreading on the RRC, the authors used truck tires from the same manufacturer, with the same age and comparable usage conditions. The sample included casings of two different sizes (315/80 R22.5 and 385/65 R22.5) that were retreaded using hot or cold retreading processes. Also in this case, no detailed results were published from this last part, but only some general conclusions were obtained: the difference between the RRCs due to the retreading process may be mainly due to the quantity of material added, and studying other related variables such as the final outside diameter or the profile of the shoulder is suggested; on the contrary, the variation of residual rubber thickness after buffing seems to have a little effect on the RRC; hot retreaded tires display a higher RRC than the cold retreaded ones that were tested; and tires retreaded with a rubber composition with a higher percentage of natural rubber have a lower RRC.

On the other hand, the study carried out by the ETRTO association[21] considered that the main contribution of a tire to the RRC derives from the casing, and since the retreading process requires an end-of-life tire, it is essential to verify its influence. To analyze this, tests were performed on a sample of retreaded tires whereby 33% were tested without tread (buffed). To analyze the influence of the casing, two tire sizes were selected (315/80 R22.5 and 385/65 R22.5), aged between 3 and 5 years, that differed in types of usage (regional and long distance), usage region (North or South Europe), and the number of times they had been retreaded (one or two).

Both from the results of the casings and those of the retreaded tires with these casings, it is concluded that, among other things, the origin of the casing has a strong impact on the RRC, making it difficult to have an average RRC value of a casing of the same size. Significant parameters are the brand, condition, and age of each, and the combination of all the parameters analyzed as a whole determines the influence on RRC in a nonobvious manner. The authors analyzed the global influence of these parameters on the RRC of the casings and its subsequent influence once retreaded with the same compounds. Thereupon, in their quest to analyze the impact of different retreading factors on the RRC (variation of the buffing radius, thickness remaining after buffing, undertread thickness, curing temperature, and time), the casings of new tires were used. New tires of the same sizes and types, from the same manufacturer, and with adjacent dates of manufacture, were retreaded in the same factory and on consecutive manufacturing dates. The same type of precured tread for the cold retreads, the same rubber compound, and the same mold for the hot retreads were used.

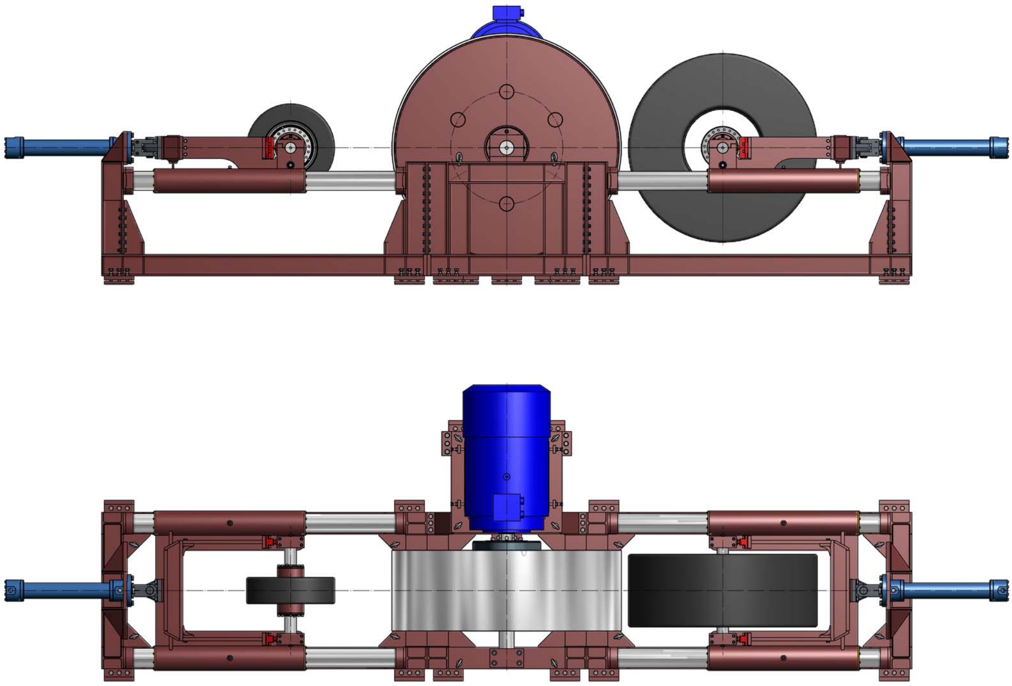

FIG. 1. — Miguel Hernández University test bench for tires.

From the results of this last study, it is inferred, on one hand, that the RRC increases with the thickness of the tread. On the other hand, it is concluded that it is not whether the retreading process is hot or cold that has a highest impact on the RRC but rather the sum of all the variables, with the formulation of the rubber used, the curing time, and the buffing geometry having the most relevance and being directly related to the distribution of material on the section of the tread. It is estimated that the combined impact of those factors may cause a variability of up to 4 N/kN on the RRC.

The conclusions published in the two previous reports are valuable for the interpretation of the factors influencing the RRC that are associated with the condition of the used casings and the retreading process and, thereby, on the RRC of the retreaded tire. It should be noted that the study undertaken and presented in this article was started in parallel with these two studies, before their results were published. Therefore, it was not possible to take the results and conclusions into account to design the test methodology. However, it is considered of special interest to make comparisons with the results shown hereinafter.

EXPERIMENTAL

METHODOLOGY

The rolling resistance tests used the test bench of the Miguel Hernández University of Elche (Figure 1), which allows for the application of the deceleration method prescribed in ISO standard 28580.[22] A test methodology has been defined as an extension of the standard that is adapted to the needs of the study, including thermographic measurements and the analysis of rolling resistance at different speeds.

It is worth pointing out that the test machine used is not aligned to the reference machines listed in European regulations; therefore, the results will not be directly comparable with those obtained by those reference machines, nor will they be valid with regard to the standardization or labeling of tires.

Notwithstanding, preliminary tests were performed with different types of tires, which enabled the test method to be adjusted, repeatability to be analyzed, and the uncertainty of the results obtained to be determined.[23] An analysis of the possible sources of uncertainty associated with the process of obtaining the RRC was undertaken, obtaining uncertainty values of 0.05 N/kN for the truck results and 0.01 N/kN, for the passenger car results.

In light of the results, it can be affirmed that the measurements obtained in the test bench will be perfectly valid for undertaking a research project such as the one described here that attempts to study the differences in RRC between different tires tested in equivalent and directly comparable conditions.

TEST PLAN

Tests were performed on class C1 (passenger car) tires and on class C3 (truck) tires. For each class, samples of new tires and used tires suitable for retreading were tested. Each tire was tested several times in different conditions, according to the following phases:

- Phase 1: Tests on the original tires
- Phase 2: Tests on the casing, after buffing the tire down
- Phase 3: Tests on the tires after retreading with a pattern and tread similar to the originals

That test plan is designed to allow the analysis of the following factors:

- Aging and condition of the casing (by comparing results obtained in phases 2 and 3 for new and used tires)
- The type of casing used (by comparing the results obtained in phase 2 for new tires from different manufacturers)
- Type of material added (by comparing the results obtained in phase 3 for new truck tires, retreaded using three different tread formulations)
- Type of retreading process (by comparing the results obtained in phase 3 for new truck tires, after hot and cold retreading process)
- Percentage influence on the RRC of casing versus tread (by comparing the results obtained in phases 1, 2, and 3 for new and used tires)
- Comparison with the requirements of regulations (by comparing results obtained in phase 3 with the values required by the regulations)
- Difference between new and retreaded tires and their contribution to CO_2 reduction (by comparing results obtained in phases 1 and 3 for new and used tires)

Test Plan for Truck Tires. — To perform the tests on the samples of truck tires, according to the phases above, the diagram represented in Figure 2 was followed. Below, we describe the characteristics of each group.

To create the sample of new truck tires, tires of the same type and from the same manufacturer were selected, from which it was expected to obtain very similar RRC values. Tires with the designation 315/70 R22.5 154/150L, which are regularly used for the long-distance transport of goods, were selected. The tread pattern is mixed with grooves and rectangular blocks, regularly used on tractor axles. All tires had been manufactured in 2015 and had the same fuel-efficiency score: B. From the rubber used in the tread, neither the formulation of the rubber nor its rheological properties were known. This sample was given the name C3_N.

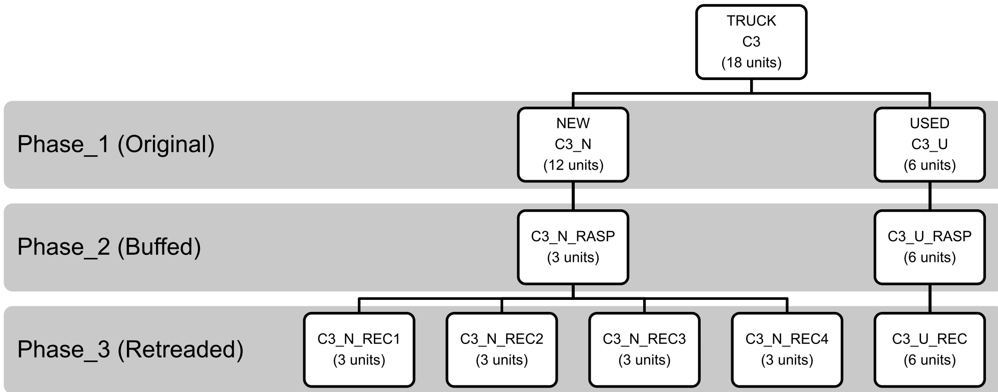

FIG. 2. — Test plan for truck tires.

For the used tires, it was decided to use tires from the same manufacturer and of the same size as the new ones, but of different types, different manufacturing dates, and different degrees of wear. Despite the fact that they would all subsequently be retreaded using the same molds and patterns, it was decided to use a sample of tires of different types and characteristics. This is because, in practice, when casings are initially received at retreading factories, an exhaustive check of their dimensions, geometry, and the state of repair of their structure is undertaken, but no differentiation is usually made between models, tread patterns, or tire types. Two of the samples had a load index and speed code of 154/150L and the rest of 156/150L. Three of the samples had a mixed tread pattern of grooves and rectangular blocks, and the rest had circumferential grooves (normally for more polyvalent use with the ability to be fitted on any axle). The samples were chosen with dates of manufacture between 2010 and 2014, with fuel-efficiency scores before being used of D, B, or C. As in the previous case, the formulation of the rubber and/or its rheological properties was not known. The name of the sample was C_U.

The sample of new buffed tires was made up of only three of the previous new tires. These were buffed and assigned the name C3_N_RASP. The sample of used buffed tires consisted of all the buffed tires from the previous phase, to which the name C3_U_RASP was assigned. The characteristics of the buffing selected were a buffing radius of 1000 mm and a remaining rubber thickness of no more than 2 mm.

Nine of the 12 tires from the new tire sample were buffed with the same characteristics as before and retreaded by hot process. They were retreaded on the same date, and the same retreading process, mold, and procedure were used to manufacture the tires of dimensions 315/70R22.5 and load index and speed code 154/150L. The mold pattern confers upon the tread a mixed pattern of grooves and rectangular blocks similar to the pattern of the new ones. To analyze the influence of the rubber employed, retreading was done with three different formulations habitually used by retreading manufacturers. The formulation of the aggregate rubber is not known, but its rheological properties are (see Table I). These tires were assigned sample names of C3_N_REC1, C3_N_REC2, and C3_N_REC3 according to the rubber used. The fuel-efficiency score was not known, as they are exempt from labeling compliance and the manufacturer is not obliged to provide it.

The other three remaining buffed tires tested in the previous phase were retreaded by cold process (using a precured tread) with the same measurements, load index, and speed code as those that were retreaded hot. The pattern of the tread added was also chosen to be as similar as possible to the previous ones. The formulation of the rubber of the tread added was also not known in this case,

TABLE I
RHEOLOGICAL PROPERTIES OF THE COMPOUNDS

Property	REC1	REC2	REC3
Abrasion resistance index	69	65	43
Delta tangent at 0°, °C	0.139	0.13	0.094
Delta tangent at 60°, °C	0.113	0.097	0.092
Glass transition temperature, °C	−47.6	−48.6	−52.6
Rebound at 23°, % of °C	42	42	49
Rebound at 60°, % of °C	52	53	57

nor was its fuel-efficiency score. These tires were assigned the sample name C3_N_REC4. To the average value of the results of all the truck tire samples retreaded, whether hot or cold, was assigned the name C3_N_REC.

Finally, using the rubber that obtained the best results from the previous phases, all used tires from the previous phase were retreaded hot. To do so, they were all retreaded on the same date, and the same mold and procedure were used as for the new retreaded samples. In this case, the sample name C3_U_REC was assigned.

Test Plan for Passenger Car Tires. — In this case, the diagram represented in Figure 3 was followed for testing the passenger car tires. Below, we describe the characteristics of each group.

To create the samples for the new passenger car tires, tires of two types and from two manufacturers were selected: (1) one sample of four tires of a first brand and (2) a further four tires of a second low-cost brand. Both samples enabled conclusions to be drawn about the influence of the type of casing used for retreading. Tires with the designation 185/65 R15 88H and with a mixed tread pattern of grooves and rectangular blocks, habitually used by small light utility vehicles, represent a large proportion of the European fleet and also comprise the segment (along with all-terrain vehicles) constituting a large proportion of retread sales for passenger cars. The name C1_N1 was assigned to the sample of tires of the first brand and C1_N2 to those of the second brand.

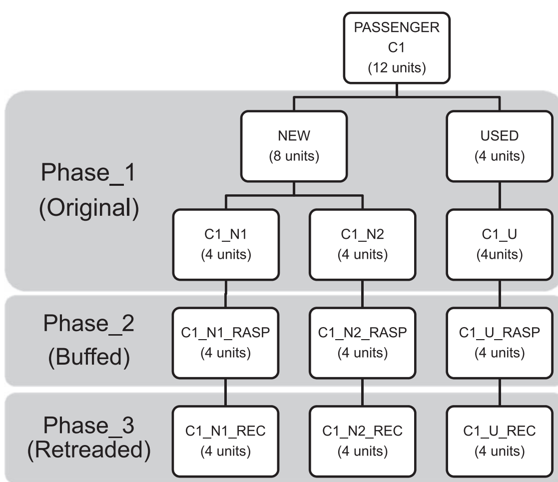

FIG. 3. — Test plan for passenger car tires.

For both samples, tires were chosen with manufacturing dates between 2011 and 2012, with a fuel-efficiency score C for the C1_N1 and unknown for C1_N2 (manufactured prior to the European label becoming compulsory). In this case, the formulation of the rubber and/or its rheological properties was also not known for either sample.

For the used passenger car tires, samples of tires were selected of the same brand, type, tread pattern, and designation as the new ones of the first brand, except for the speed code, which was T in this case. The date of manufacturing was 2010. It is also worth mentioning that this is a complete set of tires from the same vehicle, which, despite displaying similar aging conditions, may display different degrees of wear due to where they were fitted to the vehicle. The fuel-efficiency score of the tires before being used was C. As in the previous case, from the rubber used in the tread, the formulation of the rubber and/or its rheological properties was not known. The name of the sample was C1_U.

The buffed tire sample is made up of eight new tires and four used ones from the previous phase to which was assigned the name C1_N1 RASP for the new buffed ones from the first manufacturer, C1_N2_RASP for the new buffed ones from the second manufacturer, and C1_U RASP for the buffed used ones. The buffing characteristics selected were a buffing radius of 295 mm and a thickness of remaining rubber of no more than 2 mm.

All the tires from the previous phase were retreaded hot, using the same mold and procedure to obtain tires with the designation 185/65 R15 88H. The mold pattern confers upon the tread a mixed pattern of grooves and rectangular blocks similar to the pattern of the new ones. The formulation of the aggregate rubber and/or its rheological properties is not known either in this case. All tires were retreaded on the same date, and they were assigned the sample names C1_N1_REC, C1_N2_REC, and C1_U_REC, according to the origin of the sample from the previous phase.

RESULTS AND DISCUSSION

MAIN RESULTS

In Table II and Figure 4, the main average results for the mass, outside diameter, and RRC at 80 km/h are shown for the truck samples tested. In Table III and Figure 5, the results for the passenger car samples are shown.

STATISTICAL ANALYSIS (VALIDITY AND SIGNIFICANCE OF THE RESULTS)

Because the sample size is not too large, a statistical analysis of the results was carried out to verify that the deviations between tests were much lower than the differences between the average results of the samples. Thus, we can guarantee that the samples compared are representative of two different populations.

To determine which variables have a greater influence on RRC, an analysis of the Pearson coefficient correlation was made between all results. The variables with the highest correlation were the mass and the outside diameter without load. These results are displayed in Tables IV and V, and the extended results can be found within the associated reference.[23] In view of the results, it was decided to obtain a statistical analysis using only the main variable (RRC) and the variables with the highest correlation.

A postprocess analysis of variance (ANOVA; HSD Tukey) was made between different samples using the variables with the highest correlation. A 95% confidence level (0.05 alpha value) was used. The objective of this analysis was to identify homogeneous groups of samples and analyze the degree of equality between them. The ANOVA presupposes a normal distribution of the results and a variance homogeneity between samples. These two assumptions were validated with a

TABLE II
MAIN AVERAGE TRUCK RESULTS

State	Phase	Sample	Mass, kg	Outside diameter without load, mm	RRC at 80 km/h, N/kN
New	1	C3_N	61.1	1016.0	4.709
	2	C3_N_RASP	45.9	985.2	3.302
	3	C3_N_REC1	66.2	1028.4	7.563
		C3_N_REC2	66.3	1028.5	7.255
		C3_N_REC3	66.2	1028.1	7.633
		C3_N_REC4	65.9	1026.0	7.790
		C3_N_REC 1, REC2, REC3	66.2	1028.3	7.484
		C3_N_REC	66.1	1027.7	7.560
Used	1	C3_U	52.3	1001.9	4.000
	2	C3_U_RASP	43.7	985.0	3.891
	3	C3_U_REC	63.2	1025.5	7.624

Kolmogorov–Smirnov and Shapiro–Wilk statistical test as well as the Levene and Brown–Forsythe statistical test, respectively. A summary of Tukey analysis results are shown in Tables VI, VII, and VIII for trucks and in Tables IX, X, and XI for passenger cars. A more extended statistical analysis of the results can be found in ref 23.

The analysis confirms that the differences found between the samples compared are greater than the values of expanded uncertainty obtained, and the separation between the means of the results is enough to guarantee that the samples belong to two different populations. Therefore, we can conclude that the results of the comparisons are valid.

COMPARATIVE ANALYSIS OF THE RESULTS

Below, we analyze the differences between the average values of the results obtained.

Influence of Aging and Condition of the Casing. — Analyzing the truck sample results, in the graphs of Figure 6a, comparing the RRC of the new (C3_N_RASP) and used (C3_U_RASP) casings, it can be seen that the RRC of the used casings is 18% higher than that of the new ones. Comparing the results after retreading, the trend goes in the same direction, but the difference is significantly smaller: the used retreaded casings (C3_U_REC) are 5% higher than the new ones (C3_N_REC2). On the other hand, Figure 6b shows that the mass of the used casings is lower than that of the new ones and that the quantity of material added after the retreading is practically the same in both cases.

The rise in the RRC of the used casings may be due to the loss of properties of the casing materials, which may have increased the losses through hysteresis with respect to the new ones. The lower mass found in the casings may be due to the crushing caused by the centrifugal forces and the load applied in its circulation and that, having been buffed to the same outside diameter, more material may have been eliminated. Both conclusions may be consistent with the aforementioned conclusions of J. R. Luchini et al.[19] Notwithstanding, the difference in the RRC is more moderate after retreading, possibly because the second vulcanization of the casings evened out their properties. The casing materials could have increased their viscous behavior during aging, and the revulcanization could have reversed this effect. According to the conclusions drawn by Futamura

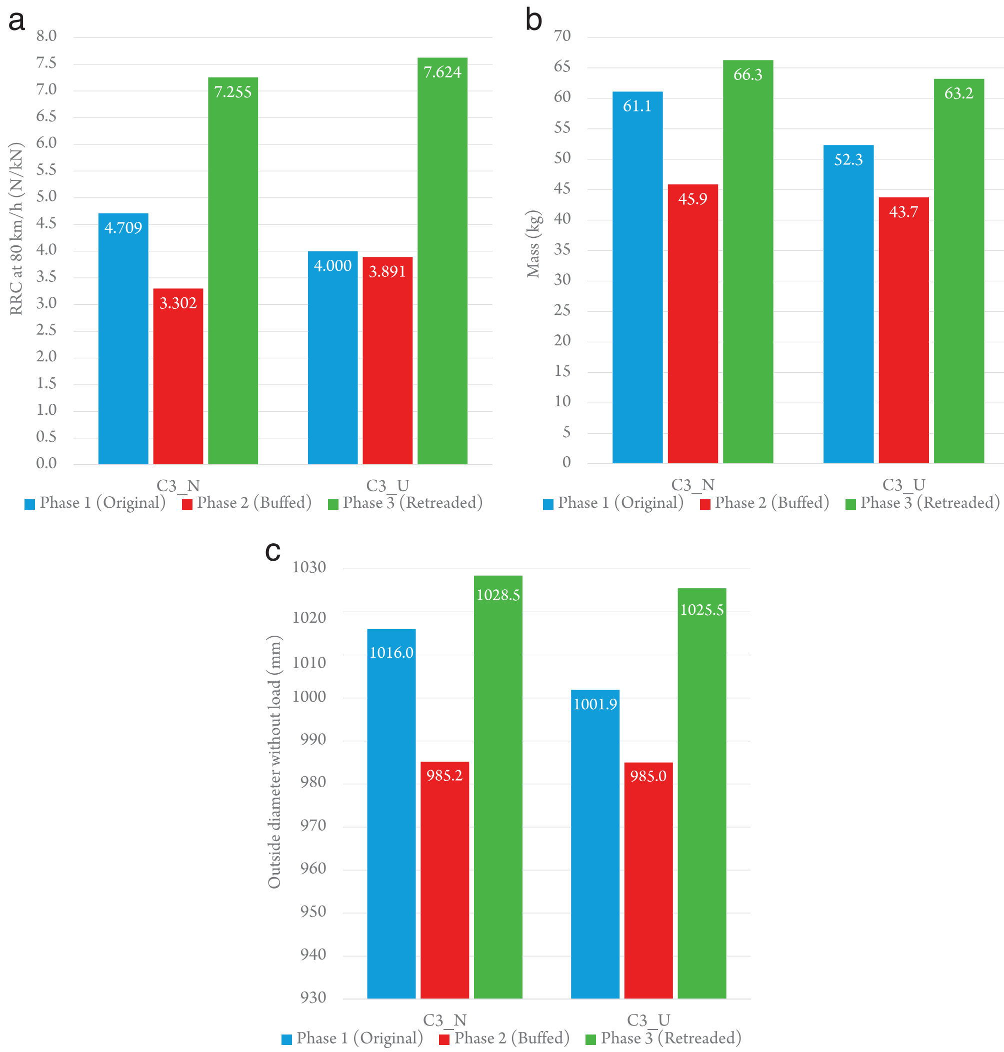

FIG. 4. — Main average truck results: (a) rolling resistance coefficient at 80 km/h; (b) tire mass; (c) outside diameter without load.

and Goldstein,[15] the change induced in the stiffness of the casing materials could also have an effect on the properties of the tread material.

Analyzing the results of the passenger car samples, in the graphs of Figure 7a, comparing the RRC of the new (C1_N1_RASP) and used (C1_U_RASP) casings, a 10% reduction in the RRC of the used casings can be seen. This effect is contrary to the one seen in the truck test but again is consistent with the results obtained by J. R. Luchini et al.[19] If we observe this same difference after retreading, the trend goes again in the same direction, with the used retreaded casings (C1_U_REC), in this case, being 2% lower than the new ones (C1_N1_REC). Figure 7b shows the masses of the new and used casings. In this case, the mass of the used casings was slightly lower, and the quantity of material added after retreading was the same. Thus, as with the truck samples, and possibly due to the same causes, the difference in the RRC was more moderate after retreading.

TABLE III
MAIN AVERAGE PASSENGER CAR RESULTS

State	Phase	Sample	Mass, kg	Outside diameter without load, mm	RRC at 80 km/h, N/kN
New	1	C1_N1	7.2	623.2	8.058
		C1_N2	8.1	628.2	9.644
	2	C1_N1_RASP	5.0	608.0	5.698
		C1_N2_RASP	5.9	612.9	6.939
	3	C1_N1_REC	8.2	625.2	9.901
		C1_N2_REC	9.4	628.0	12.007
Used	1	C1_U	6.2	617.4	6.459
	2	C1_U_RASP	4.9	609.0	5.116
	3	C1_U_REC	8.1	626.0	9.699

For the best understanding of the global aging influence, a more complex analysis would be needed to take into account all possible factors and interactions.

Influence of the Casing Used. — In Figure 8a, a 22% difference in the RRC between new casings from the first manufacturer and the second was seen, with that of the second manufacturer being higher. This difference was maintained after retreading. Thus, the type and characteristics of the casing seems to be a determining factor in this loss, which coincides with the conclusions described in the final report of the ETRTO[21] study into the type of casing used initially and its influence on the RRC once retreaded. On the other hand, in Figure 8b, it can be seen that similar percentages of mass were eliminated in the buffing and added after retreading in both cases, so the main variability in the results may be attributable to the influence of the type of casing and/or manufacturer. On the other hand, it is also worth pointing out that the retreaded samples from the first manufacturer (C1_N1_REC) almost equal the RRC values of the new tires from the second manufacturer (C1_N2). Thus, we may find new and retreaded tires on the market with equal dimensions that fulfill the same expectations with regard to fuel consumption.

Influence of the Type of Material Added. — Comparing the results of the new truck tires retreaded with different formulations of rubber, in Figure 9a, a maximum difference of 5% between the RRC of all the retreaded groups can be seen. Observing the results of the hot retreaded samples, we see a clear difference in the RRC of the C3_N_REC2 sample with respect to the other two. If we compare these results with the rheological results of the compounds in Table I, we observe that the indicative value of the delta tangent at 60°, which is directly related to the RRC, displays very low values for this sample. On the other hand, the C3_N_REC3 sample obtained even lower values, which does not coincide with the RRC results obtained and which may be due to a lower capacity to dissipate heat outward than the rest. In any event, the C3_N_REC3 sample turned out to have worse abrasion properties (resistance to abrasion index) and wet grip (delta tangent at 0°), as well as a higher RRC value than the rest. Therefore, it was considered that the C3_N_REC2 sample was the most suitable to retread the used samples.

Influence of the Type of Retreading Process. — Comparing the average of the hot retreaded results with the cold retreads, in Figure 9b, the difference seen was only 4%, with the sample retreaded cold being higher, which contradicts the results of both the RETYRE[20] and ETRTO[21] studies. It is worth noting that, as well as being a small sample, the tire sizes used in this study do not coincide with those of previous studies. On the other hand, the variety of possible rubber

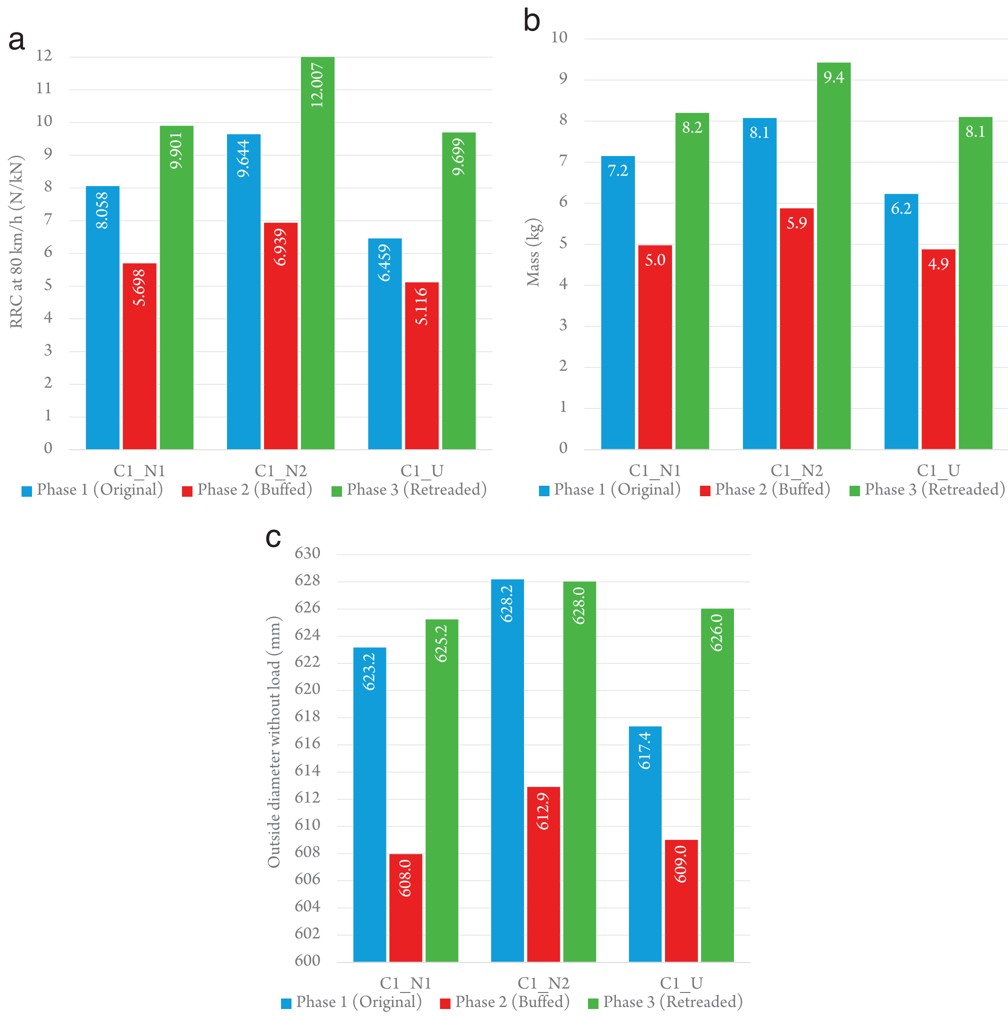

FIG. 5. — Main average passenger car results: (a) rolling resistance coefficient at 80 km/h; (b) tire mass; (c) outside diameter without load.

formulations and process parameters using for retreading is enormous. Thus, much larger samples should be studied to obtain general conclusions on the influence of those parameters.

Percentage Influence on the RRC of Casing versus Tread. — Below, the percentage influence on the RRC attributable to the tread and to the casing in relation to the total RRC of the tire is represented in pie charts. In Figure 10, we can observe the results for truck tires, while the passenger car results are shown in Figure 11. It is worth mentioning that the casing influence obtained for new truck tires (70%) is significantly higher than the that obtained by other authors,[15,20] although the types of tires are different and may not be comparable.

It can be seen that the percentage influence on the RRC of the tread rises after retreading. This influence is greater on truck tires than on passenger car tires, probably because the quantity of material added to the tread was higher in the truck samples. Note that, in Figure 11, both the samples from the first manufacturer and those from the second coincide in contribution proportions of casing and tread, which is why they are represented together.

TABLE IV
TRUCK TIRE VARIABLES WITH THE HIGHEST CORRELATION[a]

Pearson coefficient correlation for truck samples			
	RRC at 80 km/h, N/kN	Mass, kg	Outside diameter without load, mm
RRC at 80 km/h, N/kN	1	0.816	0.849
Mass, kg	0.816	1	0.972
Outside diameter without load, mm	0.849	0.972	1

[a] The correlation is significant at the 0.01 level (bilateral).

On the other hand, we can observe that the percentages of influence on the RRC of tread and casing tend to 50% in both cases after retreading used tires, because of the effect of different signs of the aging measured for truck and passenger car tires, respectively.

Comparison of the Values Demanded by the Regulations. — In this section, the average RRC value obtained from all retreaded samples compared with the levels demanded for new tires according to current regulations[2,3] was analyzed. We can see a summary of the values demanded in Tables XII and XIII.

For the retreaded truck samples, RRC values of 7.14–7.85 N/kN were obtained, with an average of 7.60 N/kN, which would be equivalent to a class E, according to labeling regulation 3, shown in Table XIII. These values would currently permit the commercialization of the retreaded tires for the values demanded by the regulation (shown in Table XII) for the first phase should these same criteria be applied to new tires. On the other hand, when the second phase comes into force, many of these would not pass the established requirements.

For the passenger car samples, RRC values of 9.39–10.10 N/kN were obtained, with an average of 9.75 N/kN, for the first manufacturer; 11.86–11.92 N/kN, with an average of 11.89 N/kN, for three tires from the second manufacturer; and 12.35 N/kN for one tire from the second manufacturer. According to the labeling regulation, these values would be equivalent to classes E, F, and G, respectively. In this case, the values would also permit the commercialization of the retreaded tires for the first phase, except for one tire from the second manufacturer. On the other hand, when the second phase comes into force, the tires from the second manufacturer would not comply, and only some of the first phase would pass the established requirements.

Difference between New and Retreaded Tires' Contribution to CO_2 Reduction. — In the graphs of Figure 12, the new tires (C3_N, C1_N1) are compared with the retreaded tires (C3_U_REC and C1_U_REC), taking the state of repair of the casing into account. In all cases, it is

TABLE V
PASSENGER TIRE VARIABLES WITH THE HIGHEST CORRELATION[a]

Pearson coefficient correlation for passenger samples			
	RRC at 80 km/h, N/kN	Mass, kg	Outside diameter without load, mm
RRC at 80 km/h, N/kN	1	0.985	0.915
Mass, kg	0.985	1	0.957
Outside diameter without load, mm	0.915	0.957	1

[a] The correlation is significant at the 0.01 level (bilateral).

TABLE VI
RRC TUKEY ANALYSIS RESULTS FOR TRUCK TIRES

HSD Tukey, RRC at 80 km/h, N/kN				
	Subset for alpha = 0.05			
Sample reference	1	2	3	4
C3_N_RASP	3.302			
C3_U_RASP		3.891		
C3_U		4.000		
C3_N			4.709	
C3_N_REC1, REC2, REC3				7.484
C3_N_REC1, REC2, REC3, REC4				7.560
C3_U_REC				7.624
Signification	1.000	0.967	1.000	0.894

observed that the RRC of the retreaded tires is significantly higher than the new ones, specifically by 62% for the truck and 20% for the passenger car samples. The truck tire samples increased the RRC after retreading to a larger extent than the passenger car tires. Applying a common return factor of 5:1,[18] an influence on fuel economy of 12.4 and 4% can be estimated for truck and passenger cars, respectively, which is directly proportional with the increase in CO_2 emissions.

For the truck samples of this study (Figure 12a), it is worth pointing out that the retreaded tires have a greater tread thickness than the new ones, because retreaded tire manufacturing regulations permit this.[24] Users usually request a greater tread thickness for longer duration, and the quantity of material added has been shown to have a great influence on the RRC. Furthermore, new tires with low RRC have been used for comparison.

For the passenger car samples (Figure 12b), the percentage increase in RRC was the same for the two brands studied. In this case, retreading with a greater diameter is not permitted, but the new tires selected for comparison from the first manufacturer also have low RRC.

TABLE VII
MASS TUKEY ANALYSIS RESULTS FOR TRUCK TIRES

HSD Tukey, mass, kg					
	Subset for alpha = 0.05				
Sample reference	1	2	3	4	5
C3_U_RASP	43.5				
C3_U_RASP	43.7				
C3_U		52.3			
C3_N			61.1		
C3_U_REC				63.2	
C3_N_REC1, REC2, REC3, REC4					66.2
C3_N_REC1, REC2, REC3					66.3
Signification	0.998	1.000	1.000	1.000	1.000

TABLE VIII
OUTSIDE DIAMETER WITHOUT LOAD TUKEY ANALYSIS RESULTS FOR TRUCK TIRES

HSD Tukey, outside diameter without load, mm				
	Subset for alpha = 0.05			
Sample reference	1	2	3	4
C3_U_RASP	985.0			
C3_N_RASP	985.2			
C3_U		1001.9		
C3_N			1016.0	
C3_U_REC				1025.5
C3_N_REC1, REC2, REC3, REC4				1027.8
C3_N_REC1, REC2, REC3				1028.4
Signification	1.000	1.000	1.000	0.622

In both cases, we are a long way from reaching low RRC values for retreaded tires and, therefore, equal or lower emission levels than the ones obtained with new modern tires. However, in the case of truck tires, a comparison undertaken on the same thickness of tread material would probably show results for retreaded tires that are better than those obtained here. Therefore, their contribution to reducing emissions would be greater.

On the other hand, for passenger cars, it is noticeable that tires retreaded using casings from the first brand can provide RRC values equivalent to new tires from secondary brands. Therefore, both their influence on fuel consumption and emissions levels would also be equivalent.

TABLE IX
ENERGY EFFICIENCY CLASS TUKEY ANALYSIS RESULTS FOR PASSENGER TIRES

HSD Tukey, RRC at 80 km/h, N/kN							
	Subset for alpha = 0.05						
Sample reference	1	2	3	4	5	6	7
C1_U_RASP	5.116						
C1_N1_RASP		5.698					
C1_U			6.459				
C1_N2_RASP				6.939			
C1_N1					8.058		
C1_N2						9.644	
C1_U_REC						9.699	
C1_N1_REC						9.901	
C1_N2_REC							12.007
Signification	1.000	1.000	1.000	1.000	1.000	0.659	1.000

TABLE X
MASS TUKEY ANALYSIS RESULTS FOR PASSENGER TIRES

HSD Tukey, mass, kg						
	Subset for alpha = 0.05					
Sample reference	1	2	3	4	5	6
C1_U_RASP	4.9					
C1_N1_RASP	5.0					
C1_N2_RASP		1.9				
C1_U			6.2			
C1_N1				7.2		
C1_N2					8.1	
C1_U_REC					8.1	
C1_N1_REC					8.2	
C1_N2_REC						9.4
Signification	0.866	1.000	1.000	1.000	0.670	1.000

TABLE XI
OUTSIDE DIAMETER WITHOUT LOAD TUKEY ANALYSIS RESULTS FOR PASSENGER TIRES

HSD Tukey, outside diameter without load, mm							
	Subset for alpha = 0.05						
Sample reference	1	2	3	4	5	6	7
C1_N1_RASP	608.0						
C1_U_RASP	609.0						
C1_N2_RASP		613.0					
C1_U			617.4				
C1_N1				623.1			
C1_N1_REC					625.2		
C1_U_REC					626.1	626.1	
C1_N2_REC						628.1	628.1
C1_N2							628.2
Signification	0.720	1.000	1.000	1.000	0.886	0.057	1.000

TABLE XII
RRC BY REQUIREMENT PHASES OF REGULATION (EC) NO. 661/2009[2]

Maximum RRC value in kg/t[a]		
Tire class	First phase	Second phase
C1	12.0	10.0
C2	10.5	9.0
C3	8.0	6.5

[a] N/kN. For snow + 1 N/kN.

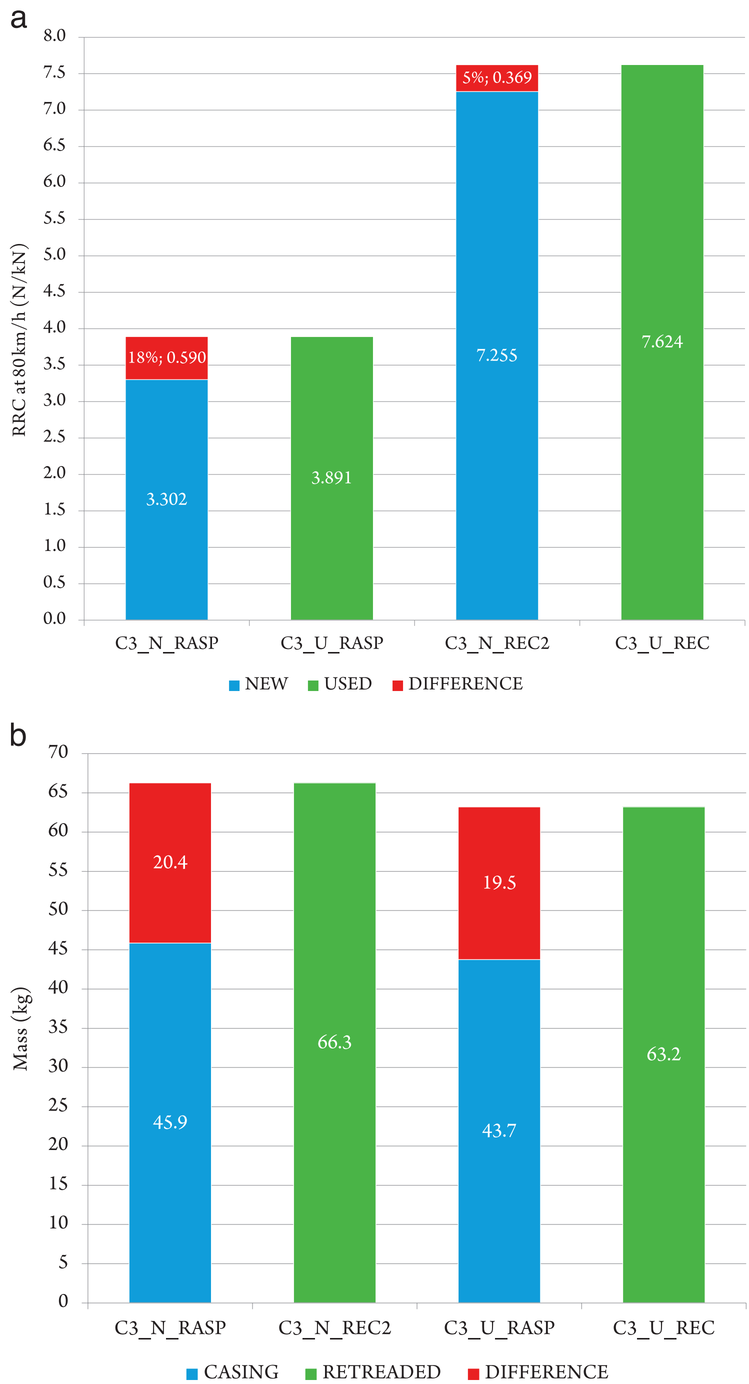

FIG. 6. — Comparison of the RRC and the mass of casings and retreaded truck samples: (a) difference in RRC; (b) difference in mass.

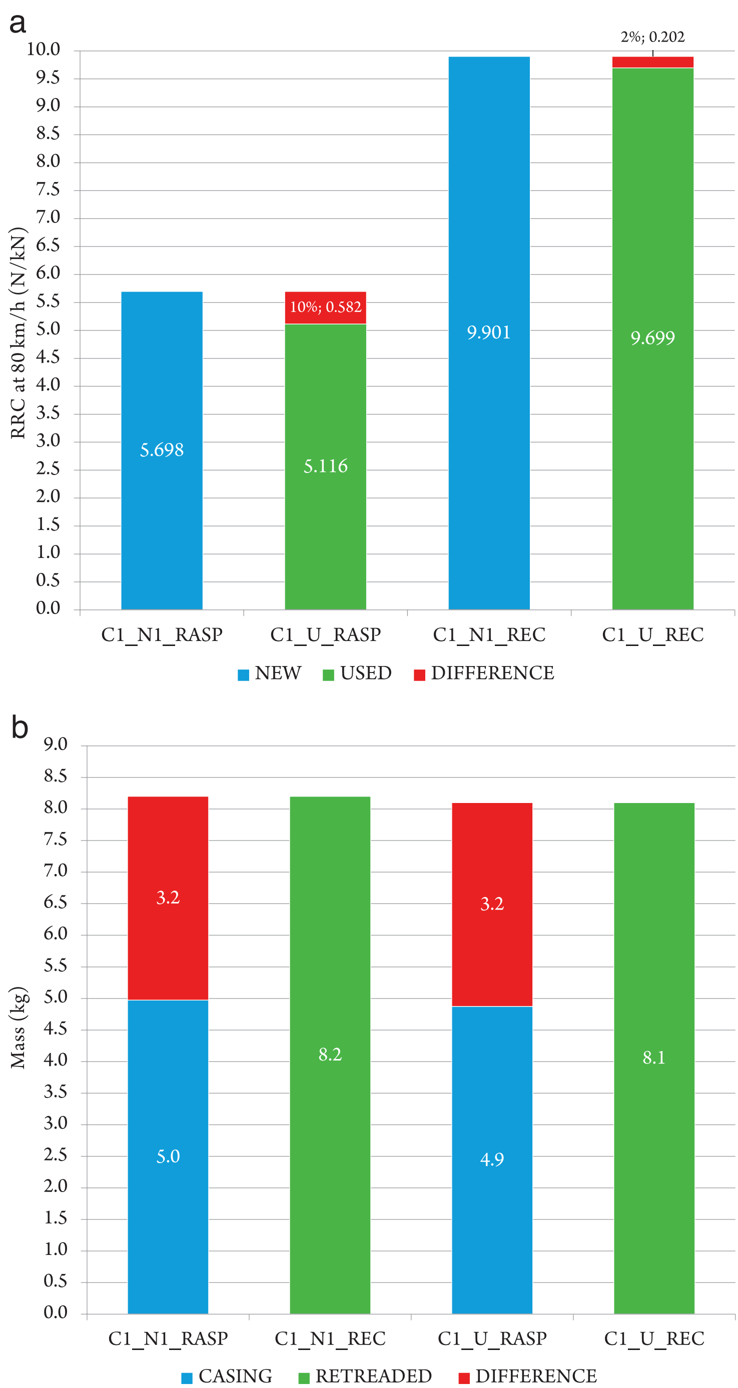

FIG. 7. — Comparison of the RRC and the mass of casings and retreaded passenger car samples: (a) difference in RRC; (b) difference in mass.

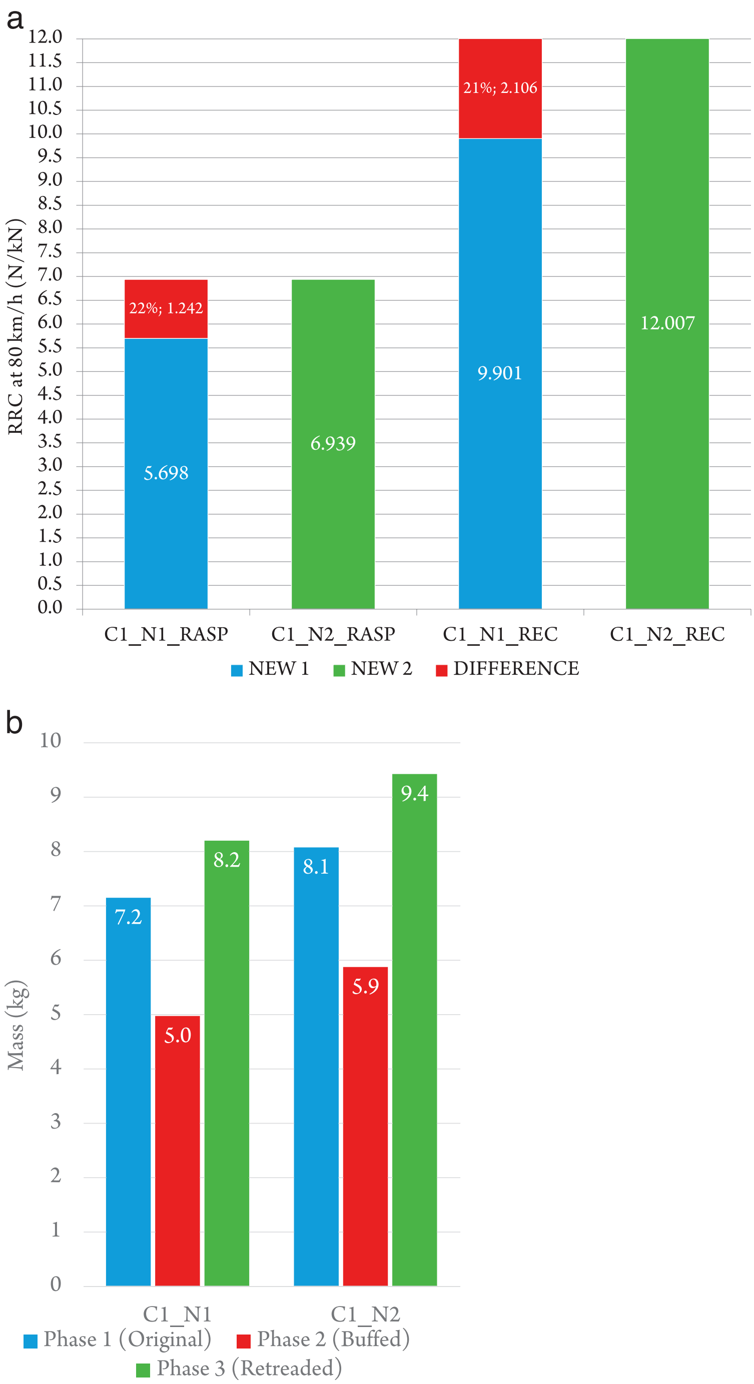

FIG. 8. — Comparison of the RRC and mass between buffed and retreaded samples from two manufacturers: (a) difference in RRC; (b) difference in mass.

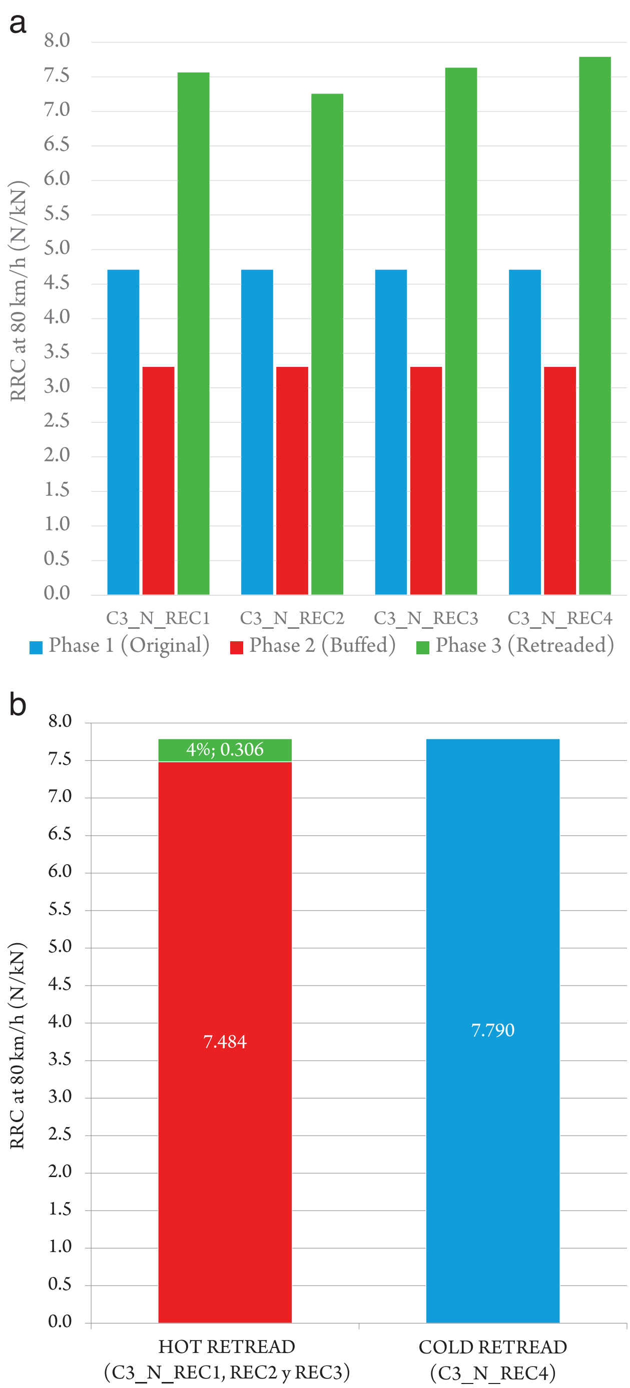

FIG. 9. — Comparison of the RRC between samples with different formulations and/or retreading process: (a) RRC new retreads; (b) difference between cold retreaded and hot retreaded tires.

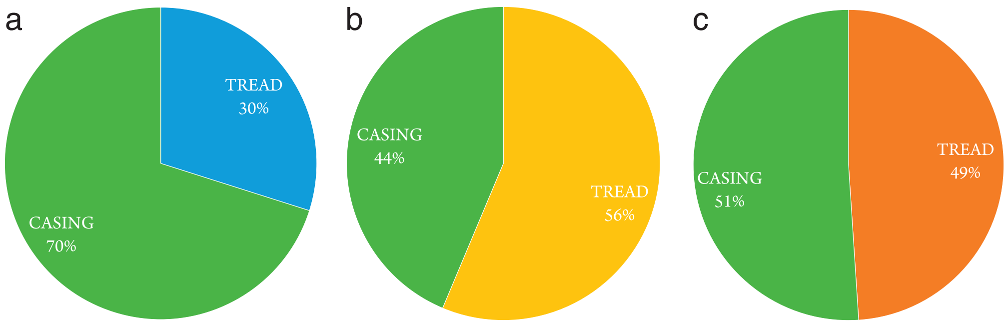

FIG. 10. — Proportion of RRC attributable to the casing and to the tread in class C3 tires: (a) new tires (C3_N); (b) retreaded new tires (C3_N_REC); (c) retreaded used tires (C3_U_REC).

RRC AT DIFFERENT SPEEDS

Using the same methodology, RRC values were obtained at different speeds of 70, 80, and 90 km/h (Figure 13). In light of these graphs, we can say that all the conclusions previously drawn for a speed of 80 km/h are also valid for speeds of 70 and 90 km/h. The RRC depends on the speed in an almost linear manner (in the speed range considered), and the influence of speed is greater for tires with higher RRC values.

Comparing these results with a graph taken from the book *The Pneumatic Tire*,[9] shown in Figure 14, we can see that the conclusions about the influence of speed on the RRC coincide for the speeds examined in this study. It is worth noting that the speeds studied can be considered representative for truck tires, because they match normal driving speeds of trucks. In the case of passenger car tires, it might have made more sense to perform an evaluation at higher speeds.

CONCLUSION

There is a great difference between the RRC of new tires and the RRC of the same tires once buffed and retreaded. This difference can also be seen, although in a different ratio, between the mass and outside diameter of the same samples. It must be taken into account that, in the retreaded truck tires, it is usual to introduce greater tread thicknesses in the pursuit of greater durability. Notwithstanding this, the quantity of material added seems to have a great influence on the RRC.

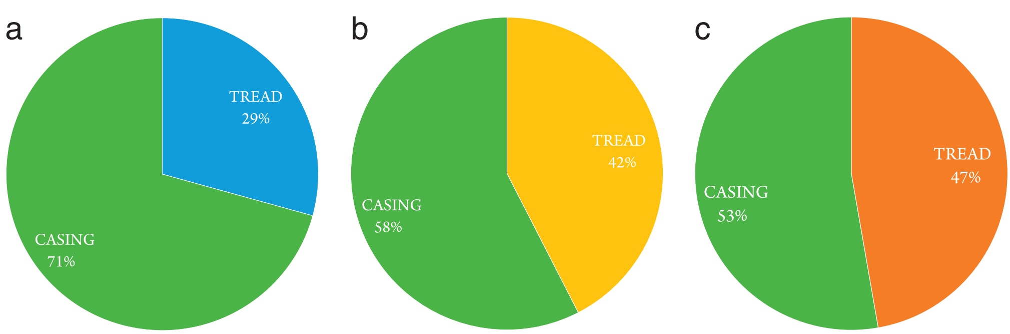

FIG. 11. — Proportion of RRC attributable to the casing and to the tread in class C1 tires: (a) new tires (C1_N1 and C1_N2); (b) retreaded new tires (C1_N1_REC and C1_N2_REC); (c) retreaded used tires (C1_U_REC).

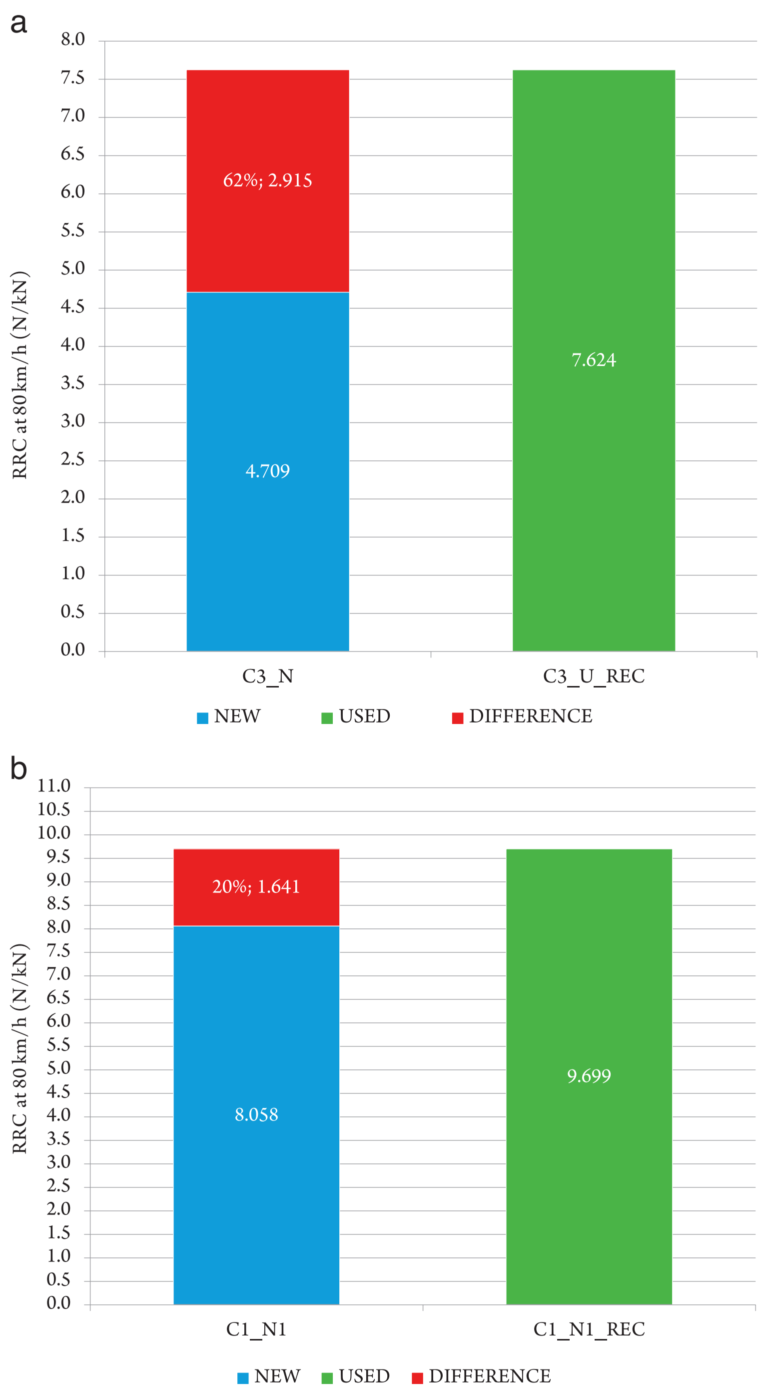

FIG. 12. — Differences between new and retreaded tires: (a) for truck tires (C3); (b) for passenger car tires (C1).

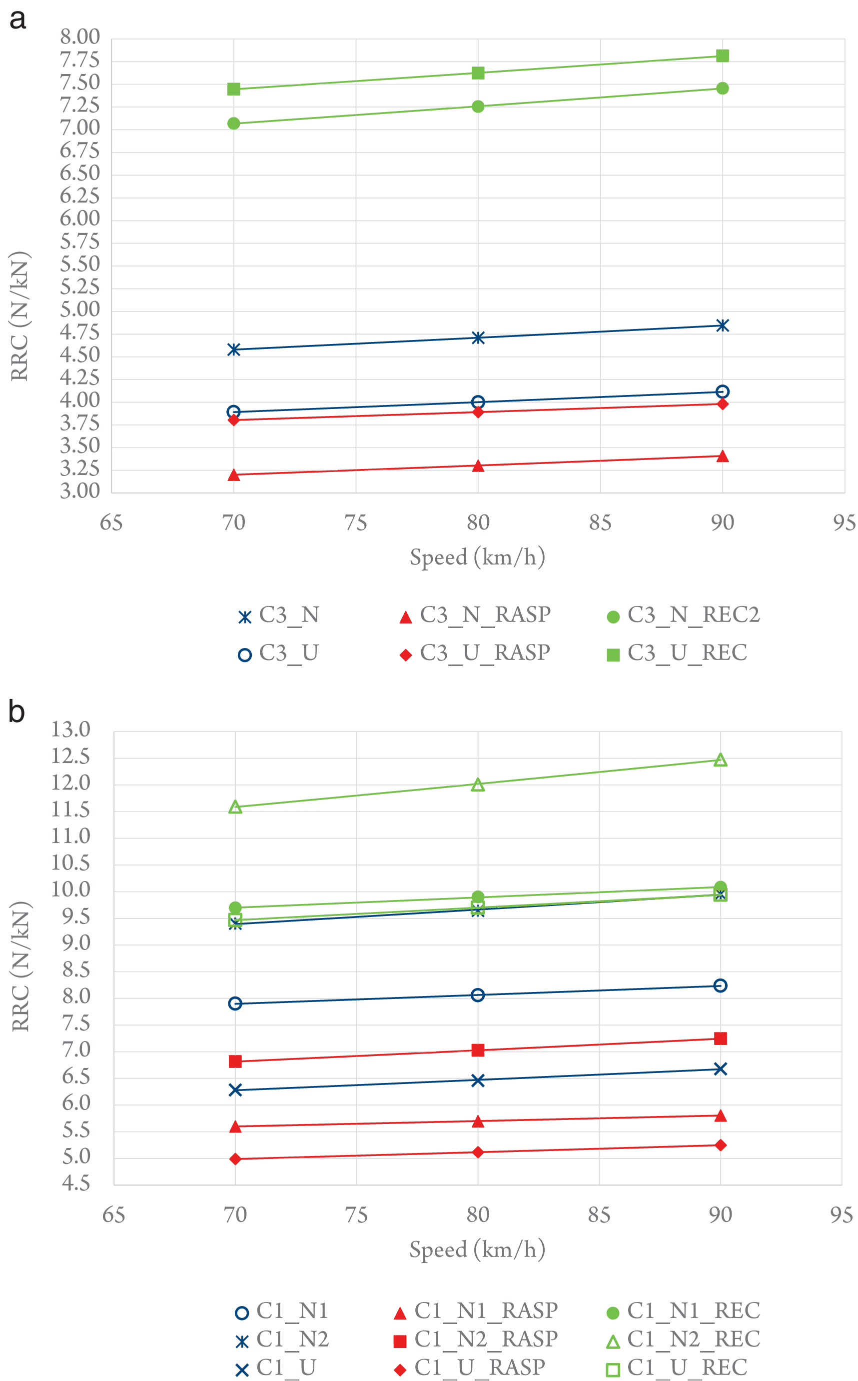

FIG. 13. — RRC at different speeds: (a) for truck tires (C3); (b) for passenger car tires (C1).

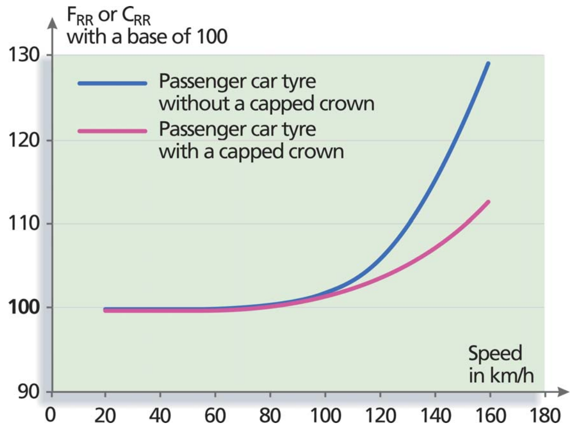

FIG. 14. — Influence of speed on the RRC.[9]

The percentage contributions to the RRC of the casings and the tread have been established. In light of the results, the percentage influence of the tread on the RRC is, in all cases, significantly higher in the retreaded tires than in the original tires.

The differences observed between the RRC of new buffed casings and used ones are reflected in a similar way on the RRC of the retreaded tires from the same tires. In the case of the truck tires, the loss of properties of the casings and the material remaining on them penalized, to a certain extent, the RRC of the retreaded tires from the buffed used casings. However, for the passenger car tires, the retreading on used casings led to slightly better results than with new casings of the same type. In any event, the differences found between the casings are more moderate after retreading; therefore, it can be interpreted that the state of the casing has a low influence on the RRC of the retreaded tire.

With respect to the retreading process and rubber used, small differences were obtained between the retreaded tires with different formulations and some differences between the cold and retreading processes of the same order. It was not possible to analyze the influence of the parameters used by different manufacturers in the retreading process, such as temperature and vulcanization

TABLE XIII
FUEL-EFFICIENCY SCORE ESTABLISHED IN REGULATION C (EC) NO. 1222/2009[3]

C1 tires		C2 tires		C3 tires	
RRC in kg/t[a]	Energy efficiency class	RRC in kg/t[a]	Energy efficiency class	RRC in kg/t[a]	Energy efficiency class
$RRC \leq 6.5$	A	$RRC \leq 5.5$	A	$RRC \leq 4.0$	A
$6.6 \leq RRC \leq 7.7$	B	$5.6 \leq RRC \leq 6.7$	B	$4.1 \leq RRC \leq 5.0$	B
$7.8 \leq RRC \leq 9.0$	C	$6.8 \leq RRC \leq 8.0$	C	$5.1 \leq RRC \leq 6.0$	C
Empty	D	Empty	D	$6.1 \leq RRC \leq 7.0$	D
$9.1 \leq RRC \leq 10.5$	E	$8.1 \leq RRC \leq 9.2$	E	$7.1 \leq RRC \leq 8.0$	E
$10.6 \leq RRC \leq 12.0$	F	$9.3 \leq RRC \leq 10.5$	F	$RRC \geq 8.1$	F
$RRC \geq 12.1$	G	$RRC \geq 10.6$	G	Empty	G

[a] N/kN.

time and differences in the geometry of the buffed casing, the geometry of the section of tread added, and so forth. In our case, all conditions were kept constant, except for the formulation of the rubber used in the hot retreading, and it was found that the differences between the rubbers were not excessively great.

With respect to the differences between different original tire manufacturers, the difference between the RRC of the two brands of new passenger car tires tested (one leading brand and one low-cost brand) was very large. This difference even increased significantly after retreading the tires. Therefore, the properties of the original casings and their capacity to maintain said properties after the retreading process also appear to be factors that are potentially very influential.

To assess the influence of the parameters used in the retreading, and also of the brand and the type of casing used, would require a study with a much wider sample that includes more types of casings and manufacturers. This would result in a very elevated sample size that would greatly exceed the possibilities of this study. Nonetheless, the conclusions drawn in this study regarding, for example, the influence of the state of the carcass are considered to be valid. Therefore, the methodology developed can be extrapolated for use in other studies of greater scope.

Although having a higher RRC value than new tires, the RRC of retreaded truck and passenger car tires meet the minimum requirements in force today for new tires, established by Regulation (EC) No. 661/2009,[2,] with respect to permissible RRC values. The values obtained in this study also correspond to fuel-efficiency scores of E for trucks and F for passenger cars, according to the provisions of Regulation (EC) No. 1222/2009[3] for European labeling of new tires. These levels are of a similar order to what can be obtained with some brands of new low-cost tires on the market at the moment.

The great difference observed between the RRC of new and retreaded tires places the latter a long way from reaching the same efficiency values obtained with new original tires. Notwithstanding, to assess the contribution of the retreading to the reduction of CO_2 emissions, a complete life cycle of the tire should be undertaken, including the emissions associated with the manufacture of new and retreaded tires, the duration of the tire due to the thickness and characteristics of the tread, and the consumption associated with the elimination and recovery of the residue that disused tires constitute. That complete life-cycle study is beyond the scope of this study and would be the subject of future work.

Finally, we must bear in mind that the conclusions have been obtained for a reduced sample of passenger car tires of a certain dimension and another sample of low-profile truck tires (aspect ratio 70, usual in European market). The general extrapolation of these results would require a much more extensive study to verify the validity of the conclusions for other types of tires.

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