Frédéric Biesse,[1,2] Jérôme Mahé,[1] and Nicolas Lévy[1]

Average Worn Profile of Tires in Europe

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ABSTRACT: Tire tread wear is a key issue in the tire development process and for tire customers. In order to measure the wear performance, tire manufacturers usually proceed to wear tests and calculate the tire life from those tests. An important point in this tire life computation is the criteria chosen for defining the tire's end of life. In Europe, there is a legal minimum tread depth set to 1.6 mm applicable to 75% of the tread pattern width. However, outside those 75% (i.e., on the shoulder part), no clear and shared limit is defined. Also, the usual behavior of customers to decide when their tires should be changed is not well known. The goal of this 2012 study was to identify an average worn profile of tires in Europe and the behavior of customers for replacing their tires. For that, 3000 tires worn out by customers have been collected in scrapyards and measured in five European countries. In this article, we will present the tire collecting method, the measurement process, the analysis method, and some general results and statistics on this 3000 tire database. Finally, the method to compute the average end of life profile and the resulting profile is given.

KEY WORDS: tire wear, worn profile, shoulder wear, scrap tire, wear bar

Introduction

A lot of research is being done in the tire industry on the subject of tread wear, since it is an important issue for tire customers. Many publications can be found on questions like wear testing or wear prediction (see, e.g., Smith et al. [*1*]), but results on wear level of end of life tires are sparse. This is, however, an important issue, especially regarding the tire wear testing. During those tests, tires are generally tested for fewer kilometers than their actual tire life, the test being stopped before the tire's end of life (for cost reasons). The tire life is then estimated with a linear regression down to the tread wear indicators. If, for the center part, the 1.6 mm value is generally used, the shoulder value is not so clear.

According to ETRMA [*2*], for example, in Europe in 2010, about 10% of the tires collected after removal are directly reused or exported. Recommendations on reusable tires are given [*3–5*], with criteria on wear such as "at least 1.6 mm or 2 mm of remaining tread depth," but with few indications on the position of the rolling footprint of this remaining tread depth.

[1] Manufacture Française des Pneumatiques Michelin, Centre de recherche Ladoux, 63040, Clermont Ferrand Cedex 09, France.

[2] Corresponding author. Email: frederic.biesse@fr.michelin.com. Phone: +33 (0)4 73 10 91 67

Based on 11 530 vehicle measurements, a statistical study done by the National Highway Traffic Safety Administration in 2001 [*6*] concluded that between 3% and 3.5% of the tires measured on vehicles had 2/32 of an inch (1.59 mm) or less of remaining tread depth, with about 10% of the vehicles having a least one tire with 2/32 of an inch or less of tread depth. A first indication on the profile is given by the measurement procedure, since the measurements were performed on the shallowest groove of the tread.

In Europe, some similar studies have been done in the United Kingdom between 2000 and 2006, some by the Tyre Industry Council (TIC, a not-for-profit, noncommercial body—funded by tire manufacturers and by the majority of U.K. tire retailers—which is known for its roadside tire check program). For example, TyreCheck 2000 examined 37 500 car tires across U.K. and found that 10% were under the minimum 1.6 mm depth and an additional 17% had less than 2 mm of tread depth left. In 2003, the TIC campaign found that 16% of the tires were below 1.6 mm (on 2500 cars). A similar study in 2004 by Motoreasy (a car care company) noted that on average 12% of tires were illegal (less than 1.6 mm) on more than 1000 tire inspections.

While the public statistical studies on worn profile are sparse, the legislation is also not so precise concerning the wear limit, especially on the shoulder. In Europe, the legal limit is harmonized at 1.6 mm across 75% of the tread width, while the limit of the remaining 25% (shoulder part) is variable among countries. In the United States, most of the states put a limit at 2/32 inch, but some have a limit of 1/32, and still others don't give any limit at all.

To gather more information on the worn profiles in Europe, Michelin conducted two statistical surveys. The first one involved a large number of tires and three tread depth measurements (one in the center and one on each shoulder), across 21 countries in Europe (with several collection locations for each country). In total 5249 tires for which the removal reason was wear (no visible puncture, road hazard, etc.) were measured, from an important variety of manufacturers. The average tread depth observed in this study was 3.1 mm in the center (with a standard deviation of 1.3 mm), and 9.7% of the tires in the scrapyards were found with 1.6 mm or less in the center (see Fig. 1). We also observes that 65.7% of the tires were above 2.6 mm, which means two-thirds of the scrapped tires are far from the legal limit of 1.6 mm in the center.

This first study had the advantage of a high geographical variety and a very important number of tires measured, but it still gave little information on the worn profile. Thus in parallel a second study was done with the objective to observe the worn profile of tires in Europe and to obtain the criteria (on remaining tread depth) for which customers decide to replace their tires, especially on the shoulder, near the end of life of the tire. This paper will now describe in detail the methodology and the results of this second study.

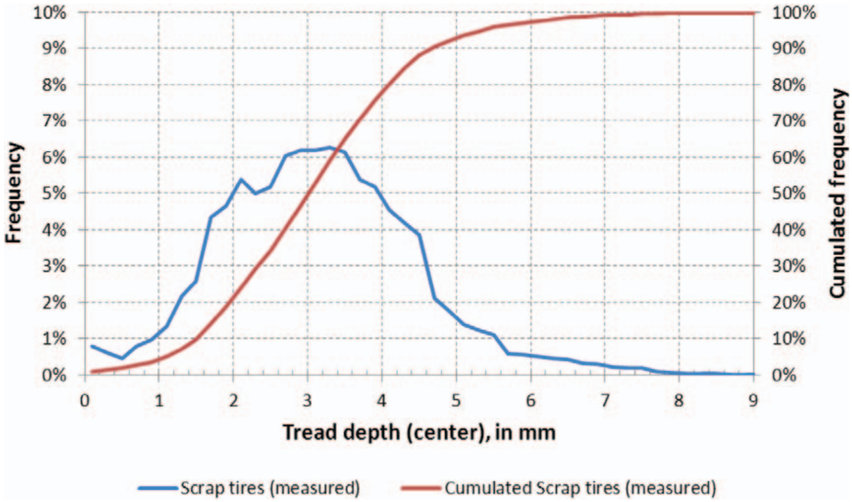

FIG. 1 — *Statistical distribution of tread depth in the center in scrapyard, on 5249 tires measured across 21 countries in Europe in 2012.*

Tire Collection and Measurement

Tire Collection Method

We observed that many tires in the scrapyards were far from the legal limit, so we decided to select mainly tires with advanced wear, based on two arguments. The first is that our intention is to know the average worn profile at the tire's end of life; thus measuring tires with more than 4 or 5 mm tread depth is not relevant. The second argument was simply a measurement capacity, because each collected tire had a complete wear measurement. Since we wanted a good representation of worn profile around a tire's end of life, it would have been necessary to measure a huge number of tires (without selection) to be representative of the end of life. This selection of tires with an advanced wear level can be a bias in the analysis. This bias is known (see Fig. 2, the average tread depth in the center with tire selection is 2.4 mm, 3.1 mm without selection), and we will see later how this bias was canceled.

The tires were collected in five countries: the United Kingdom, Germany, France, Spain, and Italy. Some beta tests in the scrapyards showed a high variability of wear status, tire manufacturers, and tire sizes as a function of the day and hour we went to the scrapyards (one of the reasons is that collections are done by the scrapyards at various tire dealers at predetermined times: small workshops on Monday morning, big tire dealers on Monday afternoon, etc.). It was then decided to go to each scrapyard at least two or three times, at different times of the week. The geographical diversity in each country was also controlled, with at least three different scrapyards at a significant distance from

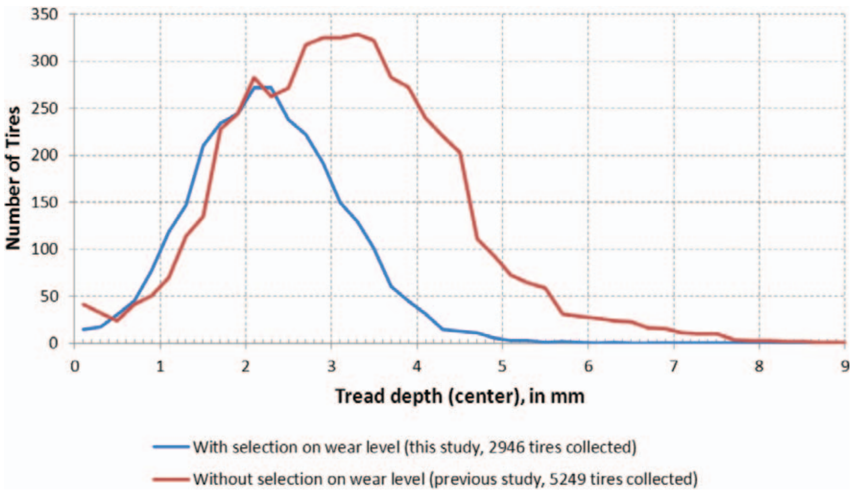

FIG. 2 — *Statistical distribution of tread depth in the center, comparison without selection (5249 tires across 21 countries) and with selection on the wear level (our study on worn profile, 2946 tires across five countries).*

each other in each country, up to 15 collection points for Germany. In this worn profile study, 2946 tires were collected and measured.

Still to ensure representativity, we decided to apply no other selection, so all tire sizes, brands, tire lines, etc., were collected. Most of the tires are passenger car tires; a few light truck tires were also collected. Some winter tires were also collected, most of them in Germany. The tire collection was done during the spring, between April and June 2012.

Tire Measurement Method

To obtain the worn profile with a good transversal accuracy, measuring the collected tires by a laser machine was a necessity. However, since the tread depth gauge is the most used measurement tool during wear tests, this tool was also used on all the tires.

Since the collected tires present a high variety of sizes, the question of comparing the measurements between tires with different widths appears. Since European regulation defines a legal limit on 75% of the tread width, in percentage of the tread width, the choice of the same approach was done, that is, to make the analysis in percentage of the tread width. We used the European Tyre and Rim Technical Organisation (ETRTO) definition of tread width for passenger cars (see [*7*]) shown in Eq. (1), with 0% corresponding to the center of the tread width and ±50% corresponding to the extremities of the ETRTO tread width. We see that sometimes tread exists beyond this ±50%.

$$C = (1.075 - 0.005 \times ar) \times s^{1.001} \tag{1}$$

where

C is tread width,
ar is aspect ratio (example 60: Series = 60), and
s is design section width.

To be comparable, the tread depth gauge measurement points must be placed repetitively between tires (since the laser measures the entire tread width, this was not an issue). We defined the tread depth gauge point with two rules (see Fig. 3):

- All the main grooves are measured (this corresponds usually to the center part of the tread).
- On the shoulder part, two measurement points are defined for each shoulder, respectively, at ±45% and ±52.5% of the ETRTO tread width.

In order to find the center of the tread width on a worn tire, especially when the tread is not symmetric, we built an easy-to-use tool on a pantograph principle. The two lateral plates are placed on the sidewall of the tire, while the pantograph mechanism automatically places the center of the tool at the exact middle between the two plates. The operator can mark the tread center with a

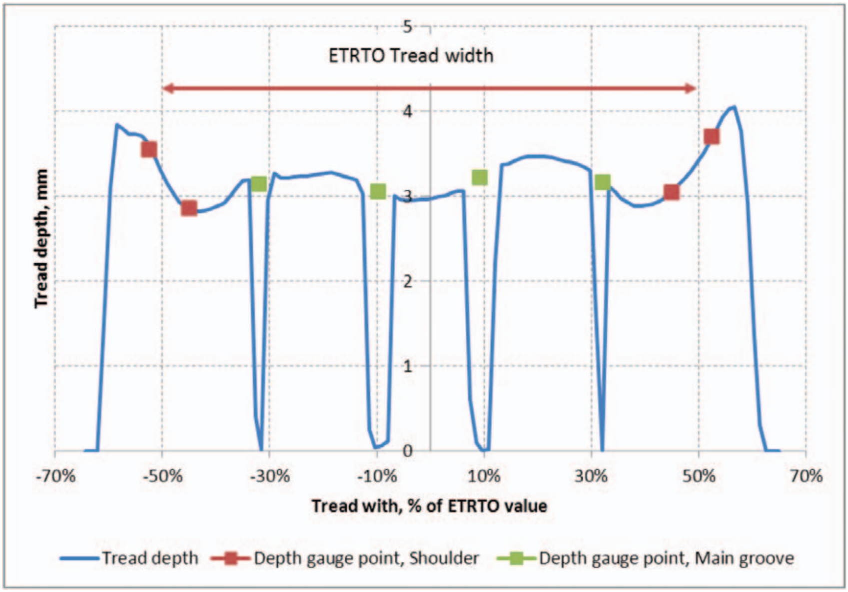

FIG. 3 — *Example of the location of the tread depth gauge measurement points, for shoulder and center part. The illustration is given on a laser measured profile.*

pen (see Fig. 4) and then measure the distance to place the depth gauge measurement point relative to this center, the value for the shoulders being given by a table as a function of the tire size (through the ETRTO tread width).

Finally, the following operations are carried out:

- The tire size, Department of Transportation (DOT) number, manufacturer, brand, tire line, season (summer/winter), type of tread (asymmetric, symmetric, directional) and location of the tread wear indicators are recorded.
- A photograph of the tire is taken.
- The tread depth gauge measurements are made (two on each shoulder plus each main groove).
- A laser measurement is performed.
- The reasons for tire removal are indicated by an expert (the same person for all 2946 tires), with a primary level (center wear, normal wear, shoulder wear) and a secondary level (10 criteria).

General Results

The aim of this section is to give some general statistics on the 2946 tires collected. The processing of the worn profile will be the object of another section.

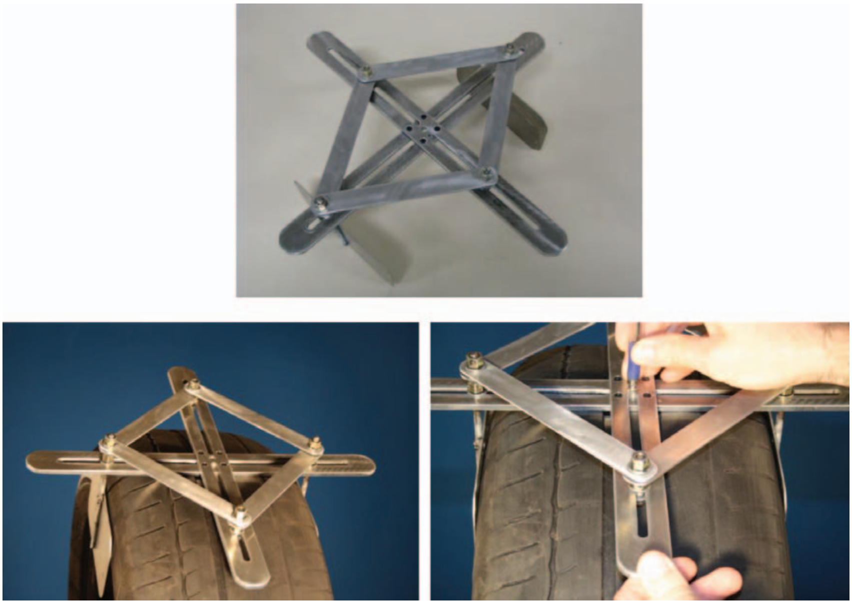

FIG. 4 — *Pantograph tool (top) and operating method to find the tread center (bottom).*

The number of tires by country is equilibrated. The most frequent tire sizes of the database are given in Fig. 5. We expected to see 205/55 R16 and 195/65 R15 as the leading sizes.

Through the DOT number, it was possible to identify the age of the tires. We observed that two-thirds of the tires were manufactured in 2008 or later (tires $\leq$4 years old), 92% of the tires with a reference year of 2005 (tires $\leq$7 years old). The distribution is given in Fig. 6.

We notice in Fig. 7 left that about two-thirds of the tires come from premium brands, while only 14% are third line brands. The brand distribution is given in Fig. 7, right.

A macroscopic wear analysis is given in Fig. 8. All the worn tires have been examined by a Michelin wear expert, who notes the most probable removal cause as well as any irregular wear. It appears that 56% of the tires present shoulder wear (see Fig. 8, left), which could occur on only one shoulder (because of vehicle static settings issues, for example) or on both shoulders. The circumferential irregular wear analysis (Fig. 8, right) shows that only 28% of the tires have no irregular wear at their end of life. Note that on the irregular wear, 60% of the cases are estimated as hardly detectable by a typical customer (whatever the kind of irregular wear). This leads to about 29% of the tires with an irregular wear easily detectable by a typical customer at the tire end of life.

It was also possible to compute the wear obliquity of the tires, to observe whether the wear is oriented toward a shoulder, flat, or oriented toward the other

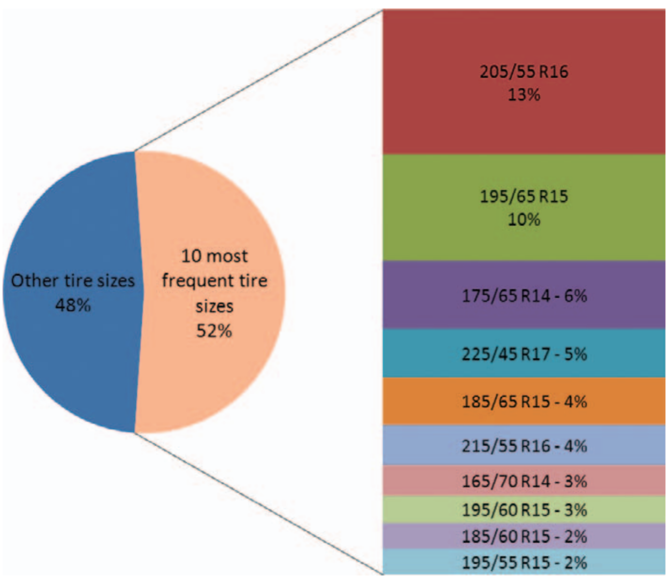

FIG. 5 — *Distribution of the tires by tire size.*

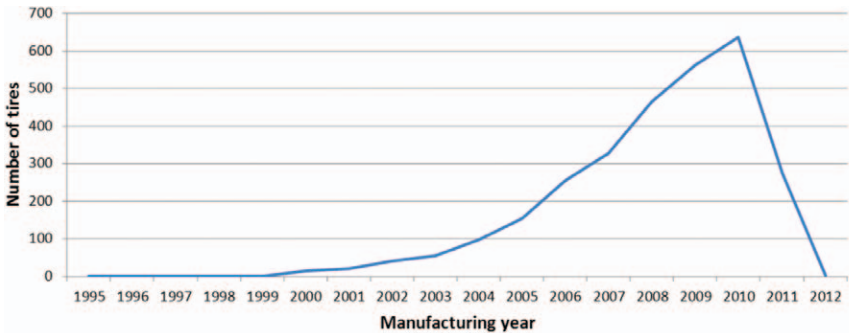

FIG. 6 — *Distribution of the tires by manufacturing year. Note that the tires were collected in scrapyards during the spring 2012.*

shoulder. For that, a linear regression is done on the tread depth respective to tread width, for each tire. The obliquity is then defined as the difference of tread depth given by this linear regression between –50% and +50% of the ETRTO tread width. Since obliquity could be also a consequence of usage or vehicle settings and not only due to the tire, the processing was done only on the asymmetric tread tires (representing 51% of our population), because it is possible to identify the interior and exterior vehicle side. The results are given in Fig. 9, which reveals a very good symmetry of the distribution (54% of the obliquities are toward interior vehicle, while 46% are toward the exterior vehicle). One can conclude through this result that the current average vehicle static settings are well centered with regard to wear profile. The front/rear mix can also contribute to the result.

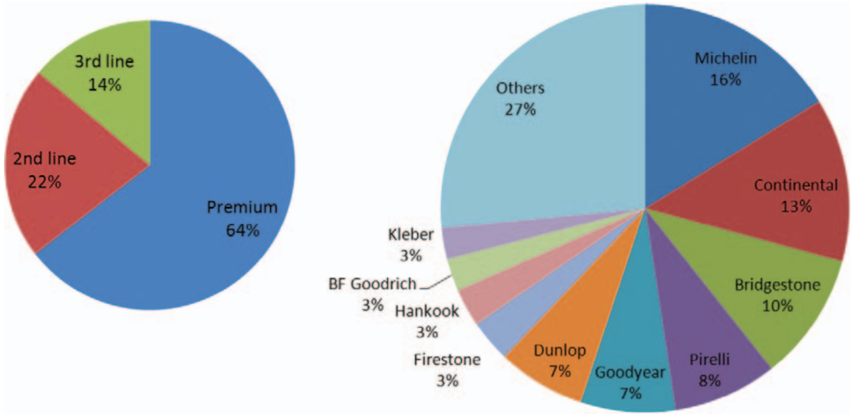

FIG. 7 — *Distribution of the brands by group (left), and brand distribution (right).*

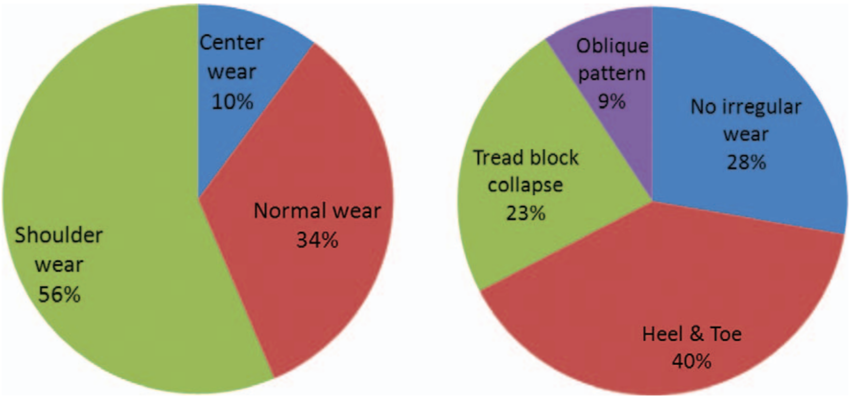

FIG. 8 — *Estimated by a Michelin wear expert: main wear removal cause of the tires (left) and irregular wear statistics (right).*

Finally, the issue of the tread wear indicator (TWI) position was also analyzed. The laws in Europe define a tread width of 75% on which TWI must be present, at 1.6 mm. For each tire the distance between the last left and the last right TWI was measured and compared with the tread width. The distribution is given in Fig. 10. It can be seen that in this database, 96% of the tires have TWI covering less than 75% of the tread width (the average coverage being 54.8%). It seems that all the manufacturers do not fully respect the regulation.

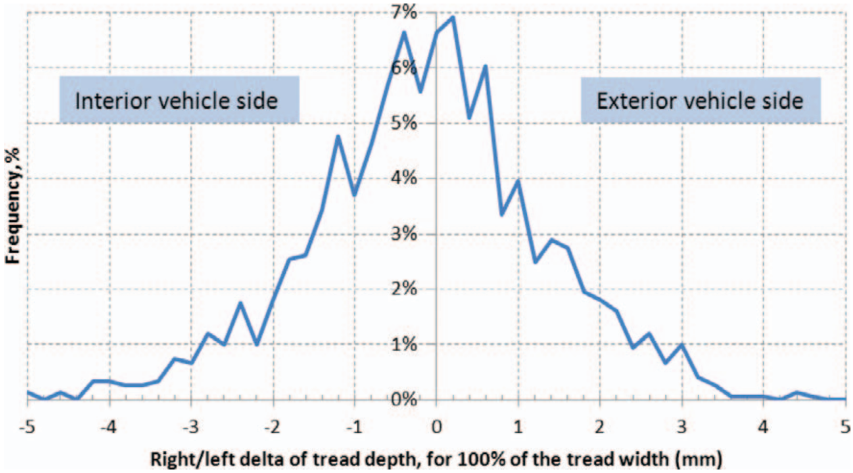

FIG. 9 — *Wear obliquity, computed by the linear slope of the remaining tread depth. The value indicated is the difference of tread depth with this slope, for 100% of the ETRTO tread width. Only the asymmetric tires have been used, to differentiate vehicle interior and exterior sides.*

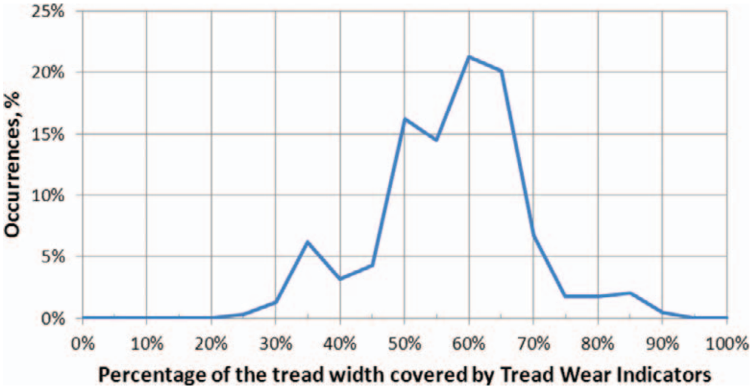

FIG. 10 — *Percentage of the tread width covered by tread wear indicators (TWI), the tread width is defined through the ETRTO formula.*

End of Life Profile

In the previous section, the methods for tire collection and measurements were described, and some general statistics were given. The aim of this section is now to focus on the worn profile, with direct observations and also the research of an average customer tread depth criteria to remove his tires, namely, the customer end of life profile.

Raw Observed Profiles

The collected tires present a huge variety of worn profile and of remaining tread depth. To give an idea of this variety, in Fig. 11 the laser measurements are plotted (1 point out of 10 for readability), as well as five randomly selected profiles.

The average worn profiles are given in Fig. 12. We observe that profiles are quite symmetric (although not completely). Shoulder worn tires show a much higher remaining depth in the center than normal or center wear. The average profile for all worn tires is between shoulder and normal wear, which is expected because only 10% of the tires have center wear. It is also observed that center worn tires have an average remaining tread depth at the center of about 1.5 mm: the 1.6 mm tread wear indicator is clearly well correlated to this value. A remaining tread depth of 1.6 mm at the center seems to be the criteria for customers to remove a center worn tire.

In order to assess the reproducibility and the relevance of the subjective expert classification (between center, normal, and shoulder wear), second order polynomial fits of the wear profiles have been done on each profile. Positive x^2 terms (named concavities) mean a center wear signature, and negative ones

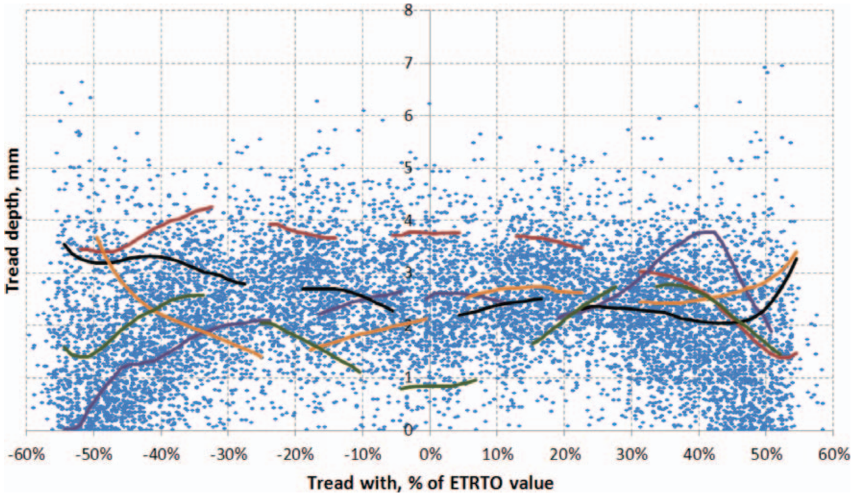

FIG. 11 — *Illustration of the database content, with all the laser measurements (1 point out of 10 for readability) and five randomly selected worn profiles, showing the variety of tires collected.*

mean shoulder wear. As shown in Fig. 13, objective and expert classifications are similar.

It was discussed in a previous section that mainly tires with advanced wear were selected (see Fig. 2), which shows a bias compared with the tires really removed. A representation of worn profiles by deciles (a set of lines that makes the limit every 10% between the least and most worn tires, Fig. 14) gives a very useful result to correct this bias: it appears that the deciles (except for the 10%

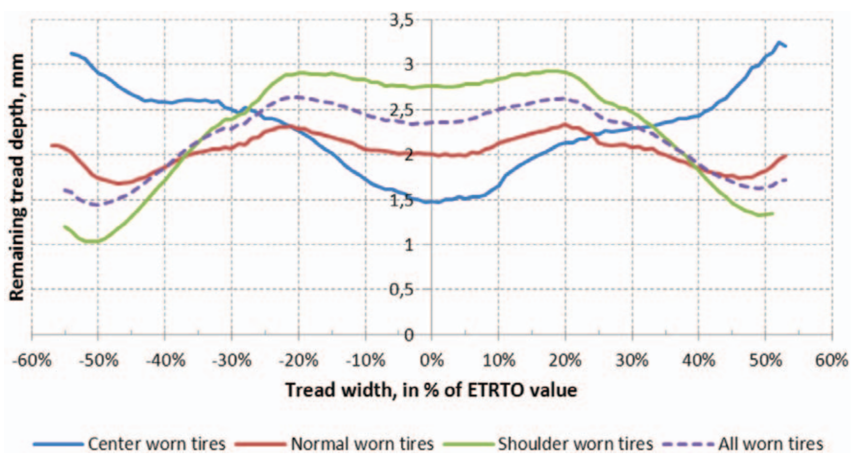

FIG. 12 — *Average worn profile of collected tires, by removal cause and for all tires together.*

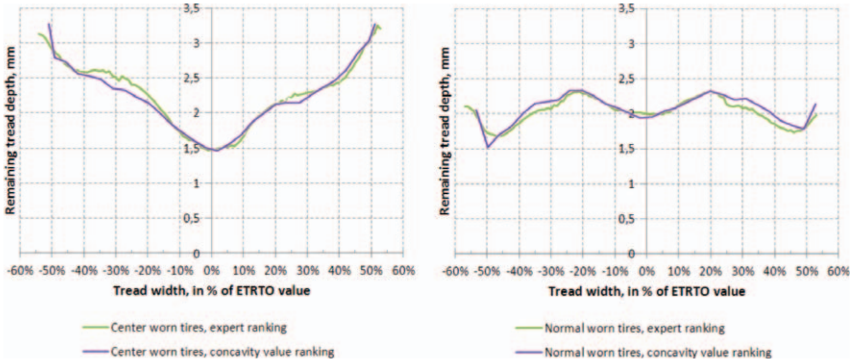

FIG. 13 — *Comparison between an expert "human" classification (center, normal, shoulder wear) and an objective one (based on a quadratic fitting of the worn profile).*

less worn, around 3.7 mm) are very well represented by a translation over each other. This means that the average wear profile is established early (around 3.5 mm of remaining tread) and is then stable. A translation of this established profile to lower depth is in very good superposition with the real profile at a more advanced worn level. It shows that the usual linear extrapolation is not

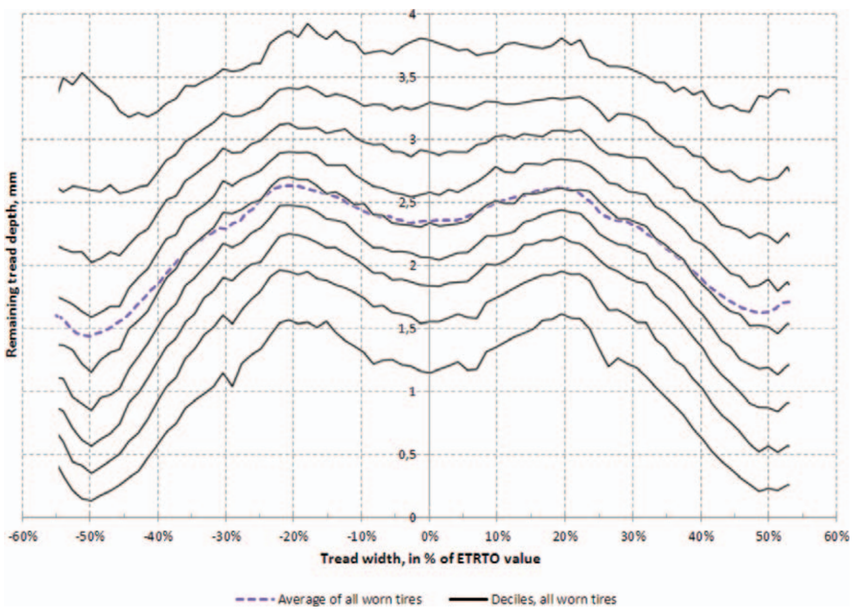

FIG. 14 — *Deciles of worn profiles, from 10% (less worn) to 90% (most worn) by step of 10%, for all removal causes.*

feasible in our study, because the profile at the new stage is not known for the 2946 tires.

The conclusion is that our collecting bias can easily be canceled, simply by a translation of the average profile. This property of profile similarity by a simple translation is also verified for center, normal, and shoulder wear, as well as when we filter the tires by obliquity.

Calculation Method for the End of Life Profile

The objective of this study is to understand the criteria with which the customers decide to remove their tires, especially at the shoulder (the criteria of 1.6 mm on the center being well known), and to define a customer end of life tire profile accordingly. To understand the customer criteria on the shoulder, many questions arise.

First, the worn level in our database is biased compared with other studies. To correct this bias, according to the previous remark that deciles of worn profiles can be superposed by a translation, it was decided to translate each tire profile to a legally reasonable end of life profile (i.e., 1.6 mm on the 75% central tread width, 0 mm on the shoulder). The translation can reduce the remaining tread depth (if the tire is above this limit) or increase it (if the tire profile is below). An illustration is given in Fig. 15.

The second question is about the tires to use in the database to define the average customer removal criteria on the shoulder. Obviously if the tire is worn in the center, the customer did not consider the remaining shoulder tread depth to remove the tire (for example, in Fig. 16, the tire No. 357—classified as center wear—was probably not removed for a shoulder wear reason). If the center worn tires are kept in the database to define an average removal criterion for the shoulder, it would induce a deviation from the result we desire: tires that are not removed for a shoulder wear reason would influence the criteria for shoulder removal. The same question can be posed for the normal wear tires. As illustrated in Fig. 16, for normal wear tires, the removal reason could be alternately center wear or shoulder wear. For example in Fig. 16, tire No. 533 (classified as normal wear) was probably removed for a right shoulder reason;

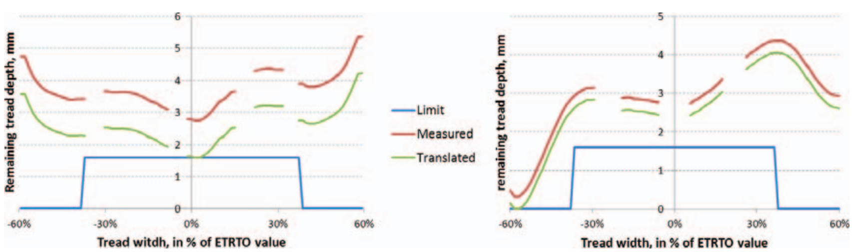

FIG. 15 — *Examples of translation of worn profiles to a legally reasonable end of life profile.*

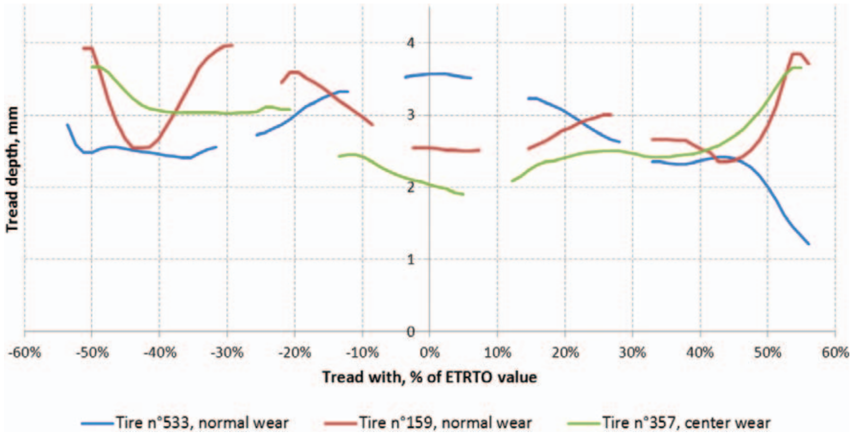

FIG. 16 — *Worn profile examples, for center wear and normal wear.*

while for tire No. 159 (also classified as normal wear) shoulder or center wear reason is not evident. Finally, to define the shoulder removal criteria, it was decided to keep the normal wear profiles in the database, to keep shoulder wear profiles, and to exclude center wear cases.

The third question concerns the obliquity: with an important obliquity, one shoulder will present an advanced wear level, while the other shoulder will have a high remaining tread depth. Obviously, the removal cause is the worn shoulder, not the one with a high remaining tread depth. It is then necessary to split the database into two parts, one for each shoulder, the aim being that a not worn shoulder must not have an impact on the average customer removal profile because it was not a customer criteria for removing the tire. For the first shoulder, we will select tires (through the obliquity value, see Fig. 9) with obliquity in the range $(-\infty; 0)$ mm, while for the other shoulder, we will select the tires with an obliquity in the range $(0; +\infty)$ mm. The result is given in Fig. 17.

Finally, the last point is to apply a linear regression on the shoulder profile, because it was observed that the profile on the shoulder part is very linear. This regression is illustrated in Fig. 18.

To summarize, the four steps of the processing are

1. translating each profile to its end of life (this step cancels the collection bias),
2. selecting normal and shoulder wear profiles only,
3. splitting the database in two parts, for positive and negative obliquity, and
4. applying a linear regression of the resulting profiles, for left and right shoulder.

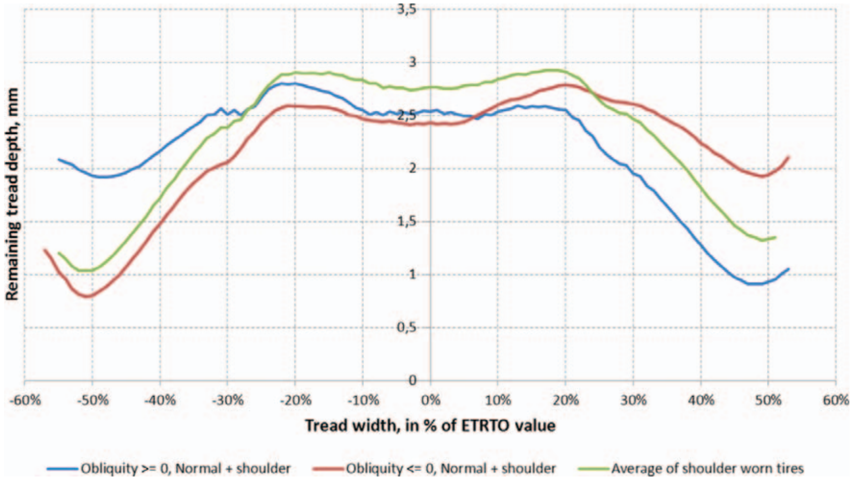

FIG. 17 — *Worn profile when splitting the database in left and right obliquities. Normal and shoulder worn tires together. For comparison, the average of shoulder wear tires (with no obliquity filtering) is plotted.*

It can be noted that the impact of step 1 is low, because the final translation on the average of the profiles (for normal + shoulder) is between 0.1 and 0.15 mm for left or right obliquity filtering (see the difference between Figs. 17 and 18, for blue and red curves).

The dispersion of the results has also been estimated. The database has been split into five sets (590 tires each), the sets have been constituted randomly.

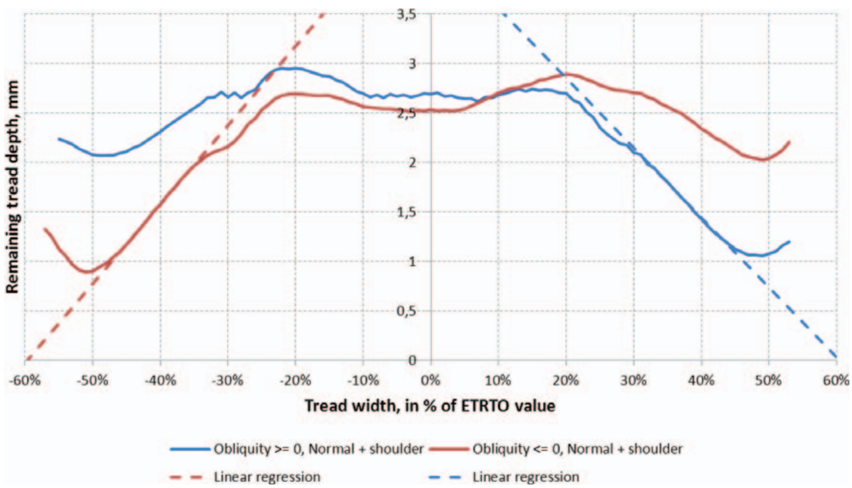

FIG. 18 — *Linear regression of the resulting profile after the four steps, for left and right shoulder.*

Multiple runs have been done, the dispersion being estimated between those runs. The critical difference was then computed (for 2946 tires), with a 95% confidence interval we obtain ±0.21 mm (for the shoulder zone, after steps 1 to 4).

Resulting End of Life Profile

Our objective in this document is to find which criteria customers use to decide to remove their tires, and in particular to find the remaining tread depth (as a function of the position on the tread width) at which average customers remove their tires.

The first limit to define is on the center of the tread width. To be coherent in our analysis, the same argument as for shoulder wear was applied: for normal wear tires, the removal criterion is sometimes the center, sometimes the shoulder. As a consequence, for the center part of the tread, we will observe center wear and normal wear tires. To summarize:

- For center removal criteria, center + normal worn tires are considered.
- For shoulder removal criteria, shoulder + normal worn tires are considered, with in addition an obliquity filtering.

The results are given in Fig. 19. We observe that center + normal worn tires results in a minimal tread depth in the center of 1.8 mm. We then decided to use a limit in the center at 1.6 mm, because it is the legal limit and it is near the customer practice (1.8 mm). In addition (as it was said before), the average profile for center wear tires reaches 1.5 mm of remaining tread depth at the

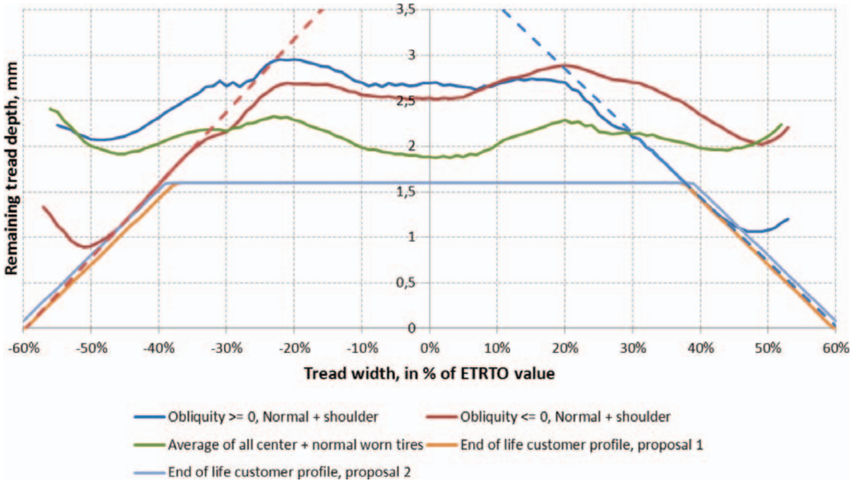

FIG. 19 — *Definition of the end of life customer profile.*

center of the tread width (see Fig. 12), revealing that the 1.6 mm legal limit in the center is on average respected by customers.

On the shoulder part, it was observed that a linear regression was a good approximation of the customer average limit, except maybe at the shoulder's extremity. To keep a simple profile, we decided to use the linear regression up to 0 tread depth. As a function of the shoulder we consider, two profiles can be proposed (see Fig. 19).

For reasons of simplicity, we kept proposal 1, because the linear parts begin at ±37.5% of the tread width (which means that the center parts make 75% of the tread width), and the line touches 0 mm at ±60% of the tread width. At ±50% of the tread width, the value is 0.7 mm. Finally, the customer end of life limit at which they decided on average to remove their tires is given in Table 1 and Fig. 20.

An illustration of the use of this end of life customer profile is given in Fig. 21. In this example, the worn profile of tire A touches the end of life profile at –44% of the tread width (red point in Fig. 21). At this –44% position, the end of life customer profile has a value of 1.13 mm. This means that average customers will remove their tires at this remaining tread depth. During a wear test, the linear extrapolation phase should reproduce this behavior and use as a limit the first point that touches this end of life customer profile. For tire B (in Fig. 21), the worn profile reaches the end of life profile at +5% of the tread width (green point). Thus the end of life tread depth at this +5% position is 1.6 mm, and the extrapolation phase should use this 1.6 mm height, since the end of life point is inside the ±37.5% part of the tread width.

Conclusion

In this study, 2946 worn tires were collected and measured in Europe. The collecting method, the processing method, some general statistics, and finally the customer limit at which average customers decided to change their tires were presented.

We observed that when a tire is removed, the wear level is not constant over the width, and it is the most worn point (i.e., the point nearest from the end of life customer profile) that forces the decision. This is, for example, clear on the center worn tires, were the lowest point is at 1.5 mm (so clearly at the 1.6 mm

TABLE 1 — *Synthesis of the customer end of life limit.*

	Center part	Shoulder part	Extremity
Width limit, %	(−37.5; 37.5)	±(37.5; 60)	±(60; ∞)
Tread height, mm	1.6	Linear	0

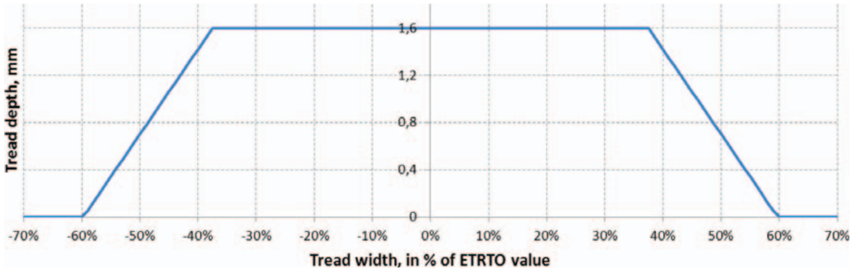

FIG. 20 — *Synthesis of the customer end of life limit.*

limit), while other points (but still in the 75% center of the tread width) are above the 1.6 mm limit.

Finally, this customer end of life profile indicates that for any tire, when the worn profile touches this reference profile on a point, average customers decide to remove their tires.

During wear testing, tires are generally tested for fewer kilometers than their actual tire life. To reduce the testing costs, the test is stopped before the tires are totally worn, the tire life being then estimated with a linear regression down to the tire wear indicators. If, for the center part, the 1.6 mm value is generally used, the shoulder value is not so clear. This study gives a robust and customer established value for the shoulder part.

This customer end of life profile is a precious aid for wear performance measurement, because it is representative of the behavior of an average

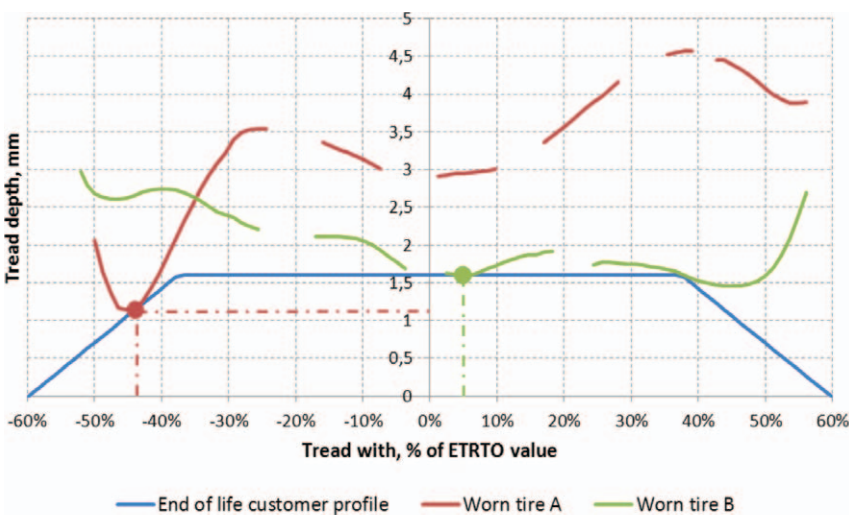

FIG. 21 — *Example of use of the end of life customer profile for wear testings.*

customer. Using this profile, the test tire life extrapolation will be consistent with the customer practice, and the tire life given with this customer end of life profile will be representative of what a customer will observe himself.

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