Submitted by the expert from OICA

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ACEA/ETRTO
Tyre Performance Aggregation Study

DEMANDEUR
APPLICANT
: **EUROPEAN AUTOMOBILE MANUFACTURERS ASSOCIATION - ACEA**
85 AVENUE DES NERVIENS
1040 BRUXELLES
&
EUROPEAN TYRE AND RIM TECHNICAL ORGANISATION – ETRTO
22-28 AVENUE D'AUDERGHEM
1040 BRUXELLES

OBJET
SUBJECT
: Rapport d'agrégation d'études ACEA et ETRTO sur la performance des pneumatiques
ACEA and ETRTO tyres performance aggregation studies

ACEA Study: GRBP-70-25 and GRBP-74-09
ETRTO Study: GRBP-73-11

Objet soumis aux essais : pneumatique, voir descriptif en annexe
Object submitted to tests: tyre, see description in annex

RESULTATS
RESULTS
: Voir Appendix B.
See *Appendix C.*

MONTLHÉRY, 19/01/2022
(day/month/year)

DIGITAL UTAC SIGNED

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DIGITALLY UTAC SIGNED

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1. CONTEXT

Both ACEA and ETRTO requested independently UTAC to perform a study in order to assess the interdependency of tyre performances (Rolling Resistance, Wet Grip, Noise level, …) on each other. The purpose was to specify any potential improvement or deterioration of noise performance in light of the other parameters and to provide the necessary information regarding the possible additional tightening of the limits, without undermining the overall balance that has to take into account also other performances.

ACEA study was presented to the working party on noise and tyres (GRBP) as documents GRBP-70-25 and GRBP-74-09, and ETRTO study, as document GRBP-73-11. Some contracting parties, as United Kingdom, kindly asked ACEA and ETRTO to rationalize the two studies in order to have a bigger sample and to confirm, or not, the conclusions.

This report is the aggregation of the two studies, for technical items that can be put in common.

It has long been believed that regulating the noise emission of vehicles, particularly their engines and exhaust systems, was sufficient to reduce road noise. This is why the regulation on vehicle noise is old and has long been the only regulatory tool in the more general field of road noise.

Since the first European directive on vehicle noise levels appeared in 1970, the authorized limits have been set according to vehicle categories defined by power, maximum authorized mass, engine type (direct injection diesel or not) and vehicle use. These limits have evolved significantly with the following regulatory texts, the division into categories having also been somewhat modified.

For passenger cars, the limit of the permitted noise level has been reduced from 82 dB(A) to 74 dB(A). It has been more pronounced for goods vehicles: the permitted limit has been reduced from 91 dB(A) to 80 dB(A) for vehicles with a maximum mass greater than 3.5 t and an engine power of 150 kW or more.

One of the most comprehensive studies on the subject was conducted at the initiative of the International Institute of Noise Control Engineering. The resulting report noted benefits related to noise regulation. For example, it has led to a uniformity of noise levels by vehicle category, which has had a positive influence on the personal protection of residents. On the other hand, in addition to the effective reduction in the sound level emitted by new vehicles, a change in the spectral characteristics of the sound pressure emitted has appeared, with less marked bands, making the spectrum less annoying for local residents.

However, this study notes that the available information on the evolution of noise levels in cities tends to show that they have remained almost constant since the introduction of the regulations. There are many reasons for this stagnation:

- The vehicle fleet did not only include products approved according to the latest regulations in force. Thus, old vehicles whose authorized noise level limit is much higher than that of newer vehicles, constitute a dominant point source of noise energy in a vehicle flow and therefore a nuisance.
- Road traffic has increased significantly, and the number of noise sources has increased accordingly.
- The noise level emitted by a vehicle can be significantly modified by making unauthorized changes that make the vehicle non-compliant with regulations.

The potential for reducing overall noise through the treatment of vehicles and tyres is already being addressed and controlled through several regulatory actions and deadlines:

- The noise levels of vehicles with four or more wheels are processed by their approval, in accordance with Regulation CE/540/2014 and UN Regulation No. 51.
- These texts require reductions in limits up to 6 dB by 2026. In addition, it is mentioned that there is a desire to label vehicles in a way that is equivalent to that of tyres.
- The noise levels of tyres are dealt by their approval imposed by GSR Regulations CE/661/2009 and UN Regulation n°117. In addition, mandatory tyre labelling is defined by EU Regulation 2020/740. It is mandatory to display the regulatory performances of tyres in terms of Rolling Resistance, Wet Grip and Noise level. For this one, the noise level of the tyre is indicated as well as its performance in relation to the regulatory limit: one wave if it is more than 3 dB below the 2016 limits, two waves if it respects the 2016 limits and three waves if it only respects the current regulations.

2. BACKGROUND

This section provides an overview of the applicable test standards for the tyre performance parameters mentioned in the existing legislation regarding tyre labelling. This description is preceded by the references of the tyres used to conduct this study.

2.1 Sample

This study has tested 20 different tyre references. The tyres dimensions are 205 55 R16 with a load index of 91 for all and speed index of H, T, V or W. These tyres are the most common size on European market.

Among the 20 tyres, there are three snow tyres: 3PMSF (1, 2 and 3) and two plain tread tyres (1 and 4).

Former list	New list	Size	DOT
A-ETRTO	1	205/55 R16 91V	No DOT
C-ETRTO	2	205/55 R16 91V	XXXXXXXX 2418
M-ACEA	3	205/55 R16 91V	XXXXXXXX 4618
B-ETRTO	4	205/55 R16 91V	No DOT
D-ETRTO	5	205/55 R16 91V	XXXXXXXX 0716
E-ETRTO	6	205/55 R16 91H	XXXXXXXX 3218
F-ETRTO	7	205/55 R16 91W	XXXXXXXX 1818
G-ETRTO	8	205/55 R16 91V	XXXXXXXX 3218
H-ETRTO	9	205/55 R16 91H	XXXXXXXX 3118
A-ACEA	10	205/55 R16 91V	XXXXXXXX 2218
B-ACEA	11	205/55 R16 91V	XXXXXXX 4318
C-ACEA	12	205/55 R16 91V	XXXXXXXX 4818
D-ACEA	13	205/55 R16 91V	XXXX 1119
E-ACEA	14	205/55 R16 91V	XXXXXXXX 2618
F-ACEA	15	205/55 R16 91V	XXXXXXXX 3618
K-ACEA	16	205/55 R16 91V	XXXXXXXX 4518
L-ACEA	17	205/55 R16 91V	XXXXXXXX 4218
N-ACEA	18	205/55 R16 91V	XXXXXXXX 2718
O-ACEA	19	205/55 R16 91H	XXXXXXXX 4818
P-ACEA	20	205/55 R16 91V	XXXXXXXX 4318

Table 2.1-1 : The 20 tested tyres used in this project

Note: *Tyre 20 is the reference tyre for Longitudinal Aquaplaning.*
Tyre 3 is the reference tyre for snow tyres.

2.2 Test: facilities and methods

Below a description of the test standards at EU and Member State level for the tyre performance parameters.

2.2.1 Rolling Resistance

Bench test / MTS 860 – Rolling Resistance
RR Coefficient

Figure 2.2-1 : UTAC Bench test for Rolling Resistance test

2.2.1.1 Rolling Resistance Test conditions

- Test Speed (kph): 80
- Load (kg): 482
- Tyre initial reference pressure (kPa): 210
- Room temperature (°C): 24<T°C<25

2.2.1.2 Rolling Resistance Test Methods

- UN-R117 procedure

The resistance to forward motion of a tyre rolling on the road is expressed as a ratio between straight-line motion drag force and vertical load, i.e. Fx / Fz, in N / kN, the result is express as Rolling Resistance Coefficient (RRC or RR).

We measure the Rolling resistance level of the tyre through the Torque Method on a roller bench:
The test measurements convert a force acting at the tyre/drum interface, the Torque input is measured at the test drum.
The tyre is launch at 80 kph with a load equal to 80% of the tyre Load-index during a certain time duration, after stabilization the measurements of the Torque and Force are proceed in order to provide the Rolling Resistance Coefficient.

2.2.2 Rolling Sound

Vehicle test / NISSAN LEAF

Figure 2.2-2 : Vehicles used for Rolling Sound test

2.2.2.1 Rolling Sound Test conditions

The measurements shall be made when the ambient air temperature is within the range from 5°C to 40°C and the test surface temperature is within the range from 5°C to 50°C.

The tests shall not be carried out if the wind speed exceeds 5m/s.

Test conditions following regulation UN-R117:

- Tyre load (kg):
  - Front left: 526.5
  - Front right: 498
  - Rear left: 383
  - Rear right: 397.5
- Tyre inflation (kPa):
  - Front left: 210
  - Front right: 210
  - Rear left: 150
  - Rear right: 150

Test conditions following regulation UN-R51:

- Tyre load (kg):
  - Front left: 486.5
  - Front right: 439.5
  - Rear left: 343.5
  - Rear right: 343.5
- Tyre inflation (kPa):
  - Front left: 250
  - Front right: 250
  - Rear left: 250
  - Rear right: 250

2.2.2.2 Rolling Sound Test Methods

Tests are based on UN-R117 and UN-R51. Those tests are both pass-by noise tests. Pass-by noise (PBN) testing includes acceleration tests, constant speed tests vehicle on a dedicated test track. Two microphones on each side of the test track are used for measuring sound pressure level.

UN-R117 procedure: 4 runs at 50 kph (R117 50) and 8 runs between 70 and 90 kph (R117 80).

UN-R51 procedure:
- Cruise at 50 kph: 4 runs (R51C 50)
- Acceleration at 50 kph: 4 runs (R51A 50).

Figure 2.2-3 : UTAC sound track for Rolling Sound test

2.2.3 Wet Grip

Trailer method test on wet surface / Dufournier Technologies RME 04
Wet Grip index

Figure 2.2-4 : UTAC means for wet grip test

2.2.3.1 Wet Grip Test conditions

- Test Speed (kph): 65
- Water depth (mm): 0,9
- Track texture depth (mm): 1
- Track Length (m): 200
- Load (kg): 461
- Ambient Temperature (°C): T°C<20

2.2.3.2 Wet Grip Test Methods

- UN-R117 procedure

The Wet Grip index is the relative braking performance on a wet surface of a skid trailer equipped with the candidate & reference tyre. This skid trailer is driven at 65kph on the wet track, then based on 6 valid brakings the Wet Grip Index is calculated.

2.2.4 Dry handling (Flat Trac)

Bench test / MTS Flat Trac III CT
Cornering stiffness

Figure 2.2-5 : Bench test for Flat Trac test

2.2.4.1 Flat Trac Test conditions

- Test speed (km/h): 80
- Test duration (min): 20
- Tyre pressure (kPa): 210
- Rim width and material (inch): 6,5 – Steel
- Room temperature (°C): 24<T°C<25

2.2.4.2 Flat Trac Test Methods

- Procedure proposed by ETRTO (Ref: UTAC RAPPORT No: AFFSAS1801813)

Simplified flat trac procedure for the measurement of the tyre cornering stiffness as a handling relevant performance.

Part 1: Warm up Sequence

1. 10 min @ vertical load [FZ] of 70% LI, 80 km/h straight rolling
2. 1 min @ slip angle [SA] of ±3° (±2°/sec constant gradient)
3. 10 min @ 70% LI, 80 km/h straight rolling

Part 2: Measurement of Cornering Stiffness

1. Sequence of vertical loads: 140%, 110%, 80%, 50%, 20% of LI
2. Slip angle: ±1° @ (±1°/sec constant gradient)
3. Each vertical load is measured for 2 complete periods of slip angle variation Data Acquisition: > 50 Hz

Evaluation:
Cornering stiffness as a function of the vertical load, by linear regression of the data (slip angle) < 0.5 deg.

2.2.5 Aquaplaning

Vehicle test / PEUGEOT 308
Aquaplaning speed and acceleration under aquaplaning condition

Figure 2.2-6 : Vehicle used for Aquaplaning test

2.2.5.1 Aquaplaning Test conditions

- Vehicle weight (kg):
  - Unladen: 863 Front and 573 Rear
- Tyre pressure (kPa):
  - Unladen: 250 Front and 240 Rear
- Average Wind (m/s): 2,1
- Average Air Temperature (°C): 16,4

2.2.5.2 Aquaplaning Test Methods

- VDA E08 Longitudinal Aquaplaning (LoA)

The driver goes through the aquaplaning area with continuous speed, and accelerates with full throttle in the bath. Then, sensors detect tyres' slip, by comparing car's speed and front wheels' speed. Aquaplaning is detected when slip reaches 15% in the first front wheel. Three repetitions were done for each tyre set and traction control was turned off to measure accurately tyres performance regarding the « E08-VDA_Testprocedure_Hydroplaning_longitudinal-03_2013 » document.

Figure 2.2-7 : Longitudinal Aquaplaning test method

- VDA E05 Lateral Aquaplaning (LaA)

The driver goes through the aquaplaning area at constant speeds from 50 km/h to 100 km/h, with steps of 5 km/h and sensors permit to measure lateral acceleration at each run. To measure accurately tyres performance, ESC was turned off for this test, done regarding the « E05 - VDA Test procedure Hydroplaning lateral - May 2011 » document. The result for each tyre is the integral calculation of lateral acceleration between 50km/h and $\text{Speed}_{40\%\text{LatAccelMAX}}$ relative to entrance speeds.

Figure 2.2-8 : Lateral Aquaplaning test method

2.2.6 Tyre weight

Each tyre reference has been weighed to evaluate the influence of the mass on the tyre's performances.

3. STATISTICAL ANALYSIS

The goal of this aggregation work between ACEA and ETRTO studies is to analyse the influence of the noise reduction of the tyres regarding their essential parameters. We used for this comparison the data of 20 tyres from both studies (detailed under §2.1).

Some tests have been performed only in one study or in a different way, for instance the Dry grip. As a consequence, those specific parameters have not been included in this aggregation work which results in the aggregation on 7 parameters available in both studies.

The statistical analysis is composed of three main stages:

- First visualizing for each tyre all tests measurements by means of spider diagrams,
- Secondly studying two by two correlations with scatter plots,
- Thirdly visualizing noise versus all of the other 7 parameters (Rolling Resistance, Wet Grip, Flat Trac 80%, Flat Trac 50, Longitudinal Aquaplaning, Lateral Aquaplaning and Weight).

For the third stage, we use a dimension reduction (factorial) method (which is Principal Component Analysis - see Appendix A: Tool Box) to select directions of maximum variability and summarize data minimizing the information loss.
According to this statistical method "Principal Component Analysis", we will select the first three principal components, and thus interpret the representations of rolling sound versus each of these three components.

3.1 Tests Results

The tests program described above generated a set of results. All the results according to the test performed are summarized in this table:

			TEST										
			Rolling Resistance	Rolling Sound				Flat Trac		Wet Grip	Longi. Aqua.	Lateral Aqua.	Weight
ID	Origin ID	DOT	RR (index)	R117 50 kph AVG (dB(A))	R117 80 kph Arr LR (dB(A))	R51A 50 kph (dB(A))	R51C 50 kph T° corr (dB(A))	80% LI (N/°)	50% LI (N/°)	WG (index)	Ratio LoA (%)	LaA (Integer m/s)	(Kg)
1	A-ETRTO	n/a	8,686	61,2	67,7	61,8	61,8	1530	1462	0,80	47,91	21,24	9,32
2	C-ETRTO	2418	10,084	63,3	70,6	67,2	63,4	1500	1127	1,08	74,07	38,85	11,81
3	M-ACEA	4718	8,389	66,0	71,6	69,0	66,9	1294	1126	1,67	89,76	63,39	8,43
4	B-ETRTO	n/a	6,663	62,6	69,2	63,5	63,4	1718	1613	0,93	43,83	18,97	7,54
5	D-ETRTO	0716	7,985	65,3	73,6	66,4	65,8	1576	1304	1,38	84,32	78,62	8,77
6	E-ETRTO	3218	8,011	64,1	70,9	67,0	65,2	1297	1089	1,39	96,22	90,42	8,03
7	F-ETRTO	1818	9,171	63,8	70,8	66,1	64,9	1647	1346	1,20	81,88	67,66	9,62
8	G-ETRTO	3218	8,439	62,9	69,2	66,9	64,0	1427	1134	1,25	74,92	49,33	9,34
9	H-ETRTO	3118	7,914	63,0	69,7	65,5	64,2	1519	1238	1,43	77,36	58,27	9,41
10	A-ACEA	2218	8,985	64,8	71,7	66,3	65,5	1417	1288	1,57	83,51	63,96	8,18
11	B-ACEA	4318	9,949	64,9	71,3	66,4	65,7	1387	1080	1,43	87,99	70,52	9,55
12	C-ACEA	4818	8,142	65,0	71,8	66,9	66,1	1265	1099	1,51	86,69	61,43	7,84
13	D-ACEA	1119	8,444	65,1	72,1	67,1	66,4	1470	1206	1,56	86,29	63,29	8,27
14	E-ACEA	2818	8,117	65,8	73,4	67,4	66,8	1669	1507	1,55	83,97	66,15	8,13
15	F-ACEA	3618	8,953	64,7	71,3	66,4	65,4	1500	1294	1,63	87,16	69,75	8,86
16	K-ACEA	4518	7,075	65,1	72,0	66,9	66,6	1351	1232	1,50	84,49	59,74	8,14
17	L-ACEA	4218	6,449	63,9	70,7	65,9	65,0	1326	1126	1,69	79,23	55,48	8,23
18	N-ACEA	2718	7,666	65,1	71,9	67,2	66,0	1618	1271	1,56	86,39	73,05	8,83
19	O-ACEA	4818	7,175	63,6	70,2	65,8	64,7	1382	1168	1,27	74,94	47,52	8,27
20	P-ACEA	4318	8,336	63,9	70,7	66,0	64,9	1505	1351	1,74	81,74	67,65	8,77

Table 3.1-1 : Summary of all test results

For tyres which were part of both ACEA & ETRTO studies, only one of them has been taken into account. *Please note except for the tyre 1, 2 and 3 that are 3PMSF and tyre 1 and 4 that are plain tread, the sequence of the list is randomly chosen without technical reasons*

For each column the best result within the group of tyres and the worst are highlighted from green to red.

As the goal of the study is to analyse the influence of the noise reduction of the tyres regarding their essential characteristics, tyre chosen technically were for the purpose to analyse the interdependencies with a wide spread of parameters.

3.1.1 Radar Charts

"A **radar chart** is a graphical method of displaying multivariate data in the form of a two-dimensional chart of three or more quantitative variables represented on axes starting from the same point." (Wikipedia, Radar chart, 2019)

In order to visualize all results for each tyre, we gave a score of 0 to 10 so that each result is comparable with each other (0 for the lowest results and 10 for the best results). The radar chart provides a first vision of tyre performances.

All the results are in the Appendix B. In the next section, we focus only on the best and worst tyres for the three factors: Safety, Noise and CO_2 Emission.

3.1.1.1 The 4 best tyres for Safety performances

Among the 20 different tyre references, we focused on the tyres with the highest Safety scores.
The graduation of the Figure 3.1-1 is the following:

- 0: defined by the worst tyre performance of the sample.
- 10: defined by the best tyre performance of the sample.

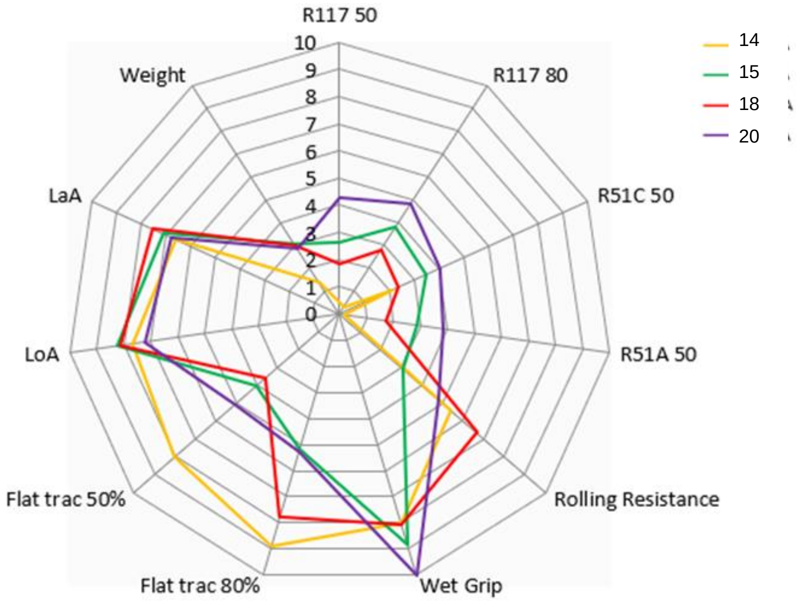

Figure 3.1-1 : The 4 best tyres for Safety

We can notice that these 4 tyres are good on the Safety performances, but they are also quite noisy.

3.1.1.2 The 4 best tyres for Noise performances

Among the 20 different tyre references, we focused on the quietest tyres.
The graduation of the Figure 3.1-2 is the following:

- 0: defined by the worst tyre performance of the sample.
- 10: defined by the best tyre performance of the sample.

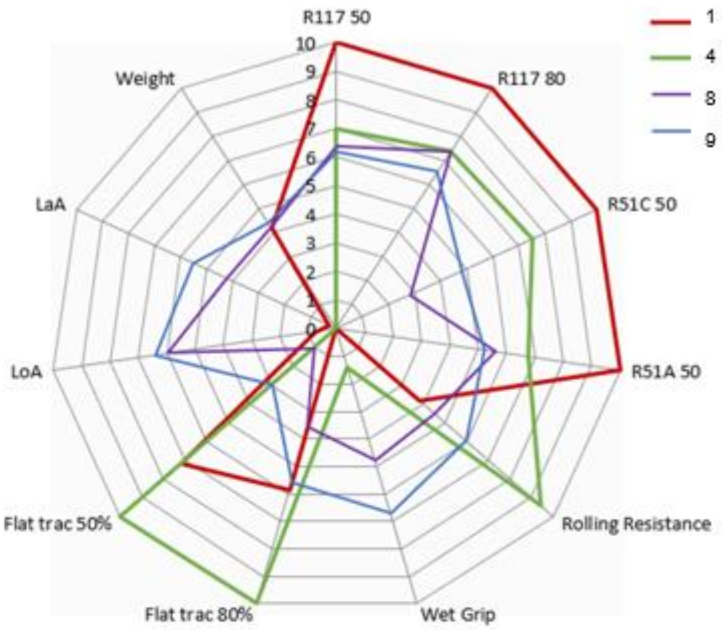

Figure 3.1-2 : The 4 best tyres for Noise

We can notice that these 4 tyres are good on Rolling Sound, but they have poor aquaplaning scores.

3.1.1.3 The 4 best tyres for CO_2 Emissions performances

Among the 20 different tyre references, we focused on the tyres with the best (=lowest) Rolling Resistance scores.
The graduation of the Figure 3.1-3 is the following:

- 0: defined by the worst tyre performance of the sample.
- 10: defined by the best tyre performance of the sample.

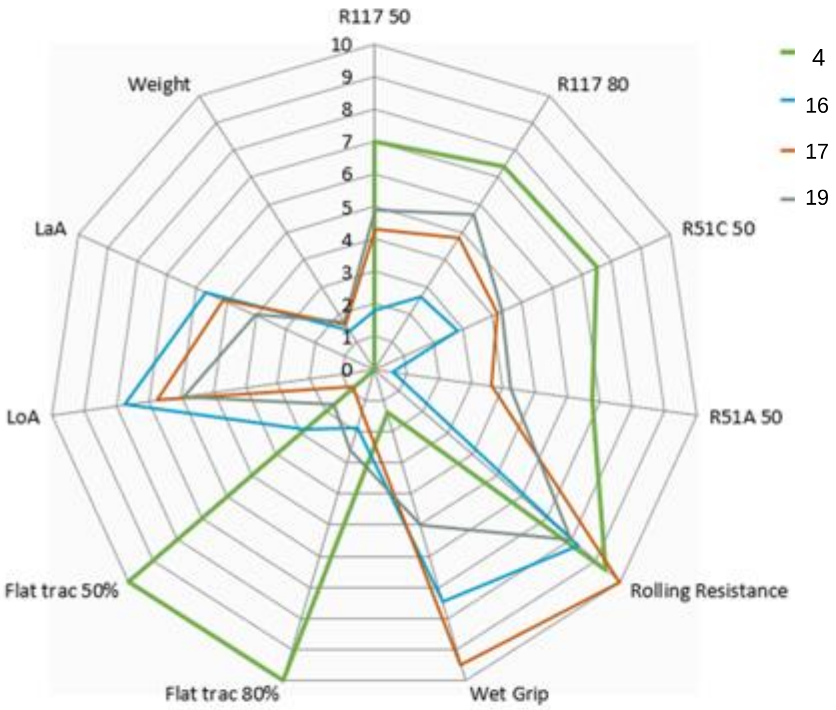

Figure 3.1-3 : The 4 best tyres for CO_2 emissions

We can notice that these 4 tyres are good on Rolling Resistance. No clear trend at this level with the radar charts vision.

3.1.1.4 Conclusion

We can see that the radar charts make it possible to visualize a performance comparing to the other parameters. However, it is not easy to show a clear correlation.

This is why we have to go further in the analysis with other statistical tools.

3.1.2 2D charts and Scatterplots

Before starting, all the methods used during this study are described in the § A.1 A.1.The first approach : Bivariate Analysis.

All the red boxes show significant correlation between two parameters considered P-value (probability value) <0.05.
The P-value or probability value is, for a given statistical model, the probability that, when the null hypothesis is true, the statistical summary would be greater than or equal to the actual observed results.

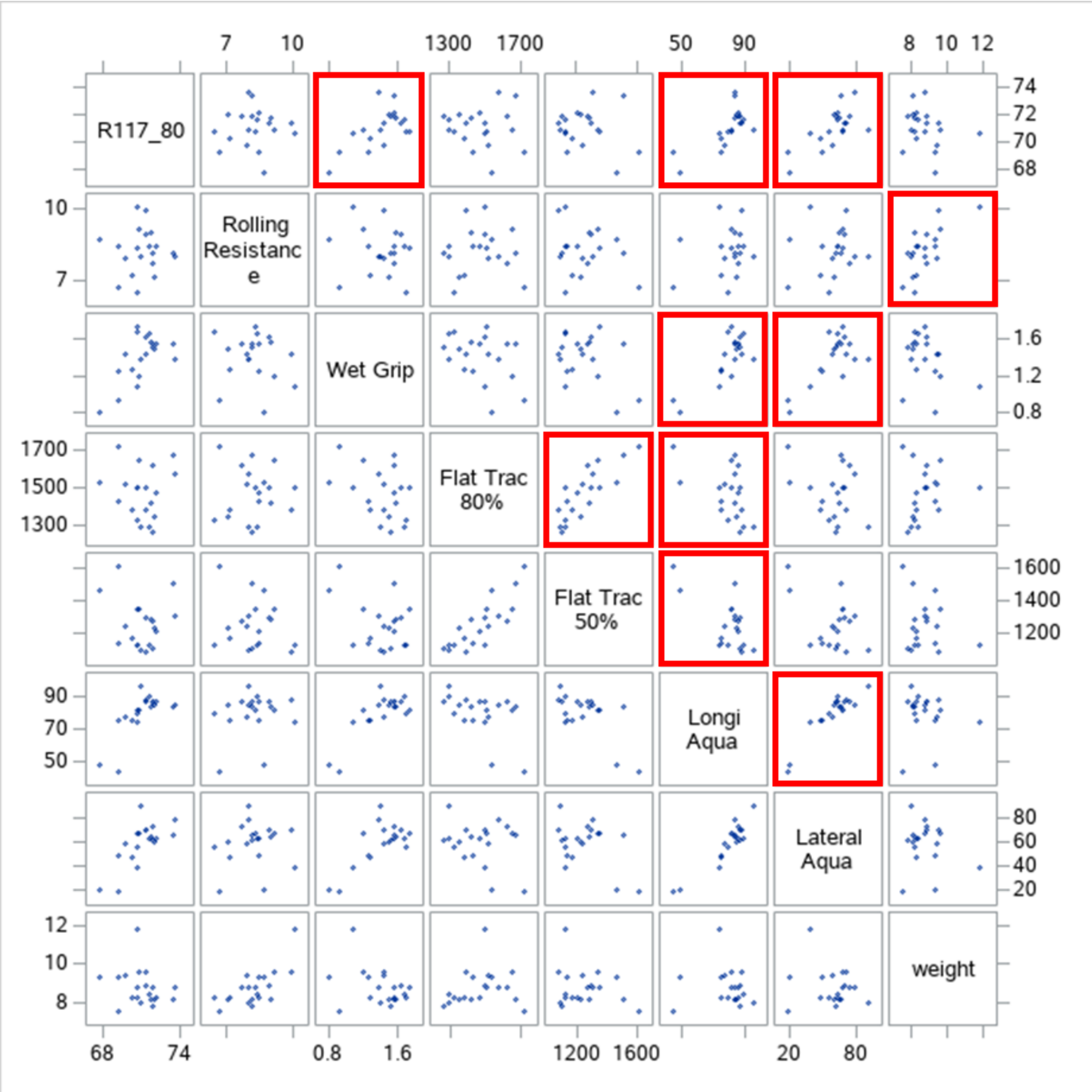

Figure 3.1-4 : Scatterplot

3.2 Rolling Sound tests correlation

There are four ways to measure rolling sound following:

1. R117 at 50km/h
2. R117 at 80km/h
3. R51A at 50km/h
4. R51C at 50km/h

The objective is to determine a correlation between these 4 ways of measuring.

3.2.1 Representing Rolling Sound

We have plotted the radar chart of all rolling sound tests according to each tyre. This radar, in opposition with the previous ones represents all tyres for the four noise performances (blue and green lines).

The tyres behave differently depending on the sensitivity of each tyre to the test procedures used (R117, R51C and R51A).

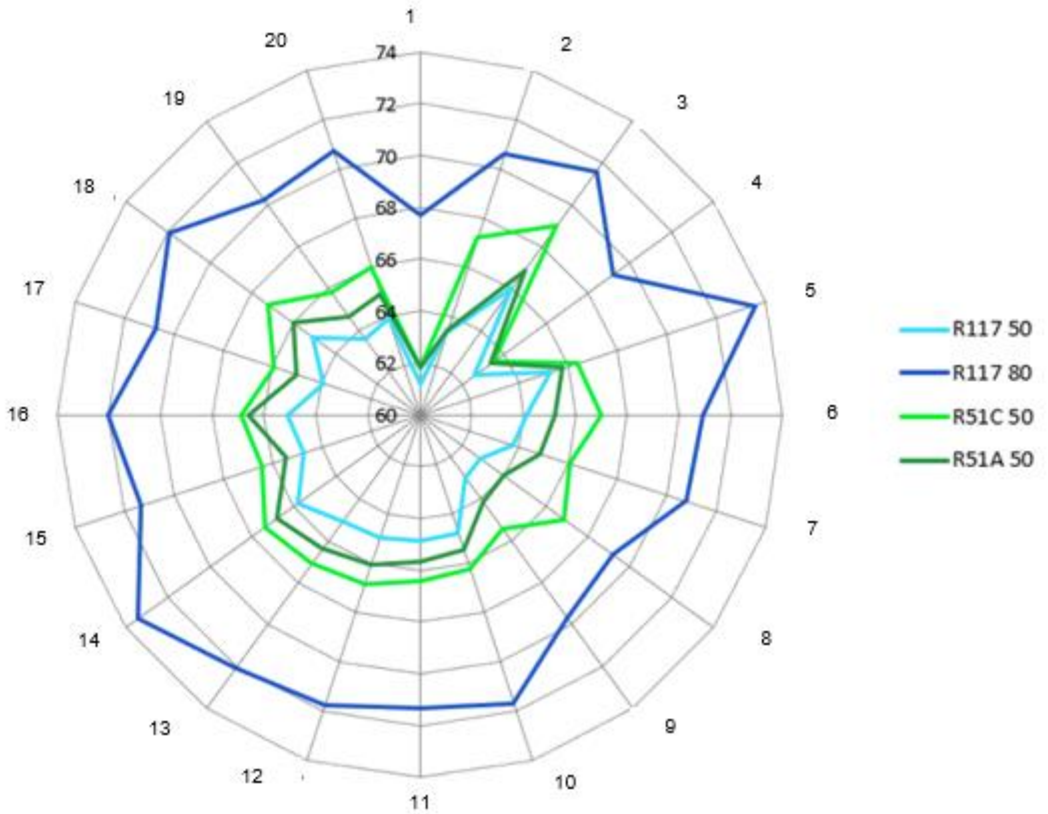

Figure 3.2-1 : Radar chart of all Rolling Sound tests according to each tyre

At first glance on the radar chart, the majority of tests follow the same trend for all tyres. In general, the shape of each “circle” shows a quite good correlation.

To confirm this trend, we carry out a correlation check.

3.2.2 2D charts and Scatterplots for Rolling Sounds

As described in described in the § A.12 The first approach : Bivariate Analysis, we used the Pearson correlation coefficient in order to research a linear correlation. A comparison between each Rolling Sound tests was performed with P-value less than 1%.

As the P-value is less than 1% we have a top level of probability of correlation.

In the following chart of scatterplots, the red boxes show a strong probability of correlation:

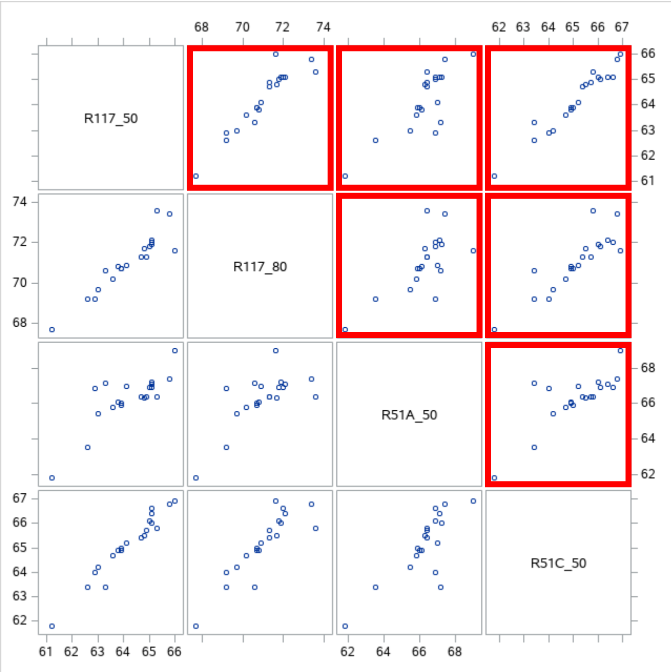

Figure 3.2-2 : 2D charts and Scatterplots for Rolling Sounds

These correlations confirm that, in this study, we can keep only one representative parameter among the four.

So, we have the opportunity to state on the Rolling Sound performance only through one noise parameter which is the R117 at 80km/h.

The R117 at 80 km/h also used for the approval of tyres with regard to rolling noise emissions is retained as the representative parameter/characteristic of the Rolling Sound.

3.3 Principal Component Analysis (PCA)

As we have quantitative data, we chose to perform a **Principal Component Analysis (PCA)**. It's a **factor analysis method** that allows multivariate analyses between quantitative variables. **This method can be considered a descriptive method** because it summarizes the information but does not explain it.

As reminder, all the methods used are described in the § A.12.The second approach: Principal Component Analysis.

3.3.1 Definition

"**Principal component analysis** (**PCA**) is a statistical procedure that uses an orthogonal transformation to convert a set of observations of possibly correlated variables (entities each of which takes on various numerical values) into a set of values of linearly uncorrelated variables called **principal components**". *(Wikipedia, Principal component analysis, 2019)*

In our case it is used to **reduce the number of 7 studied parameters** (Rolling Resistance, Wet Grip, Flat Track 80%, Flat Track 50%, Longitudinal & Lateral Aquaplaning, weight) **to 3 variables.**

3.3.2 PCA results

The inertia of the first dimensions shows if there are strong relationships between variables and suggests the number of dimensions that should be studied.

The first two components of PCA express 75% of the total dataset inertia; that means that 75% of the total cloud variability is explained by the plane. This percentage is relatively high and thus the first plane well represents the data variability.

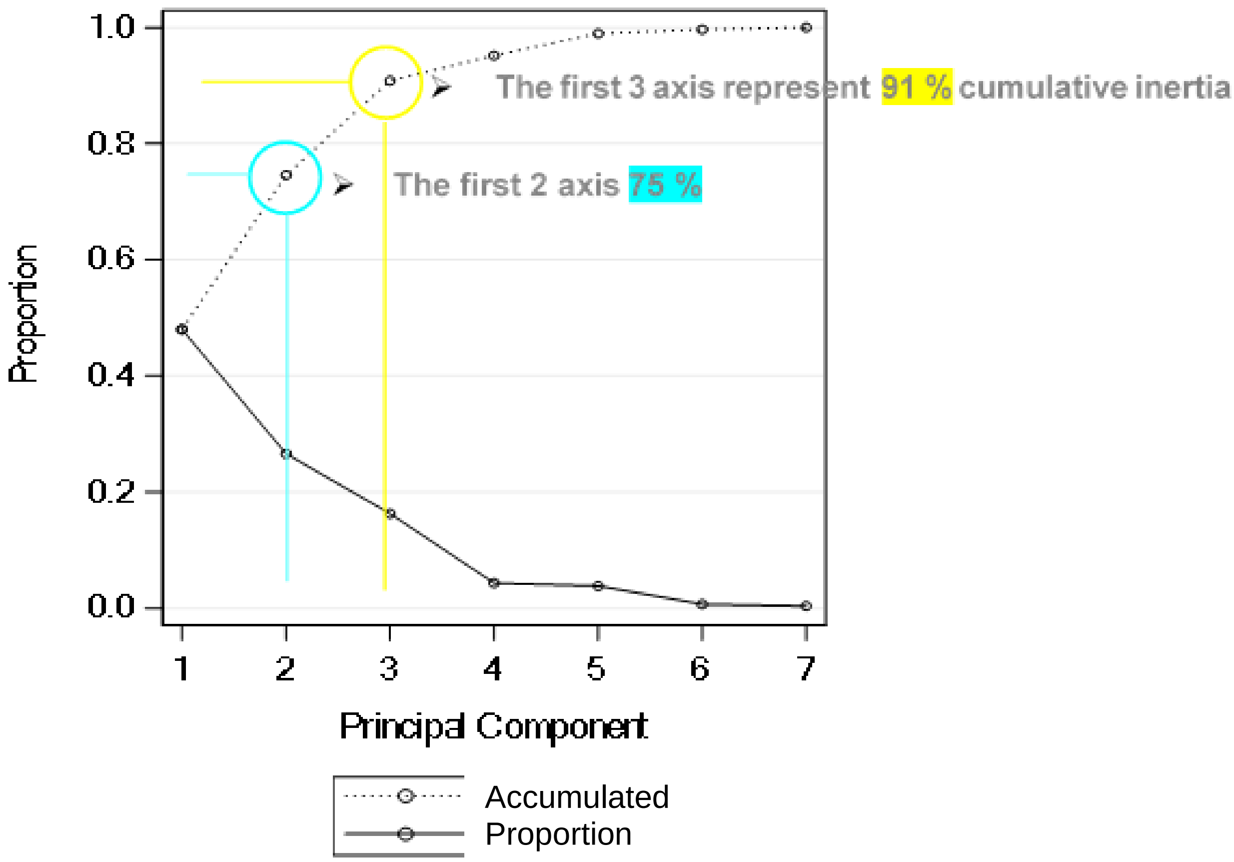

Figure 3.3-1 : Decomposition of the total inertia on the components of the PCA

An estimation of the right number of axes needed for the results interpretation suggests restricting the analysis to the description of the first 3 axes which represent 91% of the cumulative inertia.

As a consequence, the description will stand to these axes.

The description of the three components (according to the 7 parameters) selected is:

- **Axis 1** is mainly directed by **Wet Grip, Lateral/Longitudinal Aquaplaning and Flat Trac (negative)**
  - ➢ This axis should be understood as the most representative for Safety.
- **Axis 2** is mainly directed by **Rolling Resistance** and **Weight**
  - ➢ This axis should be understood as the most representative for **CO2 Emissions** because **Rolling Resistance** factor is the most important.
- **Axis 3** is mainly directed by **Flat Trac**
  - ➢ This axis should be understood as the most representative for "**Handling**"

Part of inertia	48%	27%	16%
	Axis 1	**Axis 2**	**Axis 3**
Rolling resistance	0.11447	0.88298	0.25046
Wet Grip	0.81409	-0.30913	0.25639
Flat Trac 80%	-0.68436	-0.00475	0.69410
Flat Trac 50%	-0.75908	-0.34619	0.50409
Longi aquaplaning	0.95221	0.06517	0.25576
Lateral aquaplaning	0.84282	-0.04567	0.45466
Weight	-0.14998	0.92685	0.04316

Table 3.3-1 : Correlation coefficients between variables and dimensions

All these three components are then compared with the Rolling Sound performance (from R117 at 80km/h).

3.3.2.1 1st axis

As a reminder, axis 1 is mainly directed by "**safety**" tests as shown through this "3D representation".

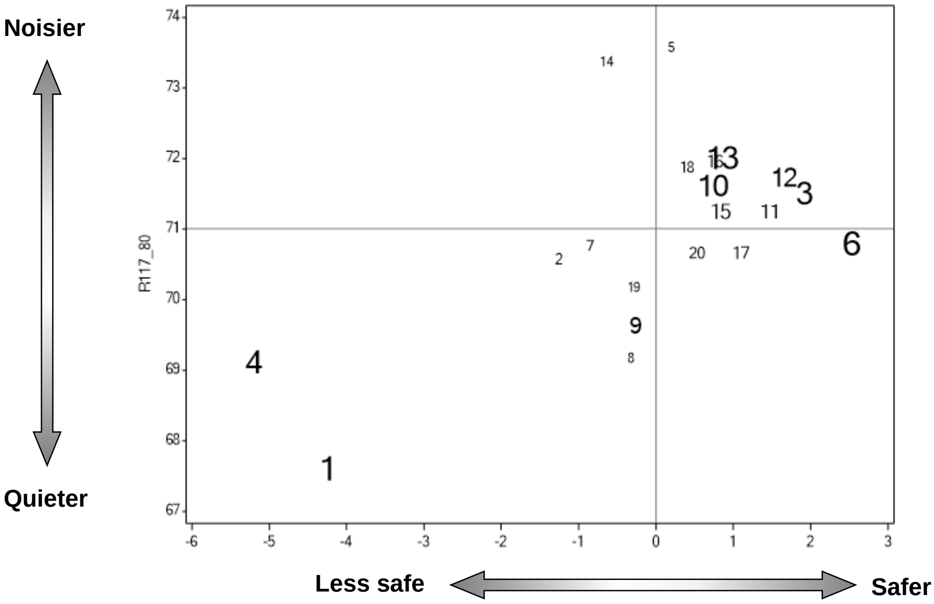

Figure 3.3-2 : R117_80 vs Axis 1 "Safety"

On top right direction, tyres are noisier and better in these axis parameters (like tires 3).
On bottom right direction, tyres are quieter and better in these axis parameters.

Most of tyres are either good in safety tests but noisier or low noise but less good in safety tests (like tyre 13).

➢ The statistical approach concerning our sample of 20 tyres shows a **conflict between Rolling Sound and Safety performances.**

3.3.2.2 2nd axis

As a reminder, axis 2 is mainly directed by CO_2 through **Rolling Resistance** and **weight** test.

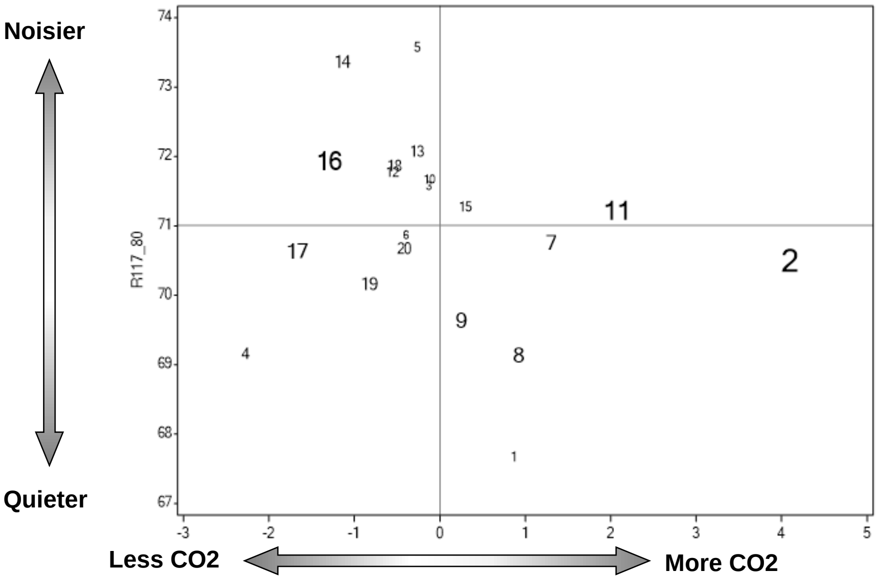

Figure 3.3-3 : R117_80 vs Axis 2 "Rolling Resistance & Weight"

Careful in this axis, the Rolling resistance performance decreases while both Longitudinal and Lateral Aquaplaning performances increase.

- **A simple conclusion cannot be drawn on Axis 2**
- A sensitivity analysis of the parameters influence suggests that the change in tyre inflation pressure has the maximum influence on Rolling Resistance. Here the inflation pressure was not changed.
- The influence of contact patch width is very moderate.

3.3.2.3 3rd axis

As a reminder, axis 3 is mainly directed by "**handling**" test.

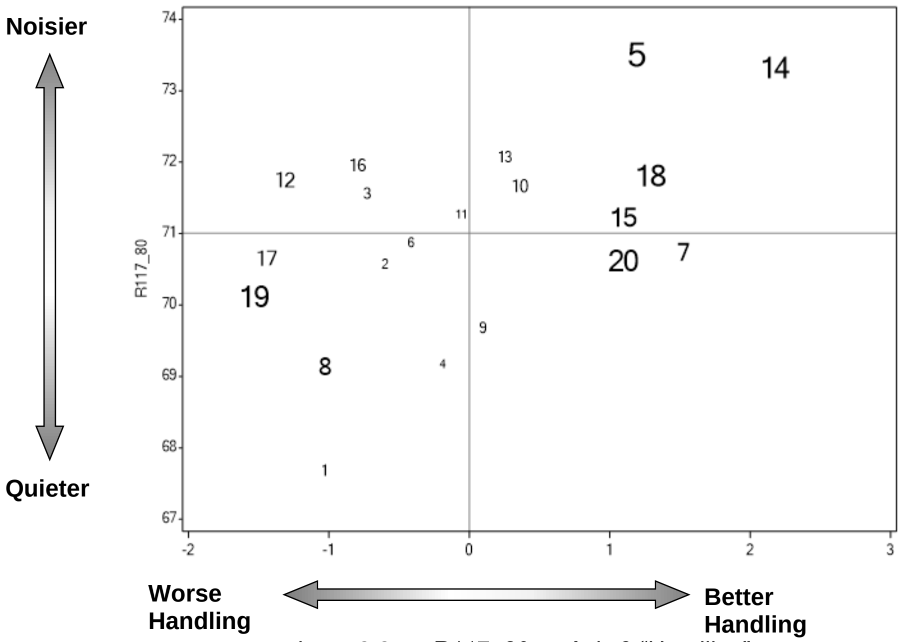

Figure 3.3-4 : R117_80 vs Axis 3 "Handling"

On bottom left direction, tyres are quieter and weak in flat trac (like tyres 19 and 8).
On top right direction, Tyres are noisier and better in flat trac (like tyres 5 and 18)

- **Better Handling performance (only flat trac) is linked to an increase of the Rolling Sound.**

4. CONCLUSION

4.1 Test Program conclusions

- The purpose of this study was to aggregate two studies on tyre performances namely ACEA and ETRTO Studies, and to compare the respective conclusion on a more representative sample.
- This aggregation of studies offers **a comprehensive toolbox to evaluate the relationship and interdependency between Rolling Sound and other tyre's performances using standard or regulatory measurement protocols**.
- Correlation analysis shows that the four acoustic parameters regarding UN-R51.03 (Vehicle measurement) and UN-R117 (Tyre measurement) at different speeds are correlated and can be chosen only one in this study as a global Rolling Sound performance. To be noted that this correlation is a linear statistical correlation and not deterministic rule.

4.2 Statistical Analysis conclusions

- We have described the relationship between the 7 parameters through 3 axes with a good level of representativeness (part of inertia is 91%).
- The radar charts and the Principal Components Analysis show **a conflict between rolling sound** (R117) **and Safety performances** (Wet Grip, Lateral Aquaplaning).
- Simple conclusions regarding Rolling Sound, Rolling Resistance, weight and Safety performance (Longitudinal Aquaplaning) cannot be drawn.

4.3 Main conclusion

4.3.1 Testing conditions

ITEM		ACEA study	ETRTO study	Aggregation Study
Tyres tested	set/size	16 x 205/55 R16 91 H/ T/ V/W	10 x 205/55 R16 91/94 H/V/W	20 x 205/55 R16 91 H/V/W
	type	14 summer, 2 snow (3PMSF)	6 summer, 2 snow (3PMSF), 2 plain tread	16 summer, 3 snow (3PMSF), 2 plain tread (including a 3PMSF)
Safety Related Tests	dry grip	ECE13H Type 0 @ 100 km/h (Peugeot 308 laden/ unladen)	ECE R117 @ 65 km/h (Trailer) comparable to wet grip	-
	dry handling	ETRTO Method @ 80 km/h with diff. loads (flat trac bench)	ETRTO Method @ 80 km/h with diff. loads (flat trac bench)	ETRTO Method @ 80 km/h with diff. loads (flat trac bench)
	wet grip	ECE R117 @ 65 km/h (trailer)	ECE R117 @ 65 km/h (trailer)	ECE R117 @ 65 km/h (trailer)
	aquaplaning	VDA E08 longit., VDA E05 lateral (Peugeot 308)	VDA E08 longit., VDA E05 lateral (Peugeot 308)	VDA E08 longit., VDA E05 lateral (Peugeot 308)
Emission Related Tests	vehicle noise	ECE R51 Cr.@ 50 & 80 km/h, Acc.@ 50 km/h (Nissan Leaf)	ECE R51 Cr.@ 50 & 80 km/h, Acc.@ 50 km/h (Nissan Leaf)	ECE R51 Cr.@ 50 & 80 km/h, Acc.@ 50 km/h (Nissan Leaf)
		-	ECE R51 Cr.@ 50 & 80 km/h, Acc.@ 50 km/h (VW Golf)	-
	tyre noise	ECE R117 @ 50 & 80km/h	ECE R117 @ 50 & 80km/h	ECE R117 @ 50 & 80km/h
	CO2	ECE R117 @ 80 km/h (bench for Rolling Resistance)	ECE R117 @ 80 km/h (bench for Rolling Resistance)	ECE R117 @ 80 km/h (bench for Rolling Resistance)
		weight, tread depth, void ratio	weight	weight

4.3.2 Results

ITEM	ACEA study	ETRTO study	Aggregation Study
Radar Charts graphical analysis	Best tyres in terms of safety, noise and CO2-emissions: - safe tyres are quite noisy - good rolling sound tyres have poor aquaplaning scores - good rolling resistance tyres have poor handling and aquaplaning scores	Best tyres in terms of wet safety, rolling sound and rolling resistance: - best for wet safety are worse for rolling sound emission - best for rolling sound emission are worst for aquaplaning - rolling resistance and rolling sound emission seem to be not correlated	Best tyres in terms of safety, rolling sound and rolling resistance: - safe tyre are also quite noisy - best for rolling sound are worse for aquaplaning - no clear correlation between rolling resistance and any other parameter
2D Scatter Charts bivariate analysis	- all rolling sound tests are highly correlated to each other - rolling sound, weight, tread void & depth and 8 other characteristics are significantly correlated in 20 cases - rolling sound is correlated to longitudinal and lateral aquaplaning"	- all rolling sound tests are highly correlated to each other - rolling sound & 7 other characteristics are significantly correlated in 7 cases - rolling sound and wet safety are statistical correlated but not deterministic ruled (some inversions of ranks)	- all rolling sound tests are highly correlated to each other - rolling sound, wet grip, dry handling, rolling resistance, aquaplaning and weight are significantly correlated in 10 cases - rolling sound is correlated to longitudinal and lateral aquaplaning - rolling sound is correlated with wet grip but no deterministic ruled
Principal Component Analysis descriptive method	summarize 8 to 3 characteristics “safety”, “handling” and “CO2-emissions” leads to: - conflict between rolling sound and safety performance - handling performance supports good rolling sound - undefined relation between sound and CO2-emission	summarize 7 to 3 characteristics “wet safety”, “dry grip/ CO2-emissions” and “flat trac 80% / dry grip” leads to: - conflict between rolling sound and wet safety - plain tread tyres represent an asymptote for rolling sound at a forbidden stage of wet safety	summarize 7 to 3 characteristics “safety”, “CO2-emissions” and “handling” leads to: - conflict between rolling sound and safety performance - handling performance supports good rolling sound - undefined relation between sound and CO2-emission - plain tread tyres represent an asymptote for rolling sound at a forbidden stage of wet safety

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5. APPENDICES

Appendix A: Tool Box

The tool box is a help to describe the methods used and how to proceed during statistical analysis.

A.1 The first approach : Bivariate Analysis

In this study, the first approach was to check if there was a relationship between the performance parameters. For this approach we used the Pearson correlation coefficient in order to research a linear correlation.

A.1.1 The P-value

The **P-value or probability value is**, for a given statistical model, **the probability that, when the null hypothesis is true, the statistical summary would be greater than or equal to the actual observed results**.

In our case the hypothesis is "**there is no correlation between parameters**".

In other words, **if P-value is low then our hypothesis is false,** and **we can conclude that there is a correlation**.
The admitted threshold value is 5%.

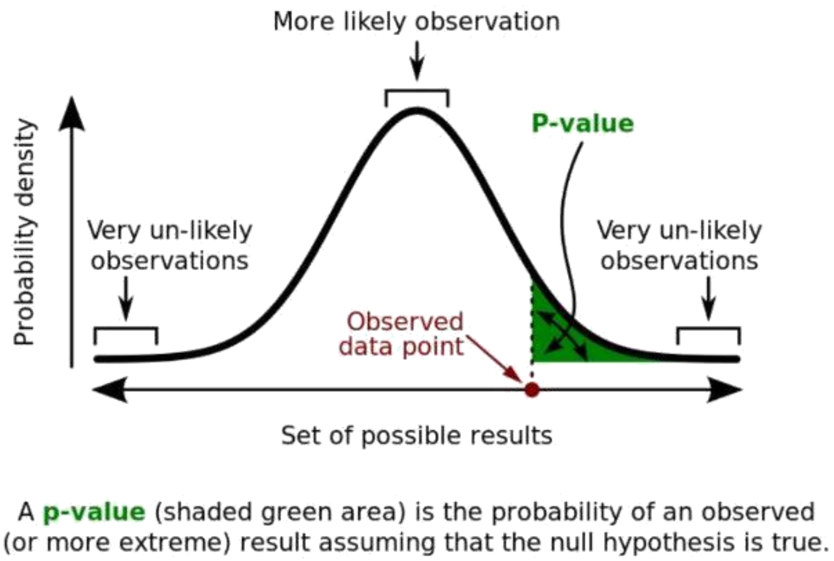


Figure A.1-1 : The P-value area in the set of possible results

A.1.2 Relationship representation

We have plotted the graphs of the 7 performance parameters: Rolling Resistance, Wet Grip, Flat Trac 80%, Flat Trac 50%, Longitudinal Aquaplaning, Lateral Aquaplaning, Weight.

The Rolling Sound parameter no enter in this scope.

All performance parameters are displayed in relation to each other. A set of 100 scatterplots is then obtained.

In the Figure A.1-3, each **red boxes show strong probability of correlation** (P-value < 5%).

The performance parameters are placed diagonally, which gives a symmetrical chart with respect to this diagonal. Thus, the grey boxes are the symmetries of the red boxes.

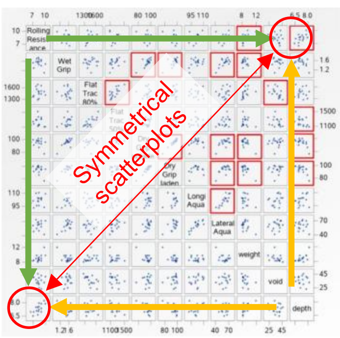


Figure A.1-2 : Symmetric explanation

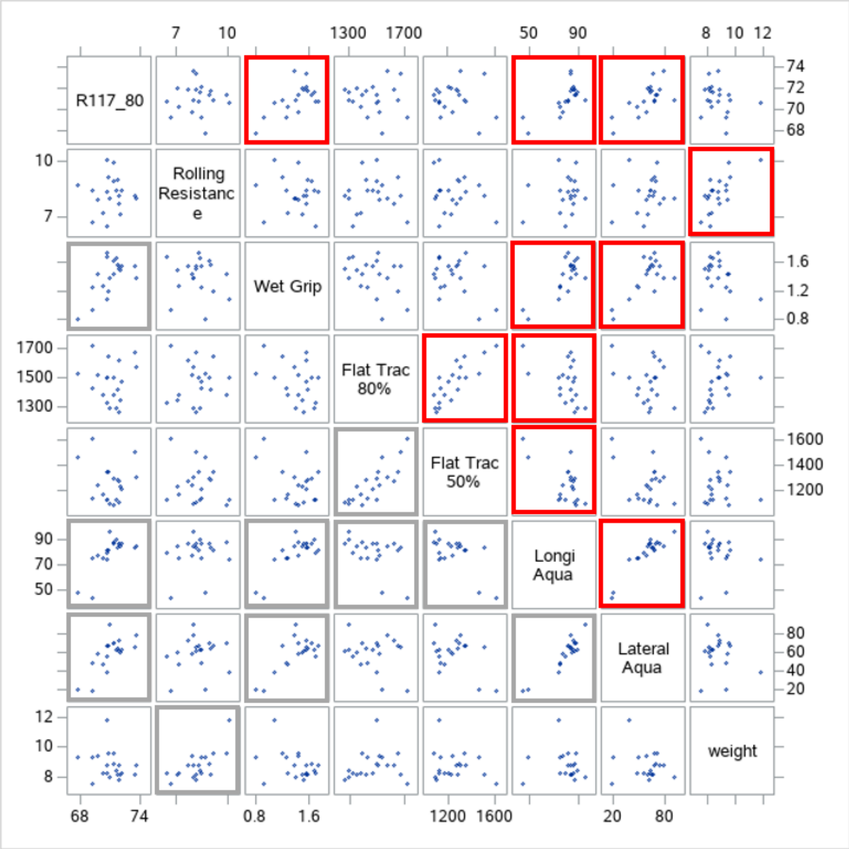


Figure A.1-3 : The chart of scatterplots

This tool allows us to show direct relationship between the parameters.

The units used in this chart as the following:

Test	Units
Rolling Resistance	RR Index
Wet Grip	WG Index
Flat Track	N/°
Longitudinal Aquaplaning	%
Lateral Aquaplaning	m/s (integer)
Weight	Kg

Table A.1-1 : Unit used in the chart of scatterplots

A.2 The second approach: Principal Component Analysis

Principal Component Analysis (PCA) is a dimension-reduction tool that can be used to reduce a large set of variables to a small set that still contains most of the information in the large set.

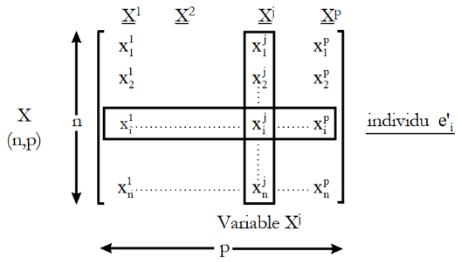
It is a mathematical procedure that transforms a number of (possibly) correlated variables into a (smaller) number of uncorrelated variables called principal components.

The first principal component accounts for as much of the variability in the data as possible, and each succeeding component accounts for as much of the remaining variability as possible.

A.2.1 The problem

A.2.1.1 Data

n individuals observed on p quantitative variables.

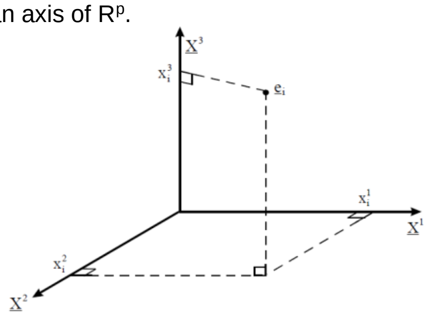


Individual: element of R^p
Variable: element of R^n

PCA allows to explore the links between variables and the similarities between individuals.

A.2.1.2 We are trying to represent the cloud of individuals

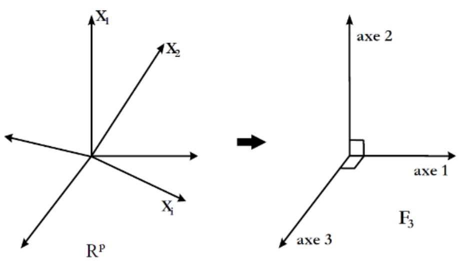
To each individual noted e_i, a point can be associated in R^p = individual space.
Each variable in table X is associated with an axis of R^p.



Unable to view as soon as p > 3.

We are looking for a representation of the n individuals, in a subspace F_k of R^p of dimension k.
In other words, we are trying to define **k new variables linear combinations of the p initial variables** that will cause as **little information loss** as possible.

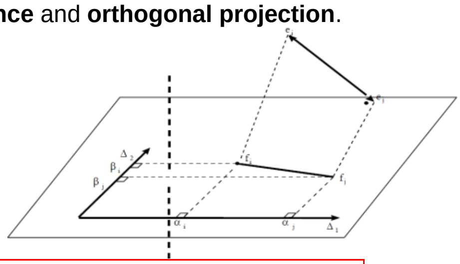
These variables will be called "**Principal Components**"
The axes they determine: "**Principal Axes**"
The associated linear shapes: "**Principal Factors**"



A.2.1.3 Loose as little information as possible

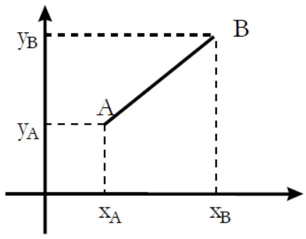
1. F_k will have to be "adjusted" as best as possible to the cloud of individuals: the sum of the squares of the distances from individuals to F_k must be minimal.
2. F_k is the subspace such that the projected cloud has a maximum inertia (dispersion).

1 and 2 are based on the notions of **distance** and **orthogonal projection**.



The distance between f_i and f_j is less or equal to that between e_i and e_j.

A.2.1.4 The choice of the distance between individuals



In the plane: $d^2(A,B) = (x_B - x_A)^2 + (y_B - y_A)^2$

In the space R_p with p dimensions, this notion is generalized: the Euclidean distance between two individuals is written:

$e_i = (X_i^1 X_i^2 \dots X_i^p) \quad e_j = (X_j^1 X_j^2 \dots X_j^p)$
$d^2(e_i, e_j) = (X_i^1 - X_j^1)^2 + (X_i^2 - X_j^2)^2 + \cdots (X_i^p - X_j^p)^2$

$$d^2(e_i, e_j) = \sum_{k=1}^{p} (X_i^k - X_j^k)^2$$

To solve the units problem, we choose to transform the data into centered-reduced data.
The observation X_i^k is then replaced by standard deviation units:

$$\frac{X_i^k - \bar{X}^k}{S_k}$$

where $\bar{\bar{X}}^k$ = mean of the variable X^k and S_k = standard deviation of the variable X^k

A.2.1.5 Total inertia

Inertia is the weighted sum of the squares of the distances of individuals at the centre of gravity g.

$$I_g = \sum_{i=1}^{n} p_i d^2(e_i, g)$$

with $\sum_{i=1}^{n} p_i = 1$

Inertia measures the total dispersion of the point cloud.

Inertia is therefore also equal to the sum of the variances of the variables studied.
By noting V the variance -covariance matrix:

$$V = \begin{pmatrix} s_1^2 & s_{12} \ldots\ldots s_{1p} \\ \vdots & s_2^2 \quad\quad \vdots \\ s_{p1} & \quad\quad s_p^2 \end{pmatrix}$$

$$\boxed{I_g = \sum_{i=1}^{p} S_i^2 = Tr(V)}$$

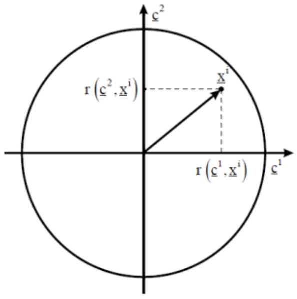
A.2.2 The solution of the problem posed

The search for axes with the maximum inertia is equivalent to the construction of new variables (with which these axes are associated) of maximum variance.
In other words, we change the reference point in Rp in order to place ourselves in a new representation system where the first axis provides as much as possible of the total inertia of the cloud, the second axis as much as possible of inertia and orthogonal to the first axis, and so on…

This reorganization is based on the diagonalization of the variance-covariance matrix.

A.2.2.1 Variable representation

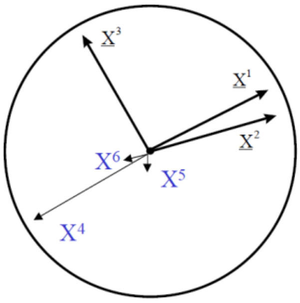
The "proximities" between the main components and the initial variables are measured by covariances, and especially **correlations**.
$R(c^j,x^i)$ is the linear correlation coefficient between c^j and x^i.



A.2.2.2 Interpretation of "proximities" between variables

A scalar product is used between variables to associate the following with the current parameters: standard deviation, linear correlation coefficient of the geometric representations. We assume the centered variables.

$$\boxed{\langle \underline{X}^i, \underline{X}^j \rangle = \frac{1}{n} \sum_{k=1}^{n} X_k^i X_k^j}$$



X^1 and X^2 have a correlation close to 1.
X^1 and X^3 have a correlation close to 0.

A.2.3 Validity of representations

A.2.3.1 Global criteria:

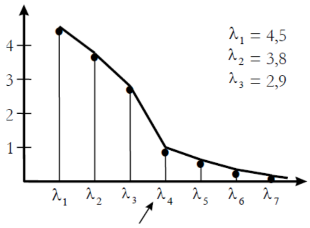
$\frac{\lambda_i}{\lambda_1+\lambda_2+\cdots\lambda_p}$ measures the inertia portion explained by the i-axis.

This criterion (often expressed as a percentage) measures the degree of reconstitution of the squares of distances.
The reduction of dimension is all the greater as the starting variables are more correlated.

How many axes?

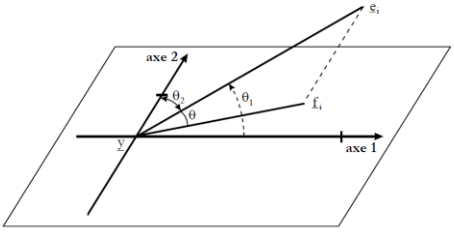
Different procedures are complementary:

1. Desired percentage of inertia.
2. Divide the total inertia by the number of initial variables: keep all axes with an inertia greater than this value.
3. Keep the axes associated with the eigenvalues located before the break (λ_4).



A.2.4 Individual criteria

A.2.4.1 Square Cosine



$$\cos^2\theta = \cos^2\theta_1 + \cos^2\theta_2$$

For each individual, the quality of his representation is defined by the square of the cosine of the angle between the projection axis and the vector $\underline{e_i}$. **The closer the value is to 1, the better is the quality of representation**.

In general, the qualities of representation are given axis by axis. To have the quality of representation in a plane, the criteria corresponding to the axes studied are added.

This criterion has no significance for individuals close to the origin.

When detecting an individual for whom the square cosine is weak, its distance at the origin must be taken into account before indicating that it is poorly represented.

A.2.4.2 Contribution

It is also very useful to calculate for each axis the contribution made by the various individuals to that axis.
Let us consider the k^{th} main component $\underline{c^k}$, c_i^k the value of the component for the i^{th} individual.

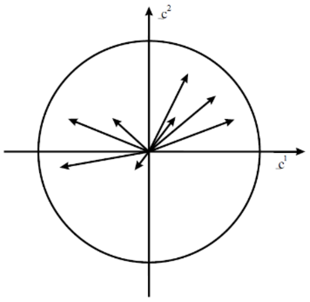
$$\sum_{i=1}^{n} \frac{1}{n}\left(c_i^k\right)^2 = \lambda_k$$

The contribution of the individual $\underline{e_i}$ to the component n° k is defined by:

$$\frac{\frac{1}{n}(c_i^k)^2}{\lambda_k}$$

A.2.5 Variable representation

The circle of correlations is the projection of the cloud of variables on the level of the main components.



Correlation = cosine

The variables well represented are those close to the circle, those close to the origin are poorly represented.

A.3 Method applied in our study

In this study:

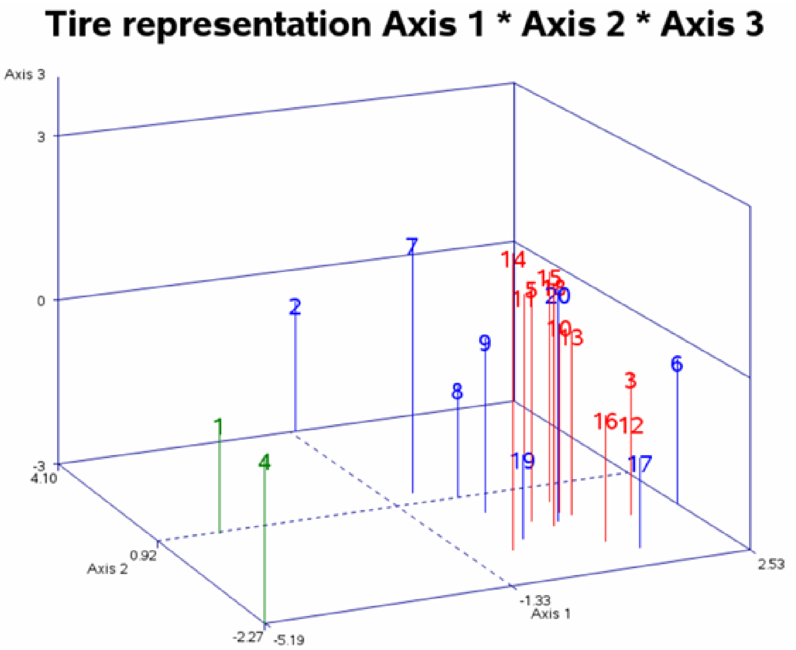
- **Individuals** (tyre references): two tyre references will be close to each other if their results to the events are close. We want to see the variability between the individuals. Are there similarities between individuals for all the variables? Can we establish different profiles of individuals? Can we oppose a group of individuals to another one?
- **Variables** (tyre performance): We want to see if there are linear relationships between variables. The two objectives are to summarize the correlation matrix and to look for synthetic variables: can we resume the performance of a tyre by a small number of variables?

A.3.1 Data

In our case it is used to reduce the **number of input parameters** (variables) from 8 to 3 to allow a 2D or 3D visualization:

Rolling Resistance Dry Grip Laden Dry Grip Unladen Flat Trac 80% Flat Trac 50% Wet Grip Longitudinal Aquaplaning Lateral Aquaplaning	➔	Axes 1 Axes 2 Axes 3

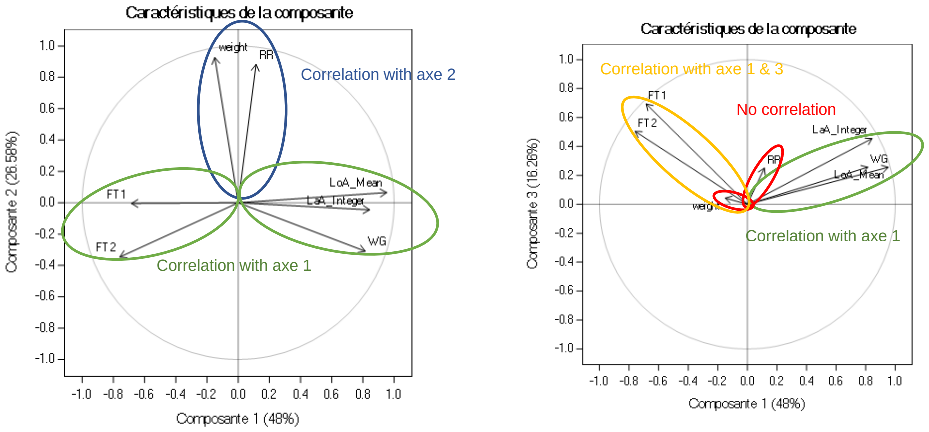
The result obtained:



Letters correspond to the 20 tyres tested (individuals). Red letters are noisy tyres, green are quiet tyres and blue are middle noise.

A.3.2 Variable representation

The "proximities" between the main components and the initial variables are the following:



RR = Rolling Resitance
FT1 = Flat Trac 80%
FT2 = Flat Trac 50%
LoA_Mean = Longi aquaplaning
LaA_Integer = Lateral aquaplaning

Figure A.3-1 : Variables factor map

A.3.3 Validity of representations

We used the Histogram method to keep the axes associated with the eigenvalues located before the break.

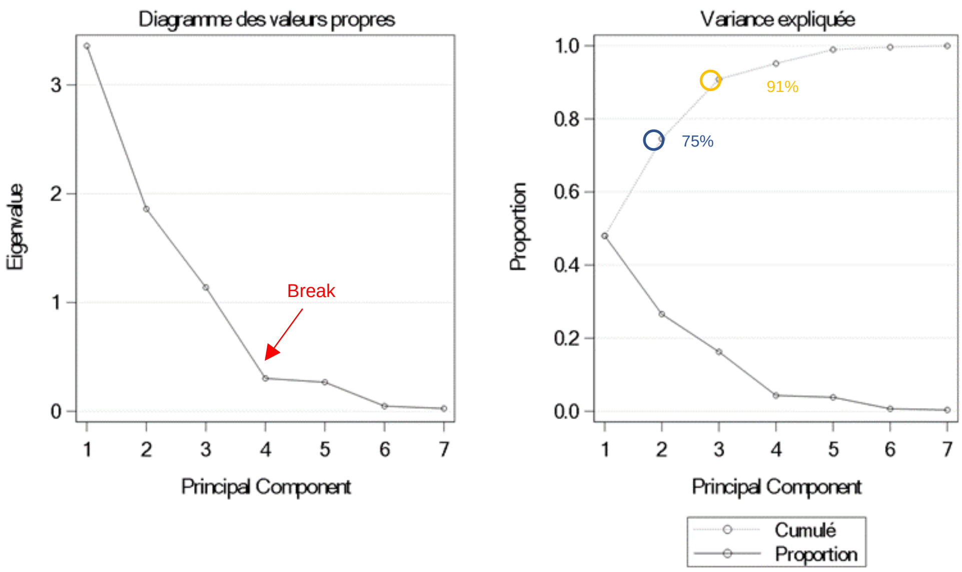


Figure A.3-2 : Decomposition of the total inertia on the components of the PCA

The percentage of cumulative inertia for the two first axes represent 75% and raise to 91% with the third axis.

A.3.4 The contribution and 2D representation

Characterization of factors using individuals is represented by the font size of the tyre in question. The formula used is:
$\boldsymbol{Police_{ij}} = (qltx_{ij} + qlty_{ij}) * 2$

Where $data\ quality = \ qlt_{ij} = \frac{(ACP\ proper\ value_{ij})^2}{Distance_j}$

$Distance_j = \sum_{i=1}^{n}(ACP\ proper\ value_{ij})^2$

With *n* the number of ACP axis
i the ACP axis
j the tyre
$qltx_{ij}$ / $qlty_{ij}$ the data quality of tyre *j* on the axis *i*
$Distance_j$ the distance of tyre (in relation to the centroid of the point cloud)

Here an example with axis 1 and axis 2.

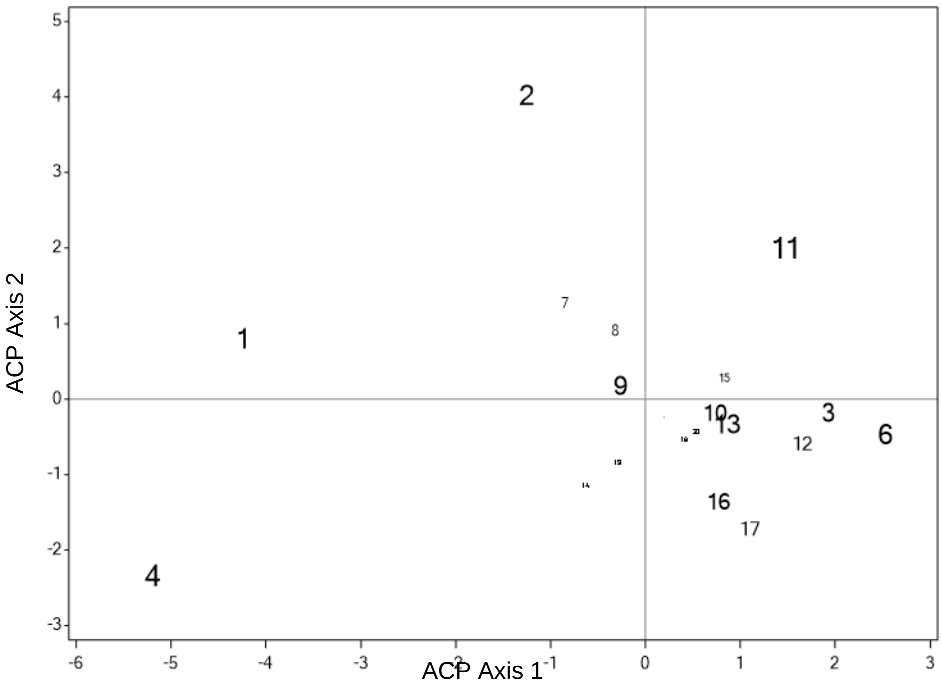


Figure A.3-3 : Individual factor map

When replacing axis 2 by Noise we choose $qlty_{ij} = 0.5$

The **bigger the number**, the **more** the **axis** is **driven** by the **tyre** in comparison to the others for this 20 tyres sample.
The **smaller the number**, the **less** the **axis** is **driven** by this **tyre** in comparison to the others for this 20 tyres sample.

Appendix B : Statistics results

B.1 Univariate Analysis

B.1.1 Data description

Variable	Unit	Minimum	Lower quartile (25%)	Mean	Median (50%)	Upper quartile (75%)	Maximum	Standard deviation
R117 50	dB(A)	61,2	63,4	64,2	64,4	65,1	66,0	1,2
R117 80	dB(A)	67,7	70,4	71,0	71,1	71,8	73,6	1,4
R51A 50	dB(A)	61,8	65,9	66,3	66,4	67,0	69,0	1,5
R51C 50	dB(A)	61,8	64,4	65,1	65,3	66,0	66,9	1,3
Rolling Resistance	Cr (N / kN)	6,449	7,790	8,232	8,239	8,820	10,084	0,955
Wet Grip	G(T)	0,80	1,26	1,41	1,46	1,56	1,74	0,25
Flat trac 80%	N / °	1265	1366	1470	1485	1553	1718	132
Flat trac 50%	N / °	1080	1126	1253	1235	1325	1613	148
Aquaplaning longi	%	43,83	76,15	79,63	83,74	86,54	96,22	12,78
Aquaplaning lateral		18,97	52,40	59,26	63,34	68,71	90,42	17,41
Weight	Kg	7,54	8,16	8,77	8,60	9,33	11,81	0,93

Table B.1-1 : Data description used

B.1.2 Box-plot graphics

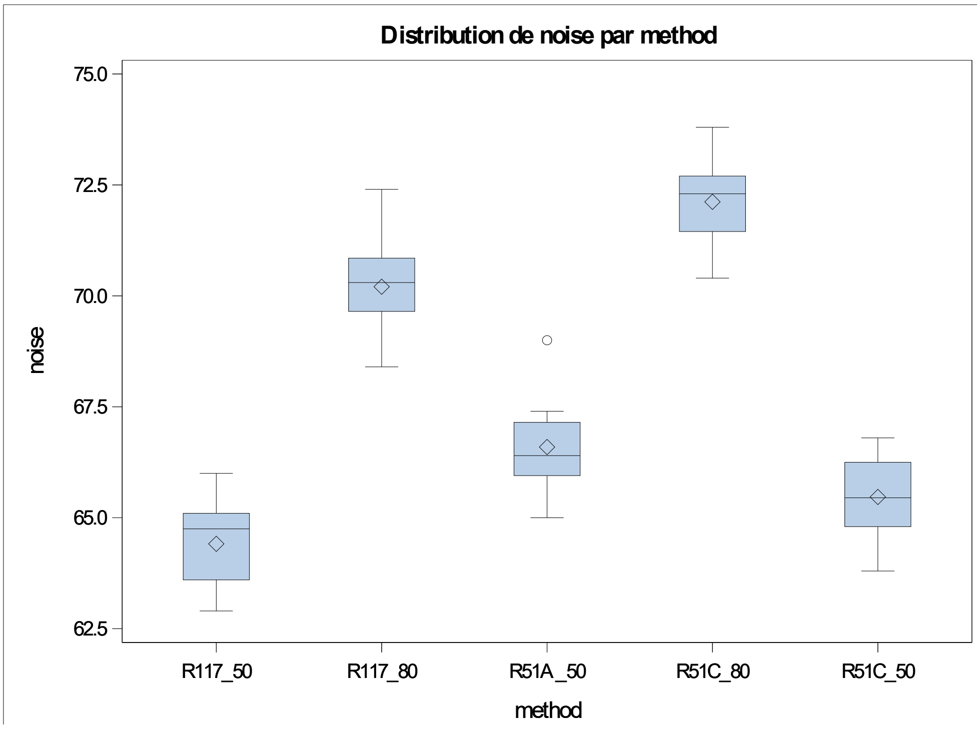


Figure B.1-1 : Noise distribution by method

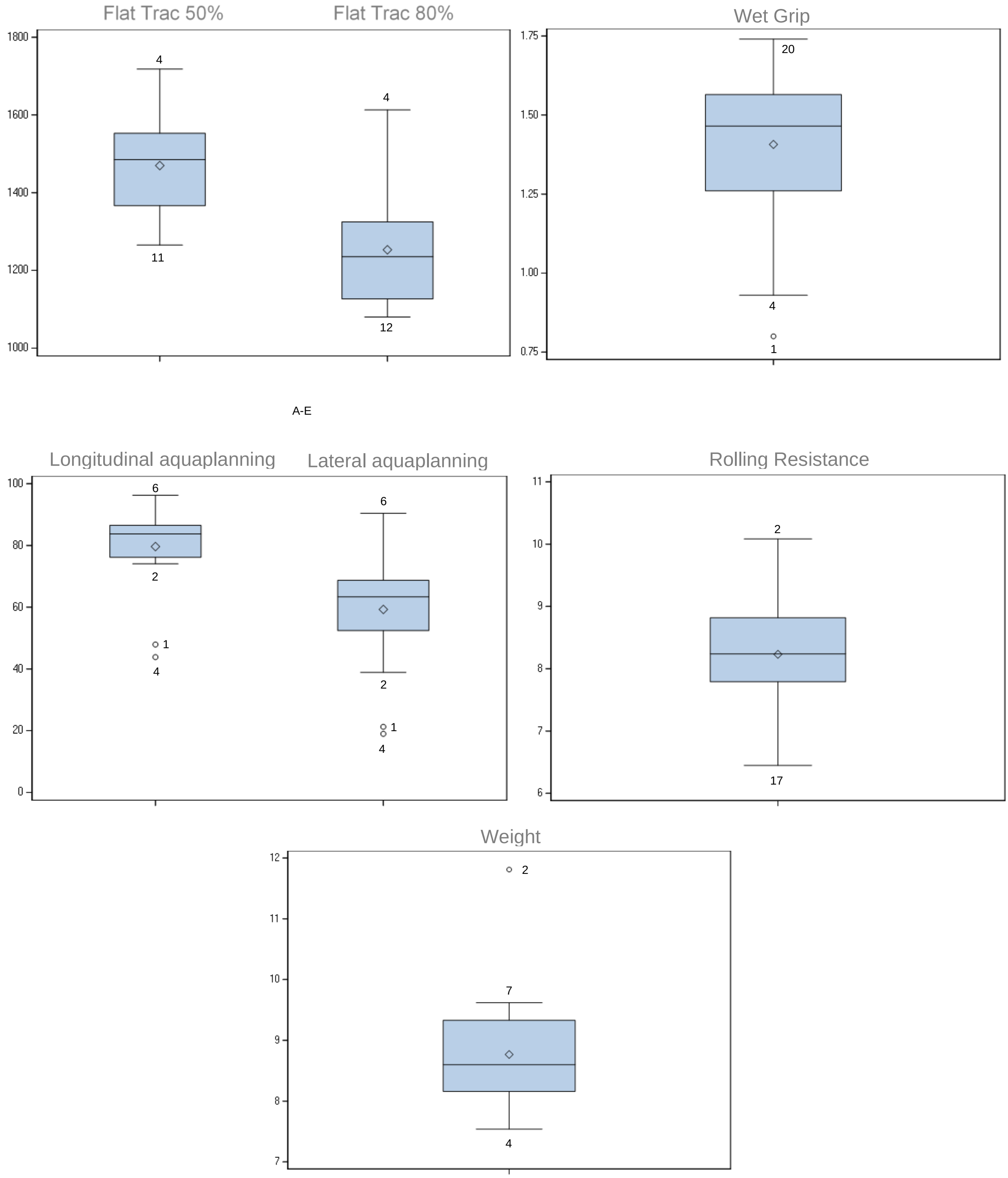


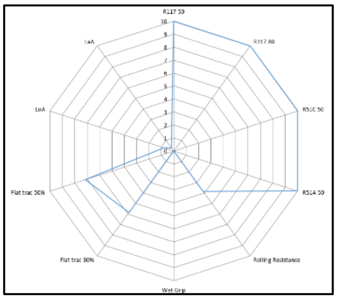
Figure B.1-2 : Box-plot graphic of each variable

The tyre 3 brings out atypical for R51A50,

B.1.3 Tyre Radar Charts

In order to visualize all results for each tire, we gave a score of 0 to 10 so that each result is comparable with each other (0 for very bad resultat and 10 for very good result). Thereby having a first visual of tyre performances.

1



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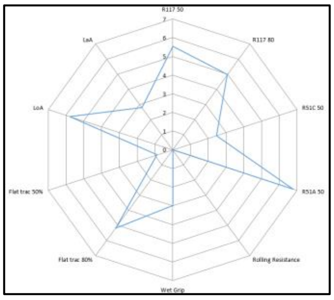

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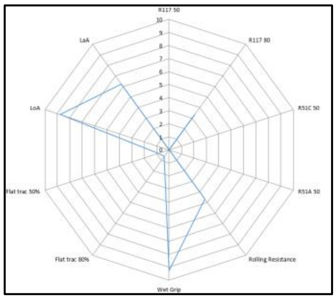

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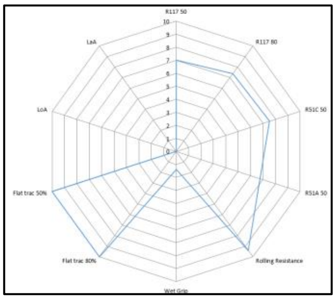

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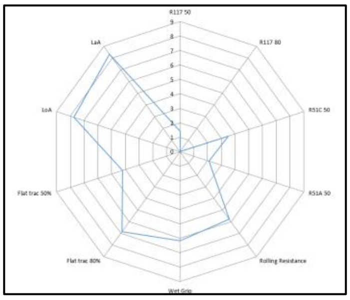

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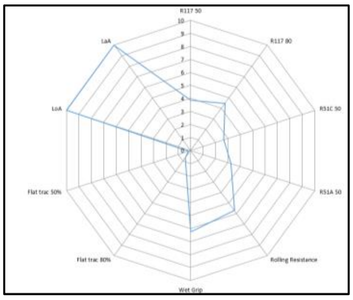

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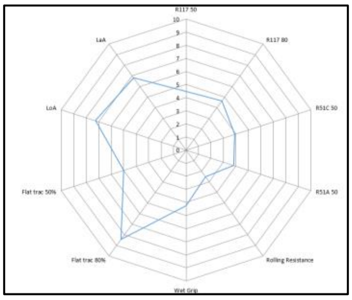

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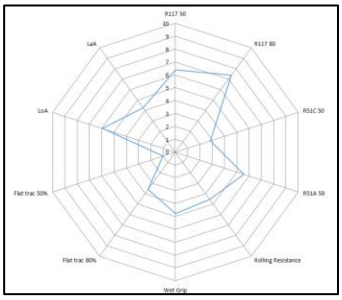

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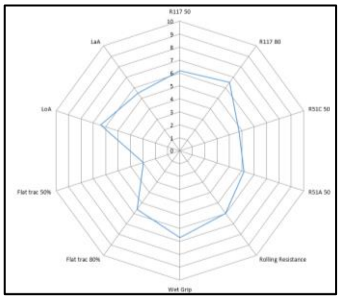

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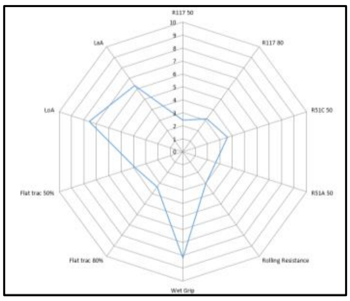

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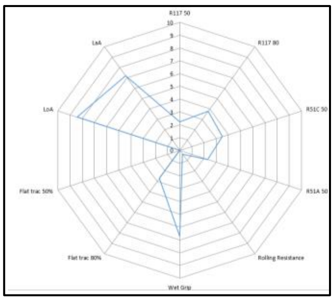

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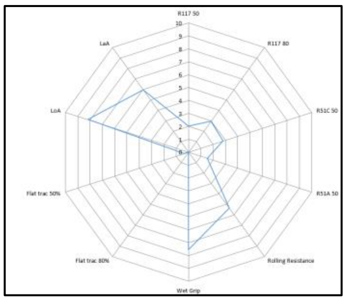

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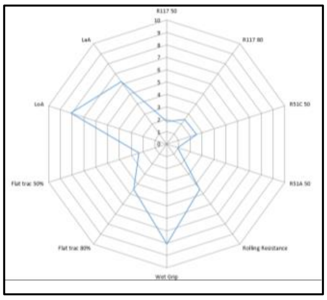

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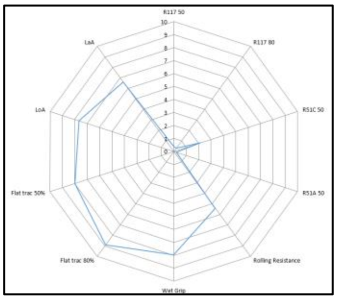

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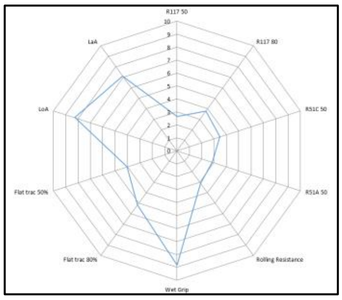

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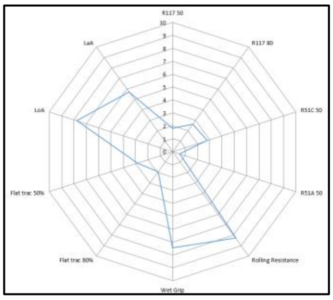

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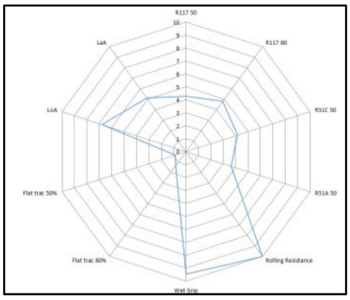

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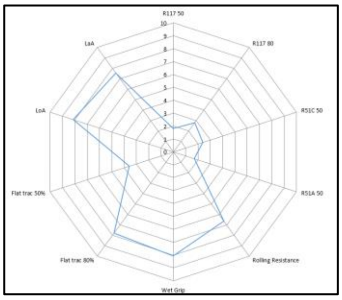

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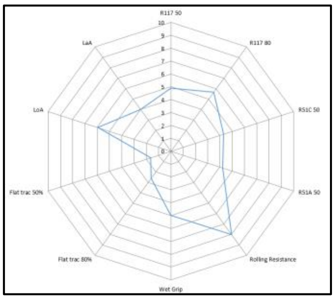

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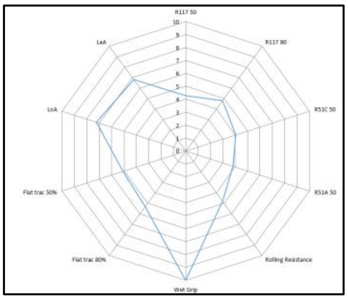

Figure B.1-3 : Radar Charts of each tyre

B.2 Bivariate Analysis

B.2.1 Correlation between each variables

We computed the correlations of each variable between them. The table below only shows the relationships for which the Pearson correlation coefficient is significant (P-value <0.05).

Obs	Variable 1	Variable 2	Pearson Correlation coefficient	Proba > |r| under H0: (P-value)
1	Longi Aquaplaning	Lateral Aquaplaning	0,92580	<,0001
2	R51A 50	Longi Aquaplaning	0,8434	<,0001
3	Flat Trac 80%	Flat Trac 50%	0,82282	<,0001
4	R51C 50	Longi Aquaplaning	0,80021	<,0001
5	R51C 50	Wet Grip	0,79434	<,0001
6	R117 50	Longi Aquaplaning	0,79055	<,0001
7	Wet Grip	Longi Aquaplaning	0,78567	<,0001
8	R117 50	Wet Grip	0,75887	<,0001
9	R51C 50	Lateral Aquaplaning	0,72397	0,0001
10	R117 80	Longi Aquaplaning	0,71741	0,0003
11	R117 50	Lateral Aquaplaning	0,71531	0,0004
12	Wet Grip	Lateral Aquaplaning	0,7113	0,0004
13	R117 80	Lateral Aquaplaning	0,7051	0,0004
14	Rolling resistance	Weight	0,69744	0,0005
15	R51A 50	Wet Grip	0,67896	0,0006
16	R51A 50	Lateral Aquaplaning	0,66624	0,001
17	R117 80	Wet Grip	0,64098	0,0013
18	Flat Trac 50 %	Longi Aquaplaning	-0,62464	0,0023
19	R51A 50	Flat Trac 80%	-0,57266	0,039
20	Flat Trac 80 %	Longi Aquaplaning	-0,4647	0,0083

Table B.2-1 : Variables correlation

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B.2.2 Linear correlations visualizations two by two

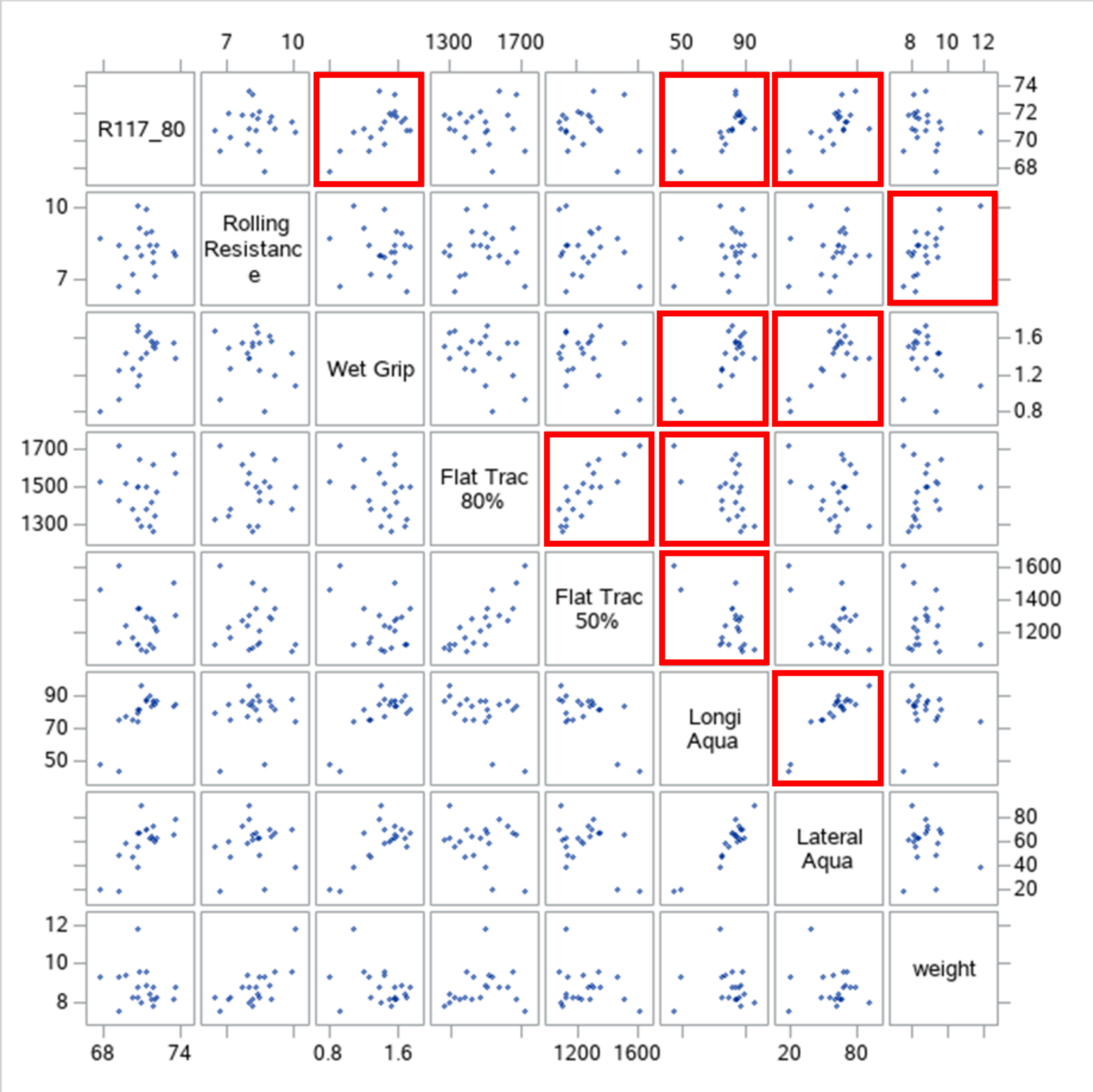

Figure B.2-1 : Scatter plot between each two-by-two variable

The graph above represents the scatter plot between each two by two variable. The graphs which have a linear correlation significant are frame in red.