Research and Innovation action

D2.4 Final report

LEON-T

Low particle Emissions and low Noise Tyres

Deliverable No.	D 2.4	
Deliverable Title	Results from the comparison of tyre tread wear and related particle emissions.	
Dissemination	PU	
Written by	Barouch Giechaskiel (JRC) David López García (IDIADA) Liliang (LingLong) Marcel Mathissen (FORD) Mats Gustafsson (VTI)	18/06/2024
Checked by	Theodoros Grigoratos (JRC) Rainer Vogt (FORD)	01/08/2024
Approved by	Juan García (IDIADA)	26/08/2024
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Revision history

REVISION	DATE	DESCRIPTION	AUTHOR (ORGANIZATION)
V1	18.06.2024	First version sent for internal review	BG (JRC) et al.
V2	05.08.2024	Revised version	BG (JRC) at al.
V3	26.08.2024	Final version	

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1. Abstract

In order to assess mass loss and tread depth reduction various tests were conducted. IDIADA tested five tyres on the proving ground with an accelerated method. One of them (from LingLong) was tested on the road under normal driving conditions at both IDIADA and LINGLONG. Additional tests were conducted at VTI and FORD with a different set of five tyres. The additional testing aimed at PM/PN emissions and characterisation, but mass loss and tread depth reduction were also measured in some cases. Only the tread depth and mass loss results are included in this **Deliverable 2.4**. In **Deliverable 2.2** it was concluded that vehicle on-board measurement of tyres PM/PN is not practical and accurate enough for regulatory purposes.

The results demonstrated a clear impact of the ambient temperature and tyre load on the abrasion rate. No correlation was found with the tyre hardness.

The accelerated method resulted in wear rates of 600-1500 mg/km (vehicle, sum of four tyres) and 0.5-0.6 mm per 1000 km (average per tyre), more than 10 times higher than the on-road tests. Urban driving had up to 5 times higher wear than rural and motorway driving. However, part of this difference was due to the different road surface. For the front-wheel driven vehicle of this study the front tyres contributed 65-85% of the total wear.

The tyre life estimated from the accelerated method did not have any correlation with the treadwear Uniform Tire Quality Grading (UTQG) used in the United States. More studies are needed to investigate if such correlation exists with the final regulated on-road protocol.

The tread depth measurement was found to have high uncertainty compared to the mass measurement. Different locations of the tyre can also have different tread depth reductions. Even though there is a correlation between tread wear reduction and mass loss, this was different for the front and rear tyres and the different tyre manufacturers.

2. List of abbreviations and acronyms

Abbreviation	Definition
CO	Continental
DSN	Driving Severity Number
DU	Dunlop
FL	Front Left
FR	Front Right
FWD	Forward
GY	Goodyear
LI	Load Index
LL	LingLong
MI	Michelin
MPD	Mean Profile Depth
PAV	IDIADA high speed track
PDC	IDIADA dynamic platform C track
PI	Pirelli
PM	Particulate Matter
PN	Particle Number
RL	Rear Left
RoR	Rolling Resistance
RR	Rear Right
SUV	Sport utility vehicle
UNECE	United Nations Economic Commissions for Europe
UTQG	Uniform Tire Quality Grading
WG	Wet Grip

Definitions

Driving Severity Number (DSN): means the index with direct correlation with tyre wear rate obtained by an accelerometer dedicated to monitoring lateral accelerations, wheel revolution counter and a module for signal processing and read-out.

Hardness: means a measure of the resistance a material has to indentation.

Principal grooves: means the wide circumferential grooves positioned in the central zone of the tyre tread, which, in the case of passenger and light truck (commercial) tyres, have the treadwear indicators located in the base.

Run-in: means the initial period of the test until the test output achieve stable values.

Tread depth: means the depth of the principal grooves.

Note: Tyres with small letter, laboratories with capital letters

3. Introduction

The main goal of work package 2 (WP2) was to identify, measure, characterise and compare, through both in-laboratory and on-road experiments, the particle emissions from both light-duty and heavy-duty vehicle tyres under different driving conditions. Moreover, this WP also aimed at assessing the potential chemical transformation of the emitted particles in the air and analysing health hazard of the transformed species. Finally, this WP aimed at creating the necessary research procedures and methods to allow for reliable and repeatable measurement and comparison of tyre emissions, particularly to develop a standardisable cost-effective tyre abrasion rate measurement methodology that enables the prediction of airborne particle emissions generated. The following deliverables were produced:

- **Deliverable 2.1:** Detailed design of research procedures and methods, including approaches and tools for sampling and characterisation of tyre particles (Confidential).
- **Deliverable 2.2:** Final results from the assessment and characterisation of tyre particle emissions (Confidential).
- **Deliverable 2.3:** Results from chemical transformations of tyre organic compounds and volatiles and health hazard potential classification (Public).
- **Deliverable 2.4:** Results from the comparison of tyre tread wear and related particle emissions (Public).

The results of the chemical characterisation of tyre particles are publicly available (**Deliverable 2.3**). The methodology of on-board vehicle particle sampling, the physical characterisation of particles on-road and in the lab have been described in two confidential deliverables (**Deliverable 2.1** and **Deliverable 2.2**). Two key elements impacted the outcomes of **Deliverable 2.4**: (i) During the project it was made clear that the vehicle on-board measurement of tyres is extremely difficult and uncertain for regulatory purposes; (ii) the activities at UNECE level defined a regulatory methodology for measurement of tyre abrasion.

In June 2024 an amendment of UNECE Regulation 117 was adopted which added a tyre abrasion measurement. The two methodologies are based on vehicle convoy on-road driving and drum method. In both methodologies the candidate tyres are compared with reference tyres tested at the same time. The reason is that the boundary conditions (e.g. temperature, road) impact the abrasion rate and would make the comparison of different candidate tyres tested under different conditions or different location impossible.

In the European Union, there is an interest to include a ‘durability’ index at the tyre labelling. The tread depth reduction during the tyre abrasion test could be a possible approach.

Based on this background, Leon-T tested different tyres under different conditions in order to assess:

- Correlation of mass loss and tread depth reduction
- Possibility to use an accelerated method to provide equivalent results
- Indices such as driving severity number (DSN) and standard deviation of acceleration

3.1. Standard Deviations

The standard deviation of acceleration were calculated from the raw files (in 10 Hz) without any filtering or smoothening or converting the time series per 1 m distance. Thus, the reported standard deviations are different compared to the ones described in the UNECE Regulation 117, Annex 10.

3.2. Driving Severity Number (DSN)

In previous projects, a concept called Driving Severity Number (DSN) was introduced to evaluate the tyre wear performance upon requirements of some manufacturers. Further information regarding the DSN found in past research studies is demonstrated below.

In 1985, Veith[1] presented a system called the "Driving Severity Monitor (DSM)" for characterising tyre force distribution as related to treadwear in either normal tyre use or in tyre fleet testing in convoy. The system consists of an accelerometer for monitoring lateral accelerations, a wheel revolution counter, and a module for signal processing and read-out.
The basic task of the DSM system is measurement of the average g-value per wheel revolution, the processing of this acquired signal, and the appropriate storage of all processed values. It provides information regarding cornering intensity influenced by route terrain, vehicle speed, and driver behaviour.
The output of the DSM is an index called the Driving Severity Number (DSN), which characterises the route-vehicle-driver system for its influence on the tyre force profile or spectrum. Investigations have demonstrated that the correlation between wear rate and lateral force is a power function as described by the following Equation 1:

$$\mathbf{R_W = K_1 F^n}$$

Equation 1. Wear rate as function of the tyre force.

Where:

- $\mathbf{R_W}$ is the wear rate in nm/m
- **F** is the tyre force in Newton (N)
- $\mathbf{K_1}$ is a constant n is an exponent, usually between 2 and 4.

When a vehicle rounds a curve of radius **R** (in m) at a constant velocity **V** (in m/s), the lateral force $\mathbf{F_y}$ in gravitational units is calculated by the following Equation 2:

$$\mathbf{F_y = (W / G) * (V^2 / R) = W\,g}$$

$$\mathbf{g = V^2 / (R\,G)}$$

Equation 2. Lateral force F_y when a vehicle rounds a curve of radius R at a constant velocity V.

Where:

[1] Veith A. G. (1985). The Driving Severity Number (DSN) A Step Toward Quantifying Treadwear Test Conditions. Tire Science and Technology, TSTCA, Vol. 14, No. 3, July-September 1986, pp. 139-159.

- **Fy** is the total lateral force of the vehicle
- **W** is the vehicle weight in N
- **G** is gravitational acceleration, 9.8 m/s^2
- **g** is acceleration expressed in dimensionless units relative to G

The application of DSN is to combine several variables (vehicle speed, vehicle handling, route characteristics and the vehicle inertia weight or tyre load) into one term, so that a sum of incremental wear over all g-levels encountered in a journey can be calculated.
During this process, a term **ĝ** is defined as average **g** in a selected distance interval. The wear loss in one tyre revolution is set as L_{1rev} that is proportional to $\hat{g}^2$, see Equation 3. A multiplier of 100 is used so that the parenthetical expression below becomes 1.0 when **ĝ** = 0.01.

$$L_{1rev} = K_1 (\hat{g}\ 100)^2$$

Equation 3. Wear loss in one tyre revolution

Hence, the total wear loss in **N** revolution is calculated by Equation 4:

$$\sum L = L_1 + L_2 + L_k + \cdots L_n$$

Equation 4. Total wear loss in N revolutions.

The wear rate per revolution then is calculated by Equation 5:

$$R_{W,N} = \sum L / N = K \sum (\hat{g}_i\ 100)^2\ W^2 / N$$

Equation 5. Wear rate per revolution.

Where $\hat{g}_i$ is the average **g** for the i^{th} revolution.

Thus, the DSN is obtained by assigning unit value to **K** and is then equal to the sum of squares of lateral accelerations (during a journey) measured once per tyre revolution (g_i), divided by the number of revolutions (n). This quotient is normalized for vehicle weight or tyre load through multiplication by the squared ratio of actual tyre load to rated tyre load.(See Equation 6).

$$DSN = \sum (\hat{g}_i\ 100)^2 (F_Z / F_{Z,R})^2 / N$$

Equation 6. Driving Severity Number (DSN)

Where, F_Z is the actual tyre load and $F_{Z,R}$ is the rated tyre load. Hence, F_Z / $F_{Z,R}$ is relative tyre load.

It should be noted that the DSN was mainly defined considering the lateral force **Fy** and the longitudinal force **Fx** was not included. This is due to the high longitudinal stiffness or modulus of tyres that may be two or three times of the lateral values. Hence, the longitudinal forces are associated with less footprint frictional work and sliding distance. Additionally, the lateral forces are shown to be more intense and prevalent than longitudinal forces in normal driving.

Table 1 shows that the relative frictional work induced by a lateral force is approximately six times of that for driving and 2.4 times that for braking force. Thus, this correlation can incorporate the longitudinal g-values into the DSN (See Equation 7).

Table 1. Relative Frictional work for each use mode

Use Mode	Relative Frictional Work
Free rolling	1.0
Driving[a]	2.0
Braking[a]	4.8
Cornering (lateral)[a]	11.6

[a] All at 800 N (180 lbf) per tire

$$DSN_T = \left[\sum (g_i / 100)_y^2 + 0.2 \sum (g_i / 100)_x^2 \right] (F_Z / F_{Z,R})^2 / N$$

Equation 7. Driving Severity Number DSN including the longitudinal forces.

Where the subscript **y** pertains to lateral **g**, subscript **x** to longitudinal **g**, and subscript **T** to the total force spectrum for both **x** and **y**.
In conclusion, DSN provides a single value directly proportional to the treadwear rate when a lateral/longitudinal force acts on a tyre.

It quantifies the tyre force input profile of a vehicle with a particular driver; it characterises the driver-vehicle system over any journey distance or test course with a single value.

The application of DSN is further validated by two wear test programs and the results show that the DSN has a high degree of correlation ($R \geq 0.95$) with treadwear when the pavement texture is held constant. However, the DSN will not relate treadwear to individual tyre forces due to load transfer or vehicle roll and pitch variables, nor to other vehicle perturbations such as those caused by suspension characteristics. It considers the vehicle and tyres as a whole system. It will not detect the variations in pavement texture or abrasiveness. It will not detect changes in tyre wear due to ambient temperature changes.

Note: The DSN of this report have not been corrected for any offset that the accelerometers might have. It is expected that this impact is small.

4. Overview of tests and tyres

Table 2 gives an overview of the tests conducted on tyre mass loss and tread depth loss. IDIADA tested five tyres (Table 3) on the proving ground with an accelerated method. One of them (LingLong) was tested on the road under normal driving conditions at both IDIADA and LINGLONG.

Table 2. Overview of tests on mass loss and tread depth

Organization	Track	Testing	Tyres	Details
IDIADA	Proving ground	accelerated	Table 3 (all)	Chapter 5
IDIADA	On-road	normal	Table 3 (LL)	Chapter 6
LINGLONG	On-road	normal	Table 3 (LL)	Chapter 7
FORD	Handling road	cornering	Table 4 (all)	Chapter 8
VTI	Road simulator	normal	Table 4 (all)	Chapter 9

Table 3. Tyres used for the on-road testing (normal driving and accelerated tests). L/S=Load/Speed; RR=rolling resistance, WG=wet grip.

Brand	Name		Dimensions	L/S	RoR	WG	Noise
LL	Batman A50 SUV Atlas	M+S	225/60 R18	100V	C	C	B
MI	Pilot Sport 4 SUV	S	225/60 R18	100V	D	A	B (70)
GY	EfficientGrip SUV	M+S	225/60 R18	100V	C	B	B (70)
DU	Grandtrek ST30	M+S	225/60 R18	100H	C	D	B (71)
PI	Scorpion Verde	S	225/60 R18	100H	C	B	B (71)

Table 4. Additional characteristics of tyres used for the on-road testing. H=hardness.

Brand	Name	Treadwear	Traction	Temp	H
LL	Batman A50 SUV Atlas	440	A	A	63.5
MI	Pilot Sport 4 SUV	220	A	A	63.2
GY	EfficientGrip SUV	440	A	A	62.3
DU	Grandtrek ST30	360	A	A	62.0
PI	Scorpion Verde	400	A	A	62.1

Figure 1. Photos of the tyres used for on-road testing.

Additional tests were conducted at VTI and FORD with a different set of tyres (Table 5). The testing aimed at PM/PN emissions, but mass loss and tread depth reduction was also measured in some cases. Details in **Deliverable 2.2**. The set included 3 different summer tyres as well as an all season and a winter tyre. Different season tyres were coming from the same manufacturer (Continental). For summer tyres, tyres from three different brands are tested: Continental, Goodyear and LingLong. In addition, a custom-made tyre has been manufactured by LingLong with approximately. 2% cobalt-boroacylate. This custom-made tyre was used at the on-road experiments, where cobalt acted as a tracer to quantify the tyre emissions.

Figure 2. Photos of the tyres used on the road simulator.

Table 5. Tyres used during the run-in tests and the road simulator testing.

Brand	Name		Dimensions	L/S index	RR	WG	Noise	H
GY	Efficient Grip Cargo	S	215/65 R16C	109/107 T	B	C	B (71)	69.5
Conti	Eco Contact 6	S	215/65 R16	102H XL	A	A	B (71)	67.2
Conti	Winter Contact TS870	W	215/65 R16	102 H	C	B	B (71)	58.2
Conti	Van Contact 4S	all	215/65 R16C	109/107 T	B	A	B (73)	67.5
LL	Green Max Van HP	S	215/65 R16C	109/107 R	C	B	B (72)	64.4
LL	With Co additive	S	215/65 R16C	109/107 R	-	-	-	67.0

All=all seasons; Conti=Continental; GY=Goodyear; H=Hardness (rubber); LL=LingLong; S=Summer; W=Winter

5. Accelerated tests (IDIADA)

The accelerated tests at IDIADA consisted of a run-in section and the tyre wear section using five different tyres (Table 3). One of them was tested at different ambient temperatures and two loads. The same vehicle was used for all tests. The following section provide the details of the testing and the results.

5.1. Abrasion test

The abrasion tyre wear followed two different sections: run-in and tyre wear procedure. The run-in had 3 sequences of 460 km, 1380 km in total. The tyre wear cycle had 5 sequences of 306.8 km, 1534 km in total. The total mileage for the abrasion test was the sum of run-in and tyre wear procedures, 2914 km. Some of the characteristics of these sections are presented in the following Table 6:

Table 6. Abrasion test. 2914 km per tyre: 1380 km run-in and 1534 km tyre wear cycle.

Run - in			
Sequence	**Step**	**Accumulated distance (km)**	**Days (1 shift)**
1	**weigh**	0	1
	Driving 130 & 80 kph	230	
	Pause	230	
	Driving 130 & 80 kph	460	
x3	**Total**	**460 * 3 = 1380**	**3**

Tyre wear procedure			
Sequence	**Step**	**Accumulated distance (km)**	**Days (1 shift)**
1	clean & **weigh**	0	1
	Rural	89.2	
	Tyre cooling	89.2	
	clean & **weigh**	89.2	
	Motorway	200.2	
	clean & **weigh**	200.2	2
	Urban	306.8	
	clean & **weigh**	306.8	
x5	**Total x5**	**306.8 * 5 = 1534**	**10**

8	**Total abrasion test**	**1380 + 1534 = 2914**	**13**

5.1.1. Run-in procedure

The objective of the run-in procedure was to eliminate the first part of the tyre surface.

In this procedure the vehicle drove 1380 km and it lasted three days, each day driving 460 km in the IDIADA high speed loop, performing the weighing procedure every day.

This procedure was performed on the High-speed track (PAV). A scheme of this track is shown in Figure 3. The speed was at 130 kph at the straight line (marked in orange in the Figure 1) and a lower speed of 80 kph in the bends (marked in blue in the Figure 1) to reduce the lateral forces. Deceleration of 0.8 m/s^2 and acceleration of 2.7 m/s^2.
The run-in procedure had the following values of driving severity number (DSN) (details for DSN at Introduction):

- DSN longitudinal → 15.9
- DSN lateral → 43.3

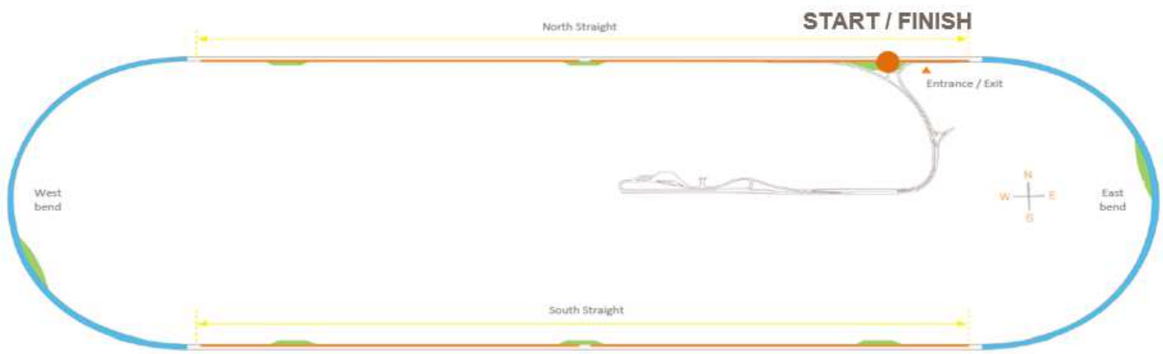


Figure 3. Run-in procedure in high-speed track (PAV)

5.1.2. Tyre wear procedure

The objective of the tyre wear procedure was to wear the tyre surface in an accelerated way. In this procedure the vehicle drove 306.8 km five times (total of 1534 km) simulating three different driving conditions: urban, rural and motorway (or highway). Some of the characteristics of these driving conditions are shown in Table 7 and also in more detail from Sections 5.1.2.1 to 5.1.2.3:

Table 7. Tyre wear procedure – parts and characteristics

Test track	PDC				PAV			
Part	Urban				Rural			Motorway
Sub-part	I	II	III	IV	V	VI	VII	VIII
Speed [km/h]	20	20	30	40	60	70	80	130
Laps	30	10	51	57	2	4.5	5.5	15
Brake events	0	10	102	114	20	27	30	15
Brake events/lap	0	1	2	2	10	6	6	1
Brake events/km	2.12				0.86			0.13
Braking [m/s^2]	-	1.11	2.94	2.94	1	1.4	2.94	2.94
Accelerating [m/s^2]	-	1.11	1	1	1	1.4	1.65	1.5
DSN longitudinal	19.2				22.8			30.8
DSN lateral	27.9				30.0			121.9
Mean long. acceleration	-0.56				-0.56			-0.60
Stand. dev. long. acc.	0.75				0.77			1.03
Mean lat. acceleration	0.46				0.89			1.58
Stand. dev. lat. acc.	0.96				0.51			1.32

Test track	PDC				PAV			
Part	Urban				Rural			Motorway
Time [Hours]	0.75	0.25	1.5	1.5	0.25	0.5	0.5	1
Distance sub-part [km]	15	5.2	40.8	45.6	15	33.4	40.8	111
Distance part [km]	106.6				89.2			111
Distance [km]	306.8							

5.1.2.1. Urban Part

Urban driving conditions had the following characteristics:

- Distance → 106.6 km
- Acceleration / deceleration rate between 1 and 2.94 m/s^2 (0.3g)
- Final speed of brake events = 20 & 0 km/h
- Driving severity number (DSN):
    - DSN longitudinal → 19.2
    - DSN lateral → 27.9
- IDIADA's Test Track:
    - Dynamic Platform C (PDC)
    - 300 m long & 40 m wide

Figure 4. Dynamic Platform C (PDC)

The different sub-parts of this urban driving conditions are presented with more detail in the following sections.

5.1.2.1.1. Urban part. Sub-part I: 20 km/h

- Constant speed at 20 km/h
- Number of brake events per loop → 0
- Laps → 30
- Deceleration rate → 0 m/s^2
- Acceleration rate→ 0 m/s^2
- Distance (km) → 15 km
- Counterclockwise direction

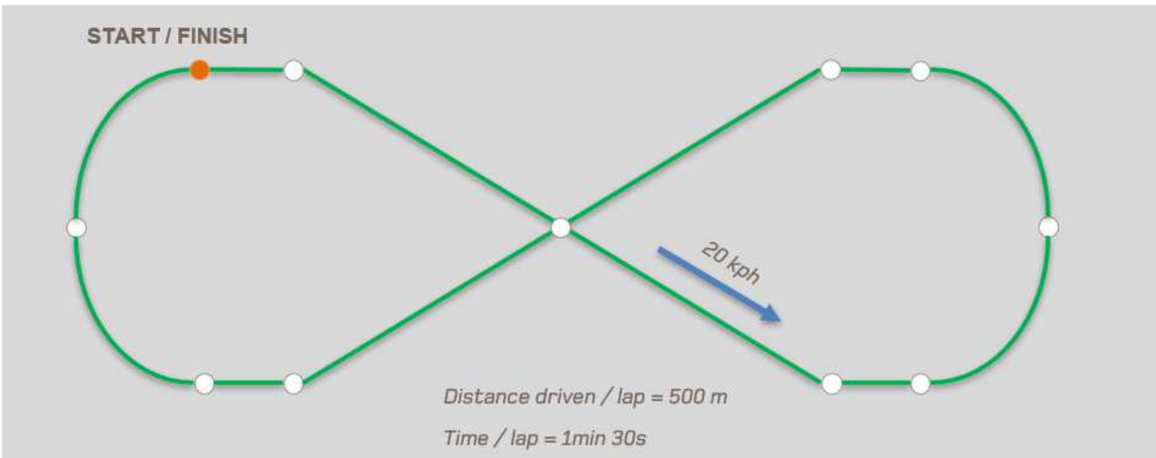


Figure 5. Abrasion test - Urban part- Subpart I

5.1.2.1.2. Urban part. Sub-part II: 20 km/h with brake events

- Initial and final brake speed → 20 km/h to 0 km/h
- Number of brake events per loop → 1 (Red line)
- Laps → 10
- Deceleration rate → 1.11 m/s^2
- Acceleration rate→ 1.11 m/s^2
- Distance (km) → 5.2 km
- Counterclockwise direction

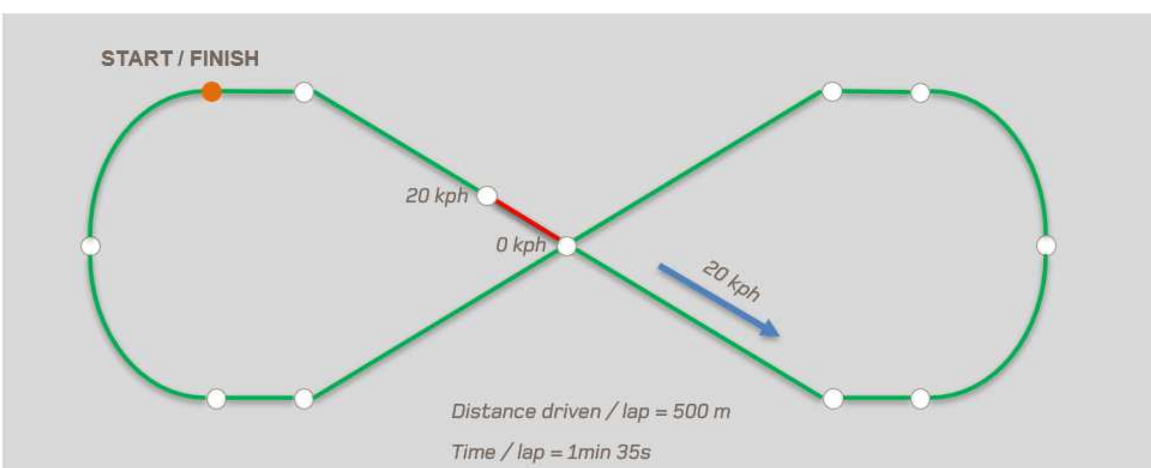


Figure 6. Abrasion test – Urban part – Subpart II

5.1.2.1.3. Urban part. Sub-part: III: 30 km/h with brake events

- Initial and final brake speed → 30 km/h to 20 km/h & 30 km/h to 0 km/h (parking manouvers)
- Number of brake events per loop → 2 (Red lines)
- Laps → 51
- Deceleration rate → 2.94 m/s^2
- Acceleration rate→ 1 m/s^2
- Distance (km) → 40.8 km
- Counterclockwise direction

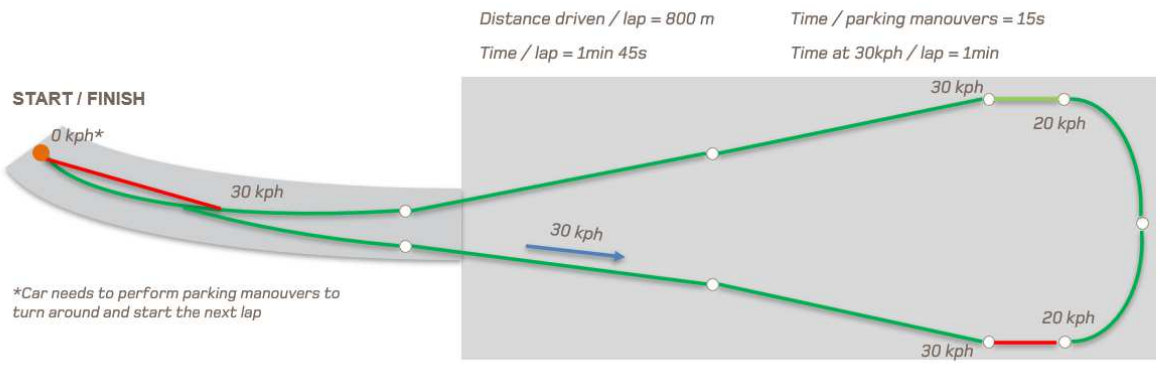


Figure 7. Abrasion test – Urban part – Subpart III

5.1.2.1.4. Urban part. Sub-part IV: 40 km/h with brake events

- Initial and final brake speed → 40 km/h to 20 km/h & 40 km/h to 0 km/h (parking manouvers)
- Number of brake events per loop → 2 (Red lines)
- Laps → 57
- Deceleration rate → 2.94 m/s^2
- Acceleration rate→ 1 m/s^2
- Distance (km) → 45.6 km
- Counterclockwise direction

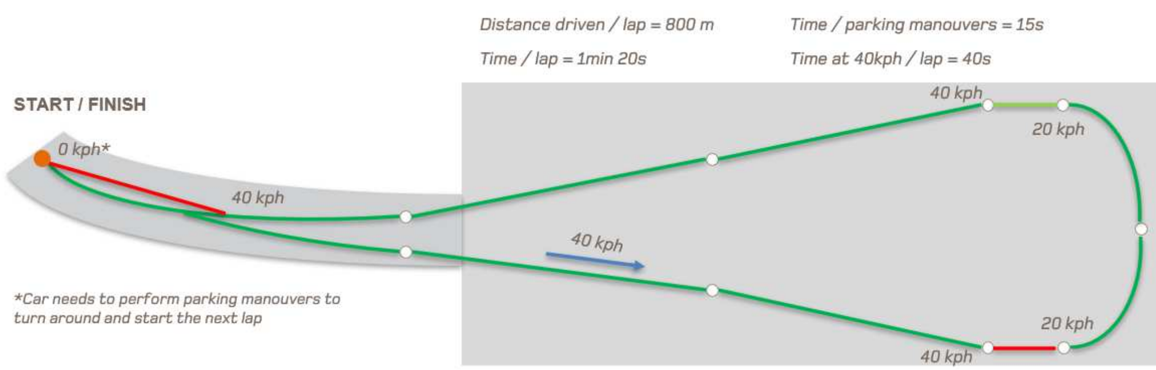


Figure 8. Abrasion test – Urban part – IV

5.1.2.2. Rural part

Rural driving conditions had the following characteristics:

- Distance → 89.2 km
- Acceleration / deceleration rate between 1 and 2.94 m/s^2 (0.3g)
- Final speed of brake events = 50 km/h.
- Driving severity number (DSN)
  - DSN longitudinal → 22.8
  - DSN lateral → 30.0
- IDIADA's Test Track:
  - High speed track (PAV)
  - Maximum Vehicle Speed
    - Lane 1 → 100 km/h
  - Rail length
    - Lane 1 → 7493 m

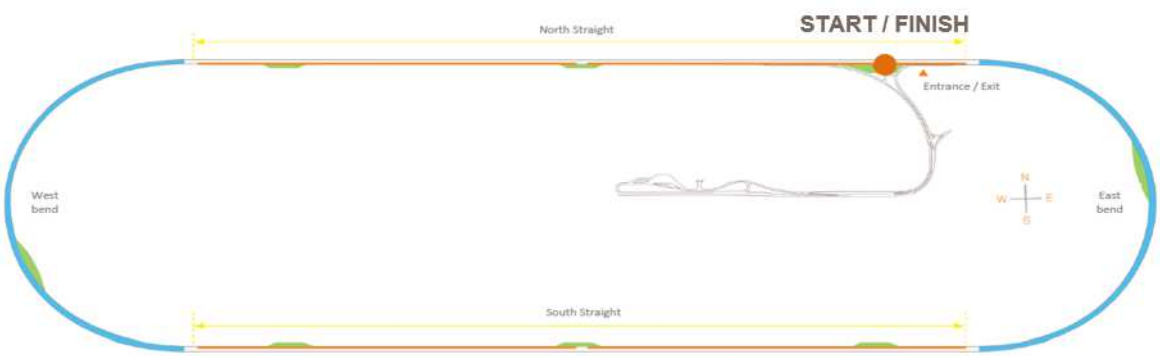


Figure 9. High speed track (PAV)

The different sub-parts of this rural driving conditions are presented with more detail in the following Section 5.1.2.2.1. to 2.3

5.1.2.2.1. Rural part. Sub-part V: 60 km/h with brake events

- Initial and final brake speed → 60 km/h to 50 km/h
- Brake events → 20
- Number of brake events per loop → 10 (red triangles ▲)
- Laps → 2
- Deceleration rate → 1 m/s^2
- Acceleration rate→ 1 m/s^2
- Distance (km) → 15 km
- Clockwise direction

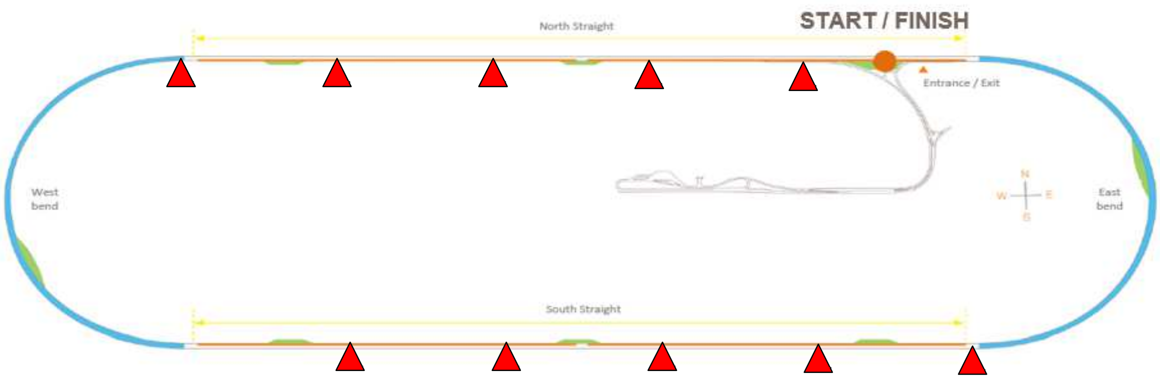


Figure 10. Abrasion test – Rural part – V

5.1.2.2.2. Rural part. Sub-part VI: 70 km/h with brake events

- Initial and final brake speed → 70 km/h to 50 km/h
- Brake events → 27
- Number of brake events per loop → 6 (red triangles)
- Laps → 4.5
- Deceleration rate → 1.4 m/s^2
- Acceleration rate→ 1.4 m/s^2
- Distance (km) → 33.4 km
- Clockwise direction

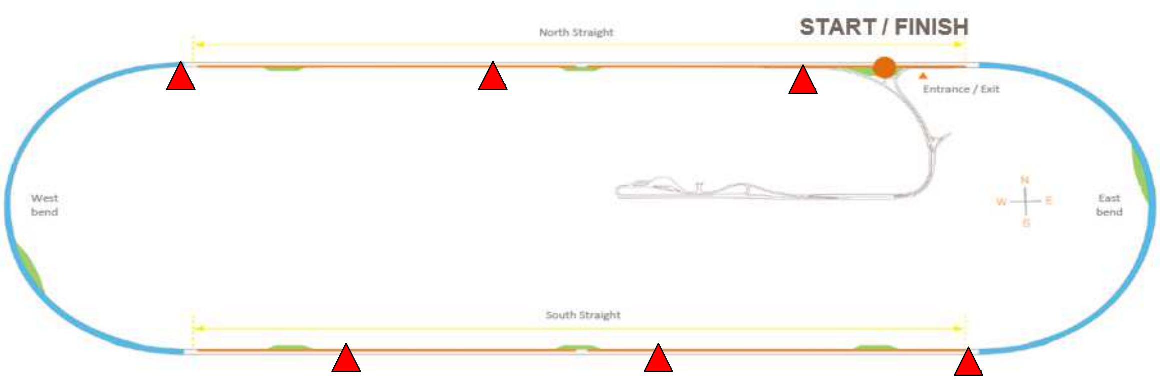


Figure 11. Abrasion test - Rural part - VI

5.1.2.2.3. Rural part. Sub-part VII: 80 km/h with brake events

- Initial and final brake speed → 80 km/h to 50 km/h
- Brake events → 30
- Number of brake events per loop → 6 (red triangles)
- Laps → 5.5
- Deceleration rate → 2.94 m/s^2
- Acceleration rate→ 1.65 m/s^2
- Distance (km) → 40.8 km
- Clockwise direction

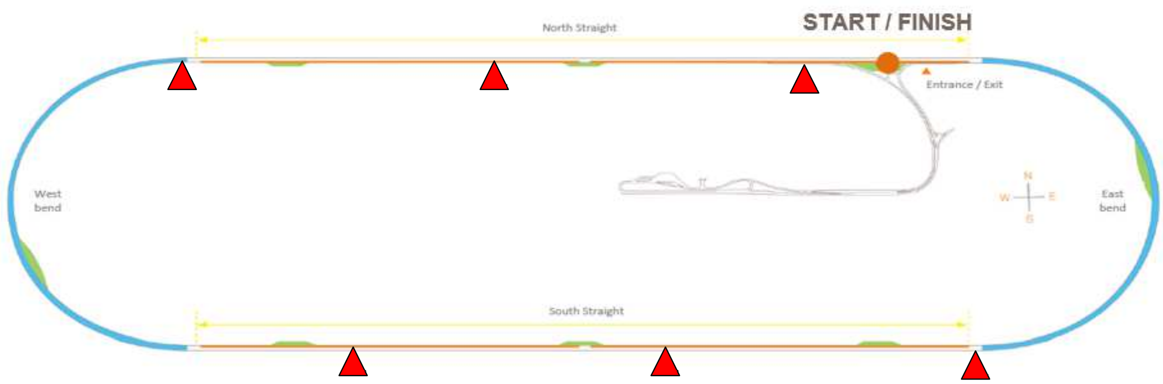


Figure 12. Abrasion test - Rural part - VII

5.1.2.3. Motorway part

Motorway driving conditions had the following characteristics:

- Motorway percentage driven = 39 + 10 %
- Acceleration / deceleration rate between 2.94 m/s^2 (0.3g)
- Final speed of brake events = 50 km/h
- Driving severity number (DSN)
  - DSN longitudinal → 30.8
  - DSN lateral → 121.9
- IDIADA's Test Track:
  - High speed track (PAV)
  - Maximum Vehicle Speed
    - Lane 2 → 150 km/h
  - Rail length
    - Lane 2 → 7513 m

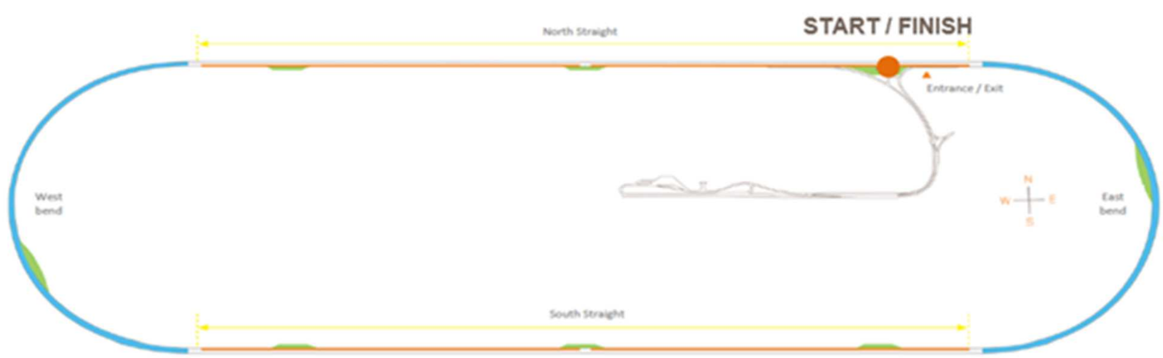


Figure 13. High speed track (PAV)

The different sub-parts of this urban driving conditions are presented with more detail in the following Section 5.1.2.3.1.

5.1.2.3.1. Motorway part. Sub-part VIII: 130 km/h with brake events

- Initial and final brake speed → 130 km/h to 50 km/h
- Brake events → 15
- Number of brake events per loop → 1 (red triangles ▲)

- Laps → 15
- Deceleration rate → 2.94 m/s^2
- Acceleration rate→ 1.5 m/s^2
- Distance (km) → 111 km
- Clockwise direction

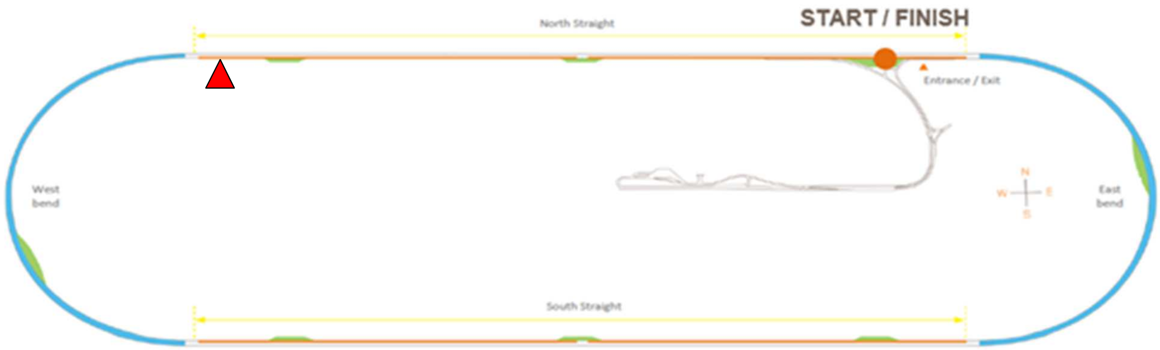


Figure 14. Abrasion test - Motorway part - VIII

5.2. Modified abrasion test

The complete test cycle defined at IDIADA's proving ground is composed by 3 repetitions of 4 different sequences as shown in the following table. It has a total length of 252,90 km. The urban, rural and motorway parts are integrated in each repetitions.

Definition of test cycle at IDIADA's proving ground:

Table 8. Modified tyre wear procedure

#	Track	Type of driving	# repetitions	Distance (Km)	Accumulated (km)
Repetition 1	General Road	General road a Vmax 90km/h regular driving	3	5,5	16,5
	Dry Handling	Handling regular driving	7	2,2	15,4
	General Road	General road at Vmax 90km/h regular driving	3	5,5	16,5
	Dry Handling	Handling regular driving	7	2,2	15,4
	General Road	City simulation	1	5,5	5,5
	High speed	High speed including braking long event	2	7,5	15
Repetition 2	General Road	General road a Vmax 90km/h regular driving	3	5,5	16,5
	Dry Handling	Handling regular driving	7	2,2	15,4
	General Road	General road at Vmax 90km/h regular driving	3	5,5	16,5
	Dry Handling	Handling regular driving	7	2,2	15,4
	General Road	City simulation	1	5,5	5,5
	High speed	High speed including braking long event	2	7,5	15
Repetition 3	General Road	General road a Vmax 90km/h regular driving	3	5,5	16,5
	Dry Handling	Handling regular driving	7	2,2	15,4
	General Road	General road at Vmax 90km/h regular driving	3	5,5	16,5
	Dry Handling	Handling regular driving	7	2,2	15,4
	General Road	City simulation	1	5,5	5,5
	High speed	High speed including braking long event	2	7,5	15
				TOTAL Km	252,9

In the following subchapters, a description of the general road, dry handling and high-speed tracks are described.

5.2.1. General road

- Number of brake events per loop: 1
- Initial brake speed: 90 km/h
- Final brake speed: 50 km/h
- Brake severity (deceleration rate): 0,3G (2,94 m/s^2)
- Definition of speed cycle:

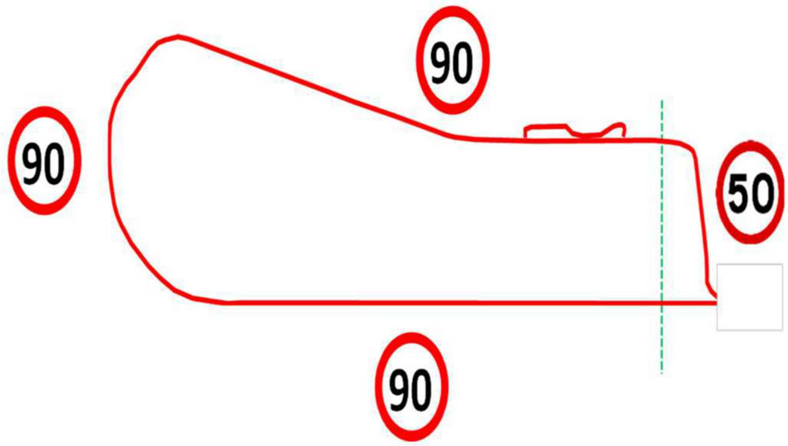


Figure 15. Abrasion test – General road

5.2.2. Dry Handling

- Number of brake events per loop: Depending on the handling track lay out
- Maximum vehicle speed: 100 km/h
- Minimum vehicle speed: 60 km/h
- Brake severity (deceleration rate): 0,4G (3,92 m/s^2)
- Definition of speed cycle:

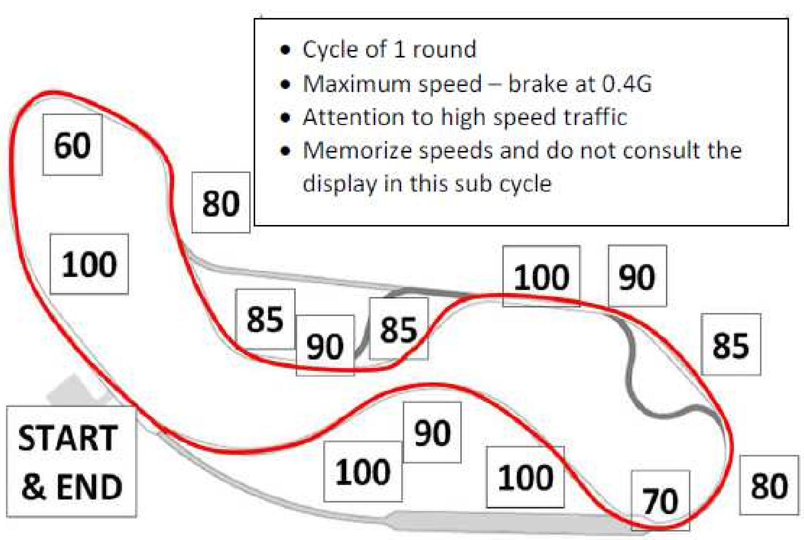


Figure 16. Abrasion test – Dry handling

5.2.3. General Road – City simulation

- Number of brake events per loop: 7
- Initial brake speed: 50 km/h – 60 km/h
- Final brake speed: 0 km/h
- Brake severity (deceleration rate): 0,4G (3,92 m/s^2)
- Definition of speed cycle:

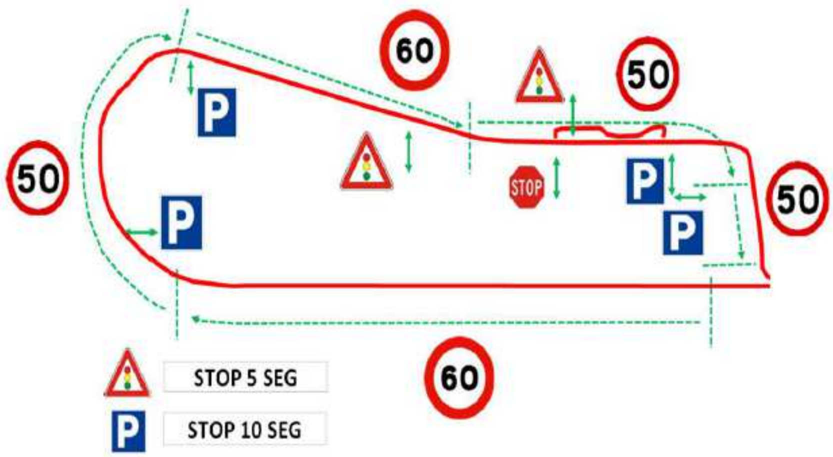


Figure 17. Abrasion test – City simulation

5.2.4. High speed

- Number of brake events per loop: 5
- Initial and final brake speed:
  - 130 km/h to 50 km/h
  - 130 km/h to 80 km/h
  - 130 km/h to 80 km/h
  - 90 km/h to 60 km/h
  - 90 km/h to 0 km/h
- Brake severity (deceleration rate): 0,4G (3,92 m/s^2) – 0,3G (2,94 m/s^2)
- Definition of speed cycle:

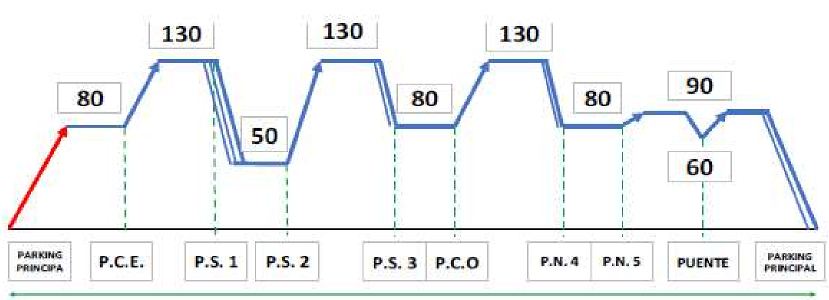


Figure 18. Abrasion test – High speed

5.3. Tyre measurement procedures

Before starting each test section and after finishing it, measurements were performed in order to characterise the evolution of the different tyres.

5.3.1. Instruments accuracy

The accuracy of the measuring instruments was the following:

- Tyre mass loss: The complete wheel and tyre weight was measured with an accuracy scale of ± 2 g.
- Tyre groove depth: Tread depth reduction was measured with depth gauge with accuracy of ± 0,1 mm.
- Tyre inflation pressure: Tyre inflation pressure was measured using a manometer with accuracy of ± 5 kPa.
- Tyre shore A hardness: Tyre shore A hardness was measured using a shore A hardness durometer with accuracy of ± 5.
- Air temperature and surface temperature: The temperature measuring devices was accurate within ± 1 °C.
- Tyre temperature: Tyre temperature was measured using a sensor with accuracy of ± 1 °C.
- Vehicle motion information: Accelerometer biaxial measuring lateral and longitudinal forces.

5.3.2. Measurements procedures description

5.3.2.1. Tyre weight measurement procedure

The steps to carry out the tyre weighing procedure are described bellow:

- Record total wheel balancers installed in each rim.
- Disassemble each wheel from the vehicle.
- Remove stones or any other elements from tyre with help of a screwdriver or similar.
- Clean the tyre with air pressure.
- Clean the rim surfaces with dry cloth to remove dust or other small particles. (See Figure 19)

Figure 19. Measurement procedure - Clean the rim surfaces.

- Set tyre pressure to 0 bar (remove valve core completely).
- Verify no balances are lost from rims.
- Repeat weight measurement 5 times per wheel (See Figure 20)

Figure 20. Measurement procedure - Weight measurement.

- Wheel should be weighted in same conditions (with hub cover and with valve cab assembled).
- Re-set tyre testing pressure.

- Re-install wheels to the vehicle in the same position. Do not rotate position, for example front-left tyre must be always in the front-left car position (See Figure 21).

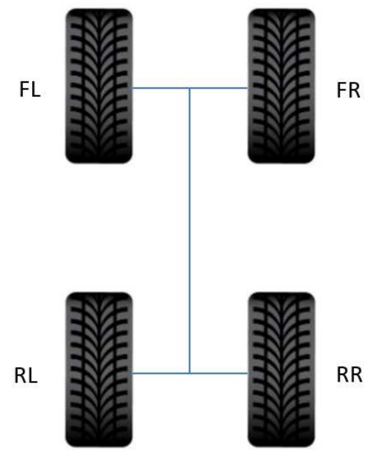


Figure 21. Measurement procedure - Tyre car distribution. FL = Front left, FR = front rear, RL = rear left, RR = rear right

5.3.2.2. Tread depth measurement procedure

The tread depth of each tyre was measured before starting the test (as initial measurement) and after each cycle (as final measurement). This measurement was performed according to the following procedure (with air pressure at the default value):

- Disassemble each wheel from the vehicle.
- Before starting the test, mark the bottom of main grooves in 4 locations at 90º using permanent marker (See Figure 22 and Figure 23). #1 is always the outside measurement.

Figure 22. Measurement procedure - Mark the bottom of main grooves

Figure 23. Measurement procedure - Mark the tyre in four places every 90º

- Measure tread depth of main grooves at central zone in each marked point (Positions A, B, C & D clockwise). 16 points on each tyre (See Figure 24).

Figure 24. Measurement procedure - Measure tread depth of main grooves

- Re-install wheels to the vehicle in the same position.

5.3.2.3. Shore A Hardness measurement procedure

The shore A hardness of each tyre was measured before starting the test (as initial measurement) and after each cycle (as final measurement). The measurement was performed according to the following procedure:

- Disassemble each wheel from the vehicle.
- Before starting the test, mark the bottom of main grooves in 4 locations at 90º using permanent marker.

- Measure hardness shore A at 3 points on the tyre surface (1, 2 & 3) and in each marked point. (Positions A, B, C & D). 12 points on each tyre (See Figure 25 and Figure 26)

Figure 25. Measurement procedure - Measure points shore A hardness

Figure 26. Measurement procedure - Measure shore A hardness

- Re-install wheels to the vehicle in the same position.

5.4. Asphalt characteristics

In addition to DSN and ambient temperature, asphalt characteristics, such as friction and roughness, influence tyre abrasion and must be considered to compare the abrasion values obtained between different tests. Two different tracks were used in IDIADA: PAV and PDC.

The macro-texture of the asphalt is measured using **MPD (Mean Profile Depth)** according to UNE-EN ISO13473-1:2020. This measurement is performed using a vehicle equipped with Laser Crack Measurement System (LCMS) from Pavemetrics (Figure 27), which is scanning the surface of the pavement by using 2 laser profilers attached to a vehicle and measuring 4 m wide each 5 mm.

Figure 27. Vehicle with laser crack measurement system

Table 9. Macro-texture characteristics (PAV)

	PAV	
	Mean value (mm)	Standard deviation
Rail 1	0.56	0.08
Rail 2	0.56	0.06
North straight rail 3	0.58	0.07
North straight rail 4	0.51	0.10
South straight rail 3	0.57	0.07
South straight rail 4	0.48	0.08
Average	**0.543**	**0.077**

Table 10. Macro-texture characteristics (PDC)

	PDC	
	Mean value (mm)	**Standard deviation**
L1	0.96	0.11
L2	0.74	0.08
L3	0.87	0.06
L4	0.81	0.10
C	0.90	0.11
R1	0.94	0.11
R2	0.86	0.08
R3	0.92	0.09
R4	0.84	0.09
Average	**0.871**	**0.092**

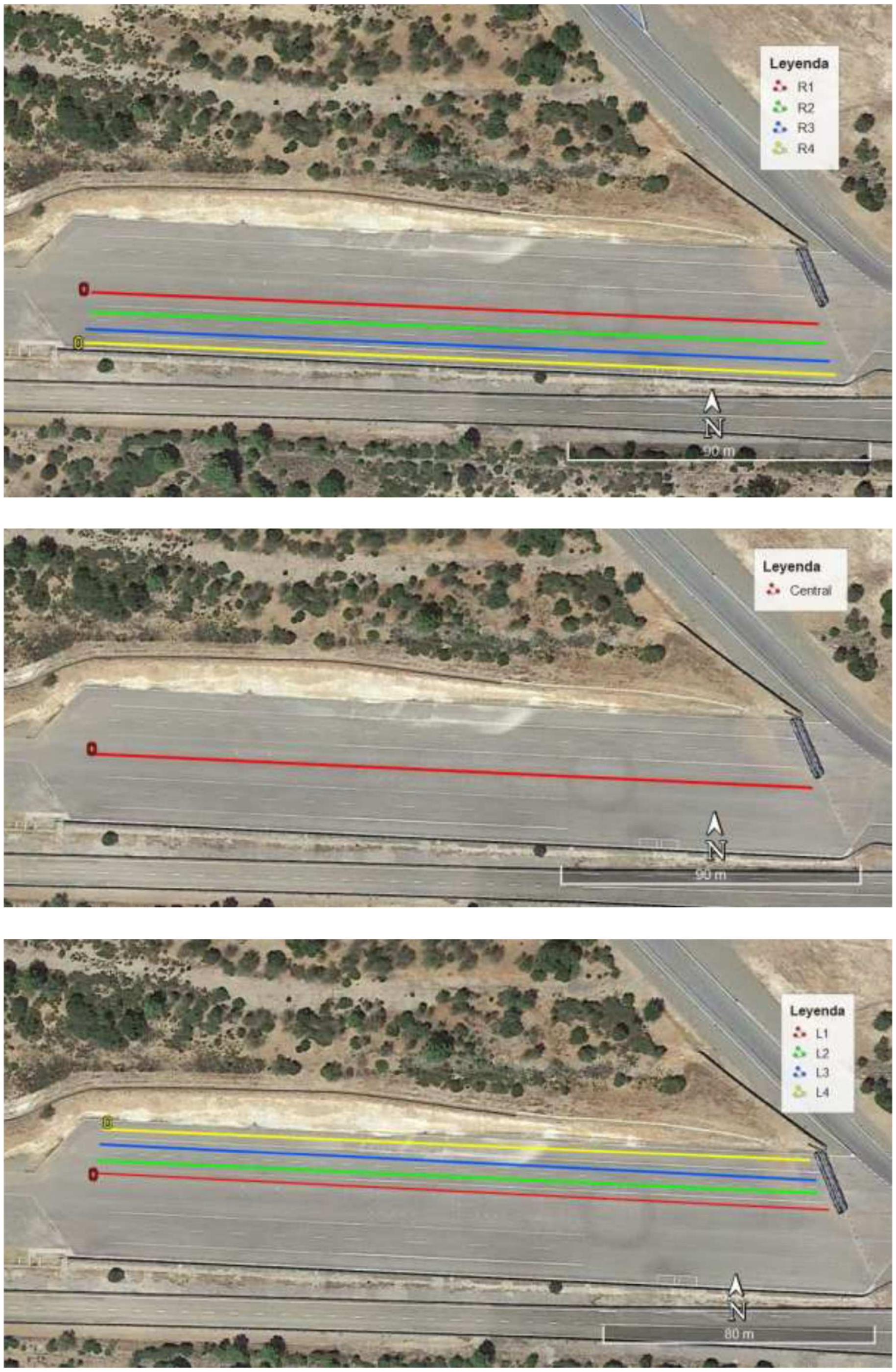


Figure 28. Road surface macr0-characyeristcs measurements.

At VTI a portable friction tester (PFT) (Figure 29) has been developed and originally used for measuring road-marking friction. The PFT at VTI has been used for several years on road surfaces, bicycle lanes, walkways and other workspaces. It is a suitable instrument to use where the measurement speed cannot be high or at difficult to access areas where traditional high-speed friction meters cannot be used.

The PFT is using the fixed slip method, which is also used for measuring skid resistance on road pavements. It uses a fixed slip between 17 and 21% depending on the version of the instrument used. It consists of a three-wheeled pushcart with the measuring wheel mounted in front of the others. Through chain transmission, the measuring wheel is connected with the rear supporting wheels of the friction tester and, thus, the wheel radius together with the gear ratio of the chain transmission decide the slip of the measuring wheel. The friction between the measuring wheel and the surface of interest is presented by the PFT as the friction coefficient, which is the frictional force on the measuring wheel divided by the normal load on the same wheel. Frictional force is evaluated from the measured chain tension in the chain transmission. Normal load is assumed to be constant during measurement and is measured in the instrument calibration procedure. This friction coefficient is henceforth referred to as the PFT friction value[2].

Figure 29. VTI portable friction tester

TECHNICAL SPECIFICATIONS

- Test wheel load: 125 N
- Test tyre with traceable, high quality rubber wear course: 4.00–6
- Weight: 35 kg
- Tyre inflation pressure: 100 kPa
- Standard measurement speed: 0.5±0.1 m/s
- Minimum measurement distance: 0.1 m
- Maximum measurement distance: 175 m

The **Peak Braking Coefficient (PBC)** was measure with the Idiada Skid trailer. The skid trailer permits the measurement of tyres in a realistic test condition since the tests are performed on real proving ground. Therefore, the tyre contact patch is between asphalt and rubber.

Figure 30. Skid trailer testing equipment

[2] Bergström, A., Åström, H., Magnusson, R., 2003. Friction measurement on cycleways using a portable friction tester. Journal of Cold Regions Engineering 17, 37-57, 10.1061/(ASCE)0887-381X(2003)17:1(37)

The skid trailer controls the tyre attitude over the ground while all the motions and forces are being registered. The parameters which are registered and controlled are:

Table 11. Skid trailer measurement parameters

Transducer / Actuator	Range	Accuracy
Wheel force load		
Fx	15 KN	0.1 % of FS
Fy	15 KN	0.1 % of FS
Fz	15 KN	0.1 % of FS
Slip angle	+/- 18° (-5°<Camber<5°) +/- 12° (Camber<-5° or Camber>5°)	+/- 0.1°
Camber	+/- 8°	+/- 0.1°
Slip angle rate	6°/s	-
Max brake torque	4000 Nm	-
Tyre tread temperature	0 – 200 °C	1 °C
Ambient temperature	-50 to 150 °C	1 °C
Road surface temperature	0 – 200 °C	1 °C
Rolling loaded radius	0.2 m	0.001
Test Tyre/wheel rotation speed	1500 r/min	0.1 % of FS
Vehicle speed sensor	0 to 200 km/h	-

The skid trailer test possibilities are summarized as follows:
• Available test tyre rim sizes: 13 to 22”
• Brake application rate to reach maximum μ: min 0.1s

The measurements have been done with the following conditions:
• Tires used:
  SRTT 16” tyre (225/60 R16)
  Uniroyal Tiger paw plus
  Load index 97
  Speed index S
Rim used:
  PDC: 112
  No. holes: 5
  Rim dimensions: 6.5Jx16
  Hub: 65
  Rim offset: ET40
• Vertical load: 5371 ± 358 N
• Speed: 65 ± 2 km/h
• Tyre inflation: 180 ± 3 KPa
• The rate of brake application: between 0.2 and 0.5 s

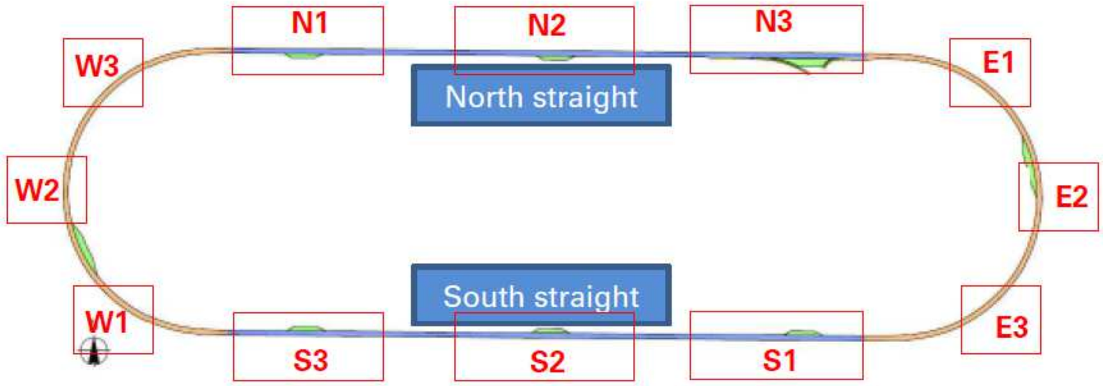


Figure 31. High speed circuit measurements

The measurements were performed on dry ground, in the normal direction of traffic:
- North straight (4 lanes): Areas N1, N2, N3 → 4 brakings per area & lane
- South straight (4 lanes): Areas S1, S2, S3 → 4 brakings per area & lane
- East corner (1st/2nd lane): Areas E1, E2, E3 → 4 brakings per area & lane
- West corner (1st/2nd lane): Areas W1, W2, W3 → 4 brakings per area & lane

Table 12. Results (PAV)

	PAV
	Mean value (µ)
N1	1.06
N2	1.08
N3	1.08
S1	1.06
S2	1.08
S3	1.07
E1	1.09
E2	1.10
E3	1.11
W1	1.09
W2	1.11
W3	1.11
Average (µ)	**1.087**


Figure 32. Dynamic platform C measurements

Table 13. Results (PDC)

	PDC
	Mean value (μ)
	1.16
	1.15
	1.14
	1.16
	1.14
	1.15
	1.13
	1.16
Average (μ)	**1.15**

Table 14. Road surface characteristics.

	Test track	Macro-texture	Friction	
		MPD	PBC	VTI
Run-in	PAV	0.543	1.087	1.105
Rural				
Motorway				
Urban	PDC	0.871	1.15	0.929

For the **modified route** the General road, Dry handling and High speed (PAV) tracks were used. The mean value for the Dry handling track was 0.93 mm with a standard deviation of 0.27. One circuit of the General road had MPD values 0.7-1.0, while the other 1.5-1.8.

5.5. Tyre abrasion test plan

5.5.1. *Test matrix*

The test matrix of this project is shown in the following Table 15:

Table 15. Test matrix

Tyre – 225 / 60 R18		Abrasion test	Vehicle load
LingLong – LLG Set#1	Batman A50 SUV ATLAS	Leon-T	Standard load
LingLong - LLG Set#2	Batman A50 SUV ATLAS	Leon-T	High load
LingLong - LLG Set#3	Batman A50 SUV ATLAS	Modified	Standard load
LingLong - LLG Set#4	Batman A50 SUV ATLAS	Leon-T	Standard load
Michelin	PILOT SPORT 4 SUV	Leon-T	Standard load
Goodyear	EFFICIENTGRIP SUV	Leon-T	Standard load
Dunlop	GRANDTREK ST30	Leon-T	Standard load
Pirelli	SCORPION VERDE	Leon-T	Standard load

As can be seen in Table 15, 8 tests with 5 different tyres (LingLong, Michelin, Goodyear, Dunlop and Pirelli) were carried out. Seven of these tests were carried out according to the Abrasion test defined in this Leon-T Project (described in Section 5.1) and 1 test was carried out according to the modified procedure described in the 5.2.

The sequence of testing was the following:

- LLG Set #1
  - Run-in (Standard load)
  - Tyre wear cycle (Standard load)
  - Weighing at the beginning and at the end of each test

- LLG Set #2
  - Run-in (Standard load)
  - Weighing at the beginning and at the end of each test

- LLG Set #3,
  - Run-in (Standard load)
  - Weighing at the beginning and at the end of each test

- LLG Set #4
  - Run-in (Standard load)
  - Weighing at the beginning and at the end of each test

- Michelin
  - Run-in (Standard load)
  - Tyre wear cycle (Standard load)
  - Weighing at the beginning and at the end of each test

- Goodyear
  - Run-in (Standard load)
  - Tyre wear cycle (Standard load)
  - Weighing at the beginning and at the end of each test

- Dunlop
  - Run-in (Standard load)
  - Tyre wear cycle (Standard load)
  - Weighing at the beginning and at the end of each test

- Pirelli
  - Run-in (Standard load)
  - Tyre wear cycle (Standard load)
  - Weighing at the beginning and at the end of each test

- LLG Set #2
  - Tyre wear cycle (High load)
  - Weighing at the beginning and at the end of each test

- LLG Set #3
  - Modified tyre wear cycle (Standard load)
  - Weighing at the beginning and at the end of each test

- LLG Set #4
  - Tyre wear cycle with summer temperatures (Standard load)
  - Weighing at the beginning and at the end of each test

5.5.2. Vehicle

The vehicle used in the test was Ford Escape for all tyres.

Figure 33. Ford Escape

Characteristics:

- Gasoline
- 1.5L in-line
- Front wheel drive
- USA Version
- VIN: 1FMCU0F63LUB50125

Table 16. Vehicle alignment values

		Target	**Measured**
Front axle			
Camber	Left	-0.74° (±0.75°)	-0.16°
	Right	-0.74° (±0.75°)	-0.44°
	Cross	0.00° (±0.75°)	0.28°
Toe	Left	0.10° (±0.10°)	0.13°
	Right	0.10° (±0.10°)	0.10°
	Total	0.20° (±0.20°)	0.23°
Caster	Left	4.84° (±0.75°)	*5.92*°
	Right	4.84° (±0.75°)	*5.74*°
	Cross	0.00° (±0.75°)	0.18°
Rear axle			
Camber	Left	-1.22° (±0.75°)	-1.11°
	Right	-1.22° (±0.75°)	-1.74°
	Cross	0.00°	0.63°
Toe	Left	0.19° (±0.20°)	0.11°
	Right	0.19° (±0.20°)	0.05°
	Total	0.38° (±0.20°)	*0.16*°
Geometrical driving axis		0.00°	0.03°

5.5.3. Vehicle load conditions

Regarding the loads used in the tyre wear tests, two weight conditions were considered:

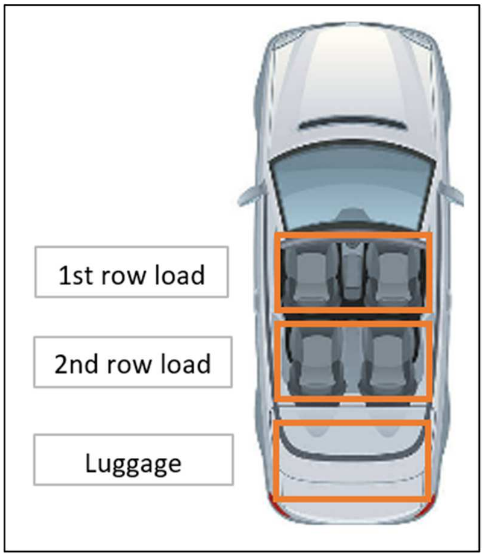


Figure 34. Vehicle load positions.

5.5.3.1. Standard load (lightly loaded)

- Full fuel tank
- Added weight: 150 kg
  - Instrumentation
  - 1st row load → 150kg
- Weight
  - Front axel
    - Left tyre → 490 kg
    - Right tyre → 460 kg
  - Rear axel
    - Left tyre → 361 kg
    - Right tyre → 333 kg
  - Total weight → 1644 kg
- Tyre pressure → 240 kPa

5.5.3.2. High load (maximum occupancy mass load)

- Full fuel tank
- Added weight: 375 kg
  - Instrumentation
  - 1st row load → 136 kg
  - 2nd row load → 204 kg
  - Luggage → 35 kg
- Weight
  - Front axel
    - Left tyre → 503 kg
    - Right tyre → 473 kg
  - Rear axel

        - Left tyre → 461 kg
        - Right tyre → 431 kg
    - Total weight → 1869 kg
- Tyre pressure → 250 kPa

5.6. Results (accelerated IDIADA)

5.6.1. LingLong #1

Standard test with the LingLong #1 Batman A50 SUV ATLAS M+S was tested.

Standard load → Lightly loaded.

- Full fuel tank
- Added weight: 150 kg
    - Instrumentation
    - 1st row load → 150kg
- Weight
    - Front axel
        - Left tyre → 490 kg
        - Right tyre → 460 kg
    - Rear axel
        - Left tyre → 361 kg
        - Right tyre → 333 kg
    - Total weight → 1644 kg
- Tyre pressure → 240 kPa

5.6.1.1. Ambient, asphalt and tyre temperature

Ambient temperatures during the abrasion test were:

- Maximum → 17.3 ºC.
- Minimum → 2.9 ºC
- Average → 9.2 ºC

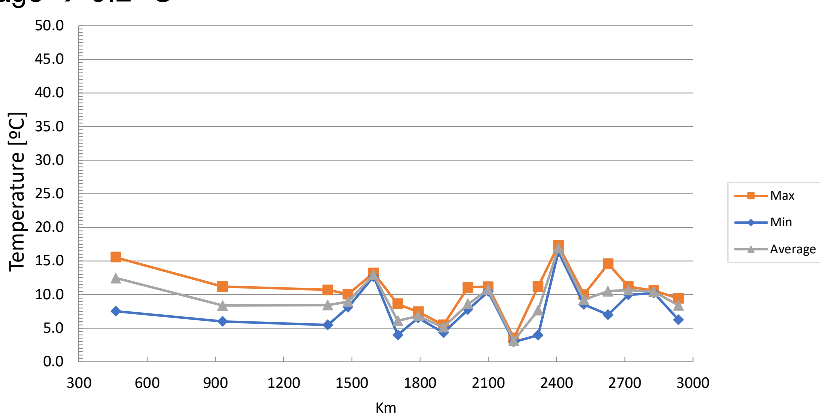


Figure 35. Ambient temperature – LingLong #1

Asphalt temperatures during the abrasion test were:

- Maximum → 21.9 ºC.
- Minimum → 5.7 ºC

- Average → 12.1 ºC

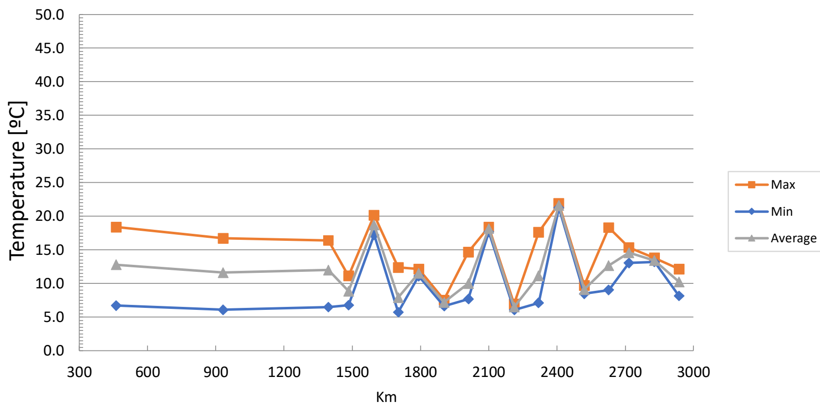


Figure 36. Asphalt temperature – LingLong #1

Tyre temperatures during the abrasion test were:

- Maximum → 31.2 ºC.
- Minimum → 10.1 ºC
- Average → 19.7 ºC

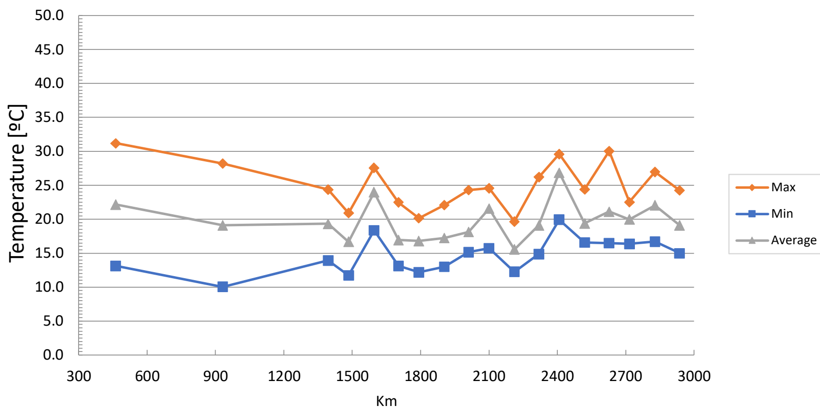


Figure 37. Tyres temperature – LingLong #1

5.6.1.2. Tyre abrasion

The LingLong #1 tyres had an abrasion mean of 633.2 grams on the front tyres and 178.6 grams on the rear tyres.

In the following figure you can see the evolution of the tyre abrasion (grams) during the test defined in Table 6. That is,

- Run-in 1 to 3 → From 0 to 1380 km
- Tyre wear sequence 1 to 5: rural, motorway and urban → From 1380 to 2914 km

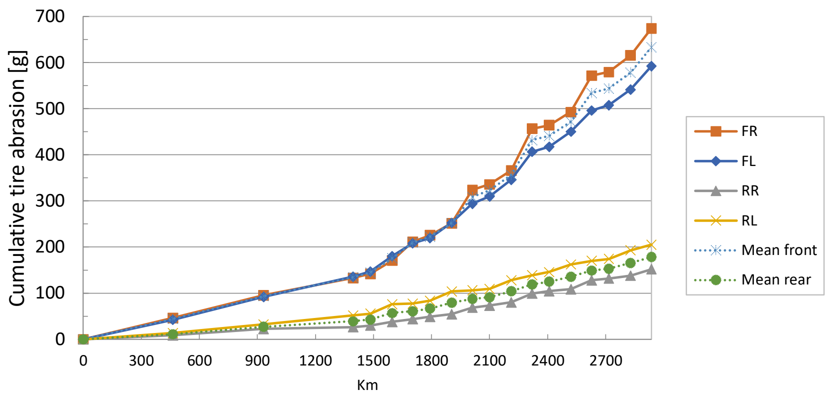


Figure 38. Abrasion - LingLong #1

Table 17 presents the average abrasion of the tyres on the front axle per tyre and on the rear axle per tyre.

Table 17. Average tyre abrasion rate – LingLong #1.

		Tyre Abrasion Rate [mg/km]				
		Run-in	Tyre wear test			
			Rural	Motorway	Urban	Av. Test
LL#1 Cold	Av. front per tyre	96.3	125.9	285.1	528.1	313.1
	Av. rear per tyre	28.1	52.4	112.0	99.5	88.0

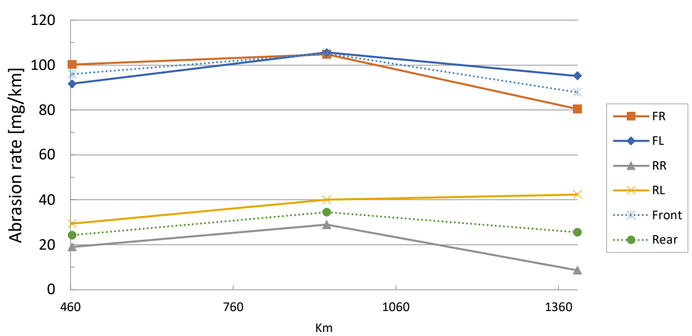


Figure 39. Run-in tyre abrasion rate - LingLong #1

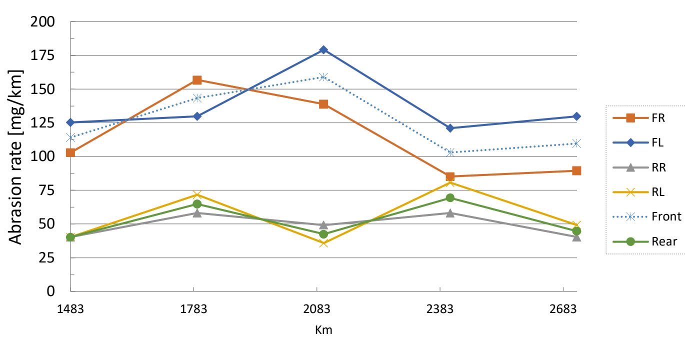


Figure 40. Rural tyre abrasion rate - LingLong #1

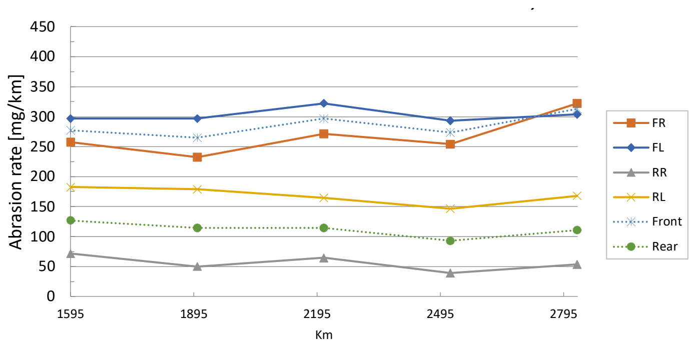


Figure 41. Motorway tyre abrasion rate - LingLong #1

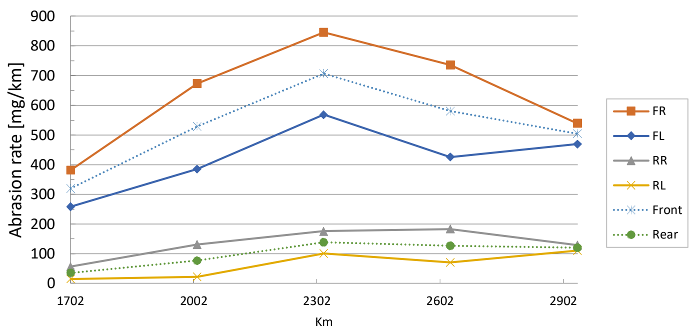


Figure 42. Urban tyre abrasion rate - LingLong #1

5.6.1.3. Other parameters

The tyres had a total life (mm) approximately 5.9 mm. We calculate these values in each tyre using the first tread depth minus 1.6 mm which is the minimum depth that a tyre should have [**Total life** = first tread depth – 1.6 mm].

At the end of the abrasion test the front tyres loss between 2.26 mm and 2.02 mm and the rear tyres loss between 0.81 mm and 0.89 mm.

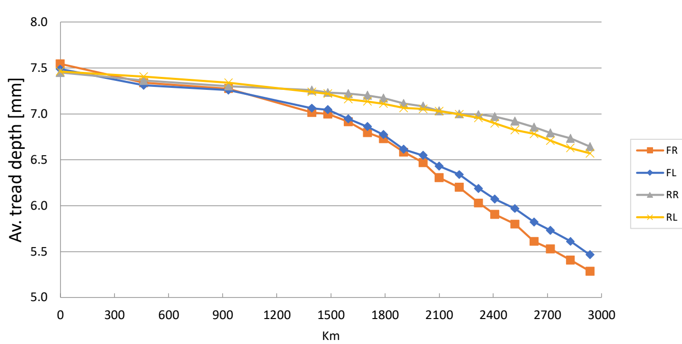


Figure 43. Tyre average tread depth - LingLong #1

Table 18. Calculated tyre life – LingLong #1.

	Total loss [mm]	Total Life [mm]	Loss [%]	Life [%]
FR set#1	2.26	5.94	38.0%	62.0%
FL set#1	2.02	5.89	34.4%	65.6%
RR set#1	0.81	5.85	13.8%	86.2%
RL set#1	0.89	5.86	15.2%	84.8%

The shore A hardness measurements were very sensitive to the point at which the measurement was made, so the results were not precise enough to see the change in the shore A hardness after each test. But it helped us to see that the initial shore A hardness is quite high between 65 and 62 and at the end of the abrasion test it was stabilized between 61 and 60 and had no significant variations during the abrasion test.

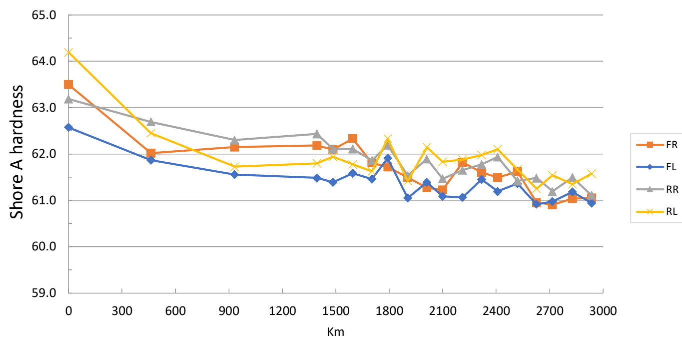


Figure 44. Tyre average shore A hardness - LingLong #1

5.6.2. LingLong #2

LingLong #2 Batman A50 SUV ATLAS M+S was tested. In the run-in we used the standard load and in the tyre wear cycle we used the high load conditions.

Two weight conditions: classes:

- Run-in
  - Standard load → Lightly loaded.
    - Full fuel tank
    - Added weight: 150 kg
      - Instrumentation
      - 1st row load → 150kg
    - Weight
      - Front axel
        - Left tyre → 490 kg
        - Right tyre → 460 kg
      - Rear axel
        - Left tyre → 361 kg
        - Right tyre → 333 kg
      - Total weight → 1644 kg
    - Tyre pressure → 240 kPa

- Tyre wear cycle
  - High load → Max occupancy mass load
    - Added weight: 375 kg
      - Instrumentation
      - 1st row load → 136 kg
      - 2nd row load → 204 kg
      - Luggage → 35 kg
    - Weight
      - Front axel
        - Left tyre → 503 kg

      - Right tyre → 473 kg
    - Rear axel
      - Left tyre → 461 kg
      - Right tyre → 431 kg
    - Total weight → 1869 kg
  - Tyre pressure → 250 kPa

5.6.2.1. Ambient, asphalt and tyre temperature

Since the run-in and tyre wear procedures were performed on different dates, we analysed temperatures separately.

Ambient temperatures during the abrasion test were:

- Run-in:
  - Maximum → 14.7 ºC.
  - Minimum → 2.2 ºC
  - Average → 11.9 ºC

- Tyre wear cycle:
  - Maximum → 34.6 ºC.
  - Minimum → 25.5 ºC
  - Average → 29.8 ºC

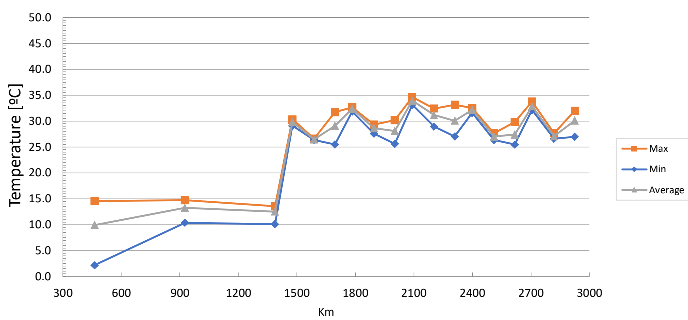


Figure 45. Ambient temperature – LingLong #2

Asphalt temperatures during the abrasion test were:

- Run-in:
  - Maximum → 23.6 ºC.
  - Minimum → 4.4 ºC
  - Average → 17.5 ºC

- Tyre wear cycle:
  - Maximum → 47.9 ºC.
  - Minimum → 35.4 ºC
  - Average → 42.4 ºC

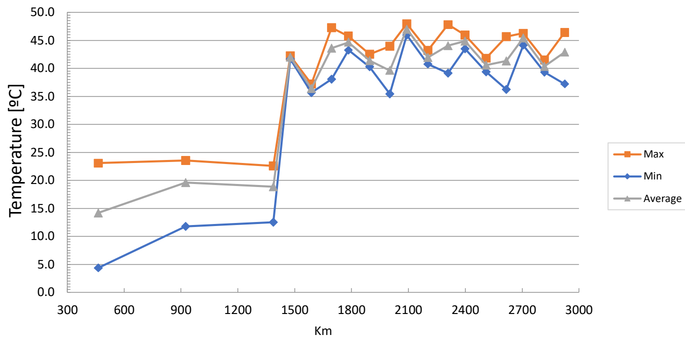


Figure 46. Asphalt temperature – LingLong #2

Tyre temperatures during the abrasion test were:

- Run-in:
  - Maximum → 29.5 ºC.
  - Minimum → 10.7 ºC
  - Average → 24.4 ºC

- Tyre wear cycle:
  - Maximum → 52 ºC.
  - Minimum → 29.8 ºC
  - Average → 42 ºC

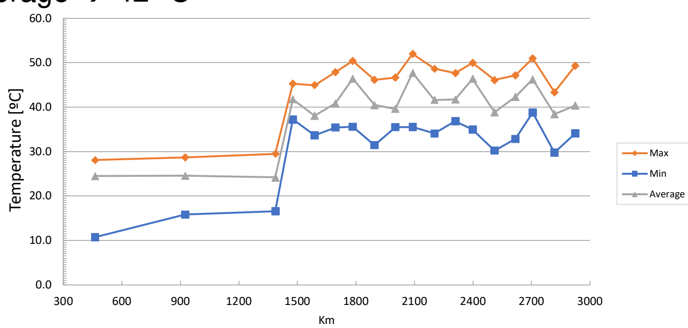


Figure 47. Tyres temperature – LingLong #2

5.6.2.2. Tyre abrasion

The LingLong #2 tyres had an abrasion mean of 1187 grams on the front tyres and 319 grams on the rear tyres.

In the following figure the evolution of the tyre abrasion (grams) during the test defined in Table 6 is plotted. That is,

- Run-in 1 to 3 → From 0 to 1380 km
- Tyre wear sequence 1 to 5: rural, motorway and urban → From 1380 to 2914 km

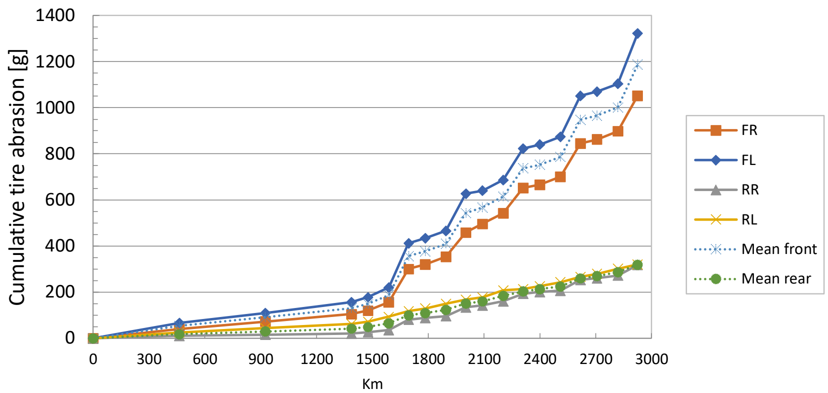


Figure 48. Abrasion - LingLong #2

Table 19 presents the average abrasion of the tyres on the front axle per tyre and on the rear axle per tyre.

Table 19. Average tyre abrasion rate – LingLong #2.

		Tyre Abrasion Rate [mg/km]				
		Run-in	Tyre wear test			
			Rural	Motorway	Urban	Av. Test
LL#2 High load	Av front per tyre	94.1	219.2	336.0	1 446.5	667.3
	Av rear per tyre	30.1	101.7	147.6	280.3	176.5

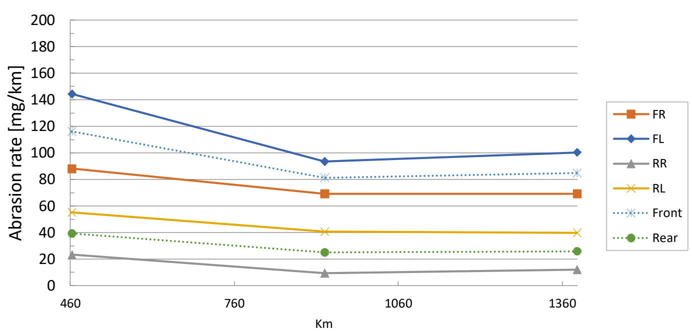


Figure 49. Run-in tyre abrasion rate - LingLong #2

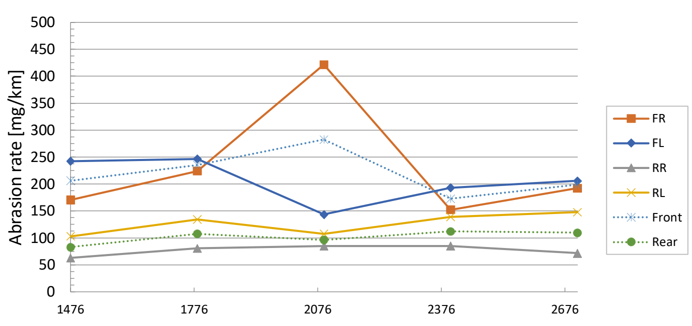


Figure 50. Rural tyre abrasion rate - LingLong #2

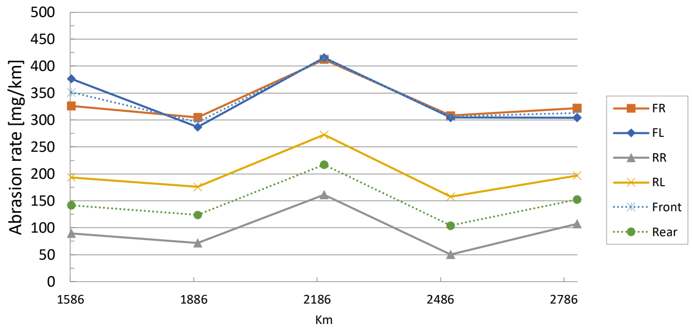


Figure 51. Motorway tyre abrasion rate - LingLong #2

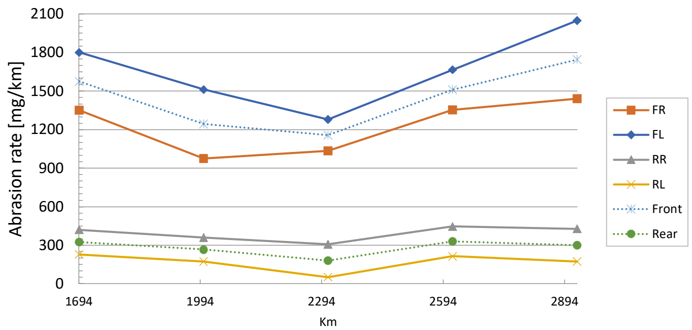


Figure 52. Urban tyre abrasion rate - LingLong #2

5.6.2.3. Other parameters

The tyres had a total life (mm) approximately 5.8 mm. We calculate these values in each tyre using the first tread depth minus 1.6 mm which is the minimum depth that a tyre should have [Total life = first tread depth – 1.6 mm].

At the end of the abrasion test the front tyres loss between 2.89 mm and 4.03 mm and the rear tyres loss between 1.03 mm and 1.23 mm.

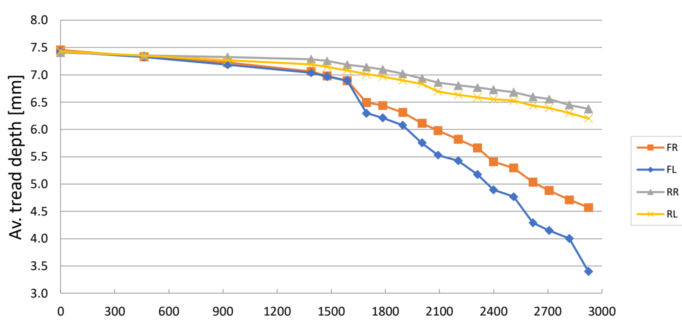


Figure 53. Tyre average tread depth - LingLong #2

Table 20. Calculated tyre life – LingLong #2.

	Total loss [mm]	Total Life [mm]	Loss [%]	Life [%]
FR set#1	2.89	5.86	49.3%	50.7%
FL set#1	4.03	5.83	69.1%	30.9%
RR set#1	1.03	5.81	17.7%	82.3%
RL set#1	1.23	5.83	21.1%	78.9%

The shore A hardness measurements were very sensitive to the point at which the measurement was made, so the results were not precise enough to see the change in the shore A hardness after each test. But it helped us to see that the initial shore A hardness was quite high between 64 and 63 and at the end of the abrasion test it was stabilized between 60.5 and 59.5 and had no significant variations during the abrasion test. The rapid change at around 1500 km is due to the different temperature of the run-in and tests (see tyres temperatures).

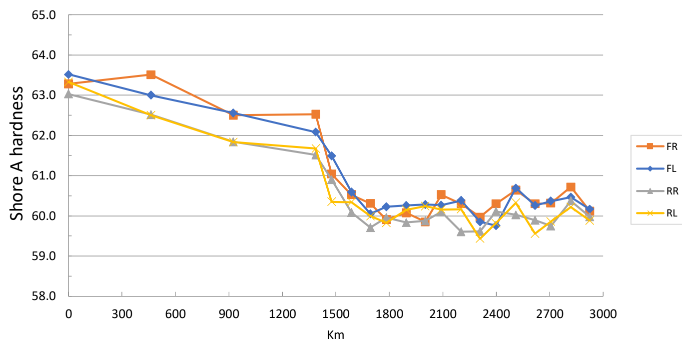


Figure 54. Tyre average shore A hardness - LingLong #2

5.6.3. LingLong #3

LingLong #3 Batman A50 SUV ATLAS M+S was tested. In the run-in we used the standard load and in the tyre wear cycle we used the modified procedure (explained in 5.2), thus there are no separate results for urban, rural and motorway parts.

Standard load → Lightly loaded.

- Full fuel tank
- Added weight: 150 kg
  - Instrumentation
  - 1st row load → 150kg
- Weight
  - Front axel
    - Left tyre → 490 kg
    - Right tyre → 460 kg
  - Rear axel
    - Left tyre → 361 kg
    - Right tyre → 333 kg
  - Total weight → 1644 kg
- Tyre pressure → 240 kPa

5.6.3.1. Ambient, asphalt and tyre temperature

Since the run-in and tyre wear procedures were performed on different dates, we analysed temperatures separately.

Ambient temperatures during the abrasion test were:

- Run-in:
  - Maximum → 20.8 ºC.

- Minimum → 1.9 ºC
- Average → 14.5 ºC

- Tyre wear cycle:
  - Maximum → 26.5 ºC.
  - Minimum → 18.4 ºC
  - Average → 23.2 ºC

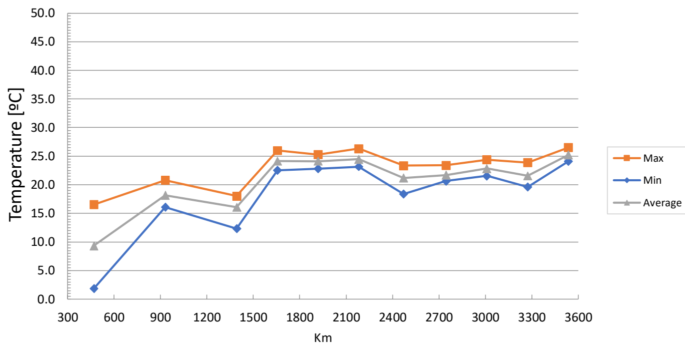


Figure 55. Ambient temperature – LingLong #3

Asphalt temperatures during the abrasion test were:

- Run-in:
  - Maximum → 27.2 ºC.
  - Minimum → 3.6 ºC
  - Average → 19.1 ºC

- Tyre wear cycle:
  - Maximum → 38.8 ºC.
  - Minimum → 25.4 ºC
  - Average → 31.7 ºC

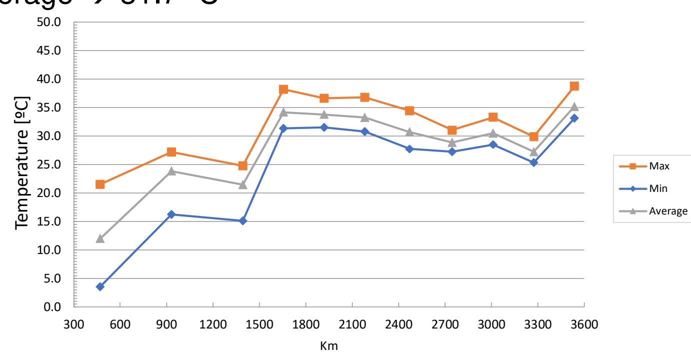


Figure 56. Asphalt temperature – LingLong #3

Tyre temperatures during the abrasion test were:

- Run-in:
  - Maximum → 32.9 ºC.
  - Minimum → 11 ºC
  - Average → 25.5 ºC

- Tyre wear cycle:
  - Maximum → 46.7 ºC.
  - Minimum → 20 ºC
  - Average → 34 ºC

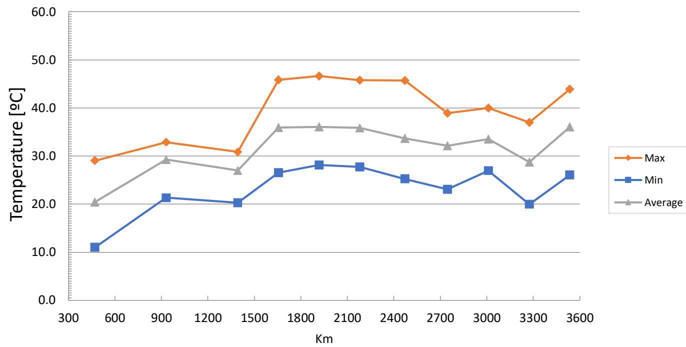


Figure 57. Tyres temperature – LingLong #3

5.6.3.2. Tyre abrasion

The LingLong #3 tyres had an abrasion mean of 650 grams on the front tyres and 199.8 grams on the rear tyres.

The following figure presents the evolution of the tyre abrasion (grams) during the test defined in Table 6. That is,

- Run-in 1 to 3 → From 0 to 1380 km
- Tyre wear sequence 1 to 5: rural, motorway and urban → From 1380 to 2914 km

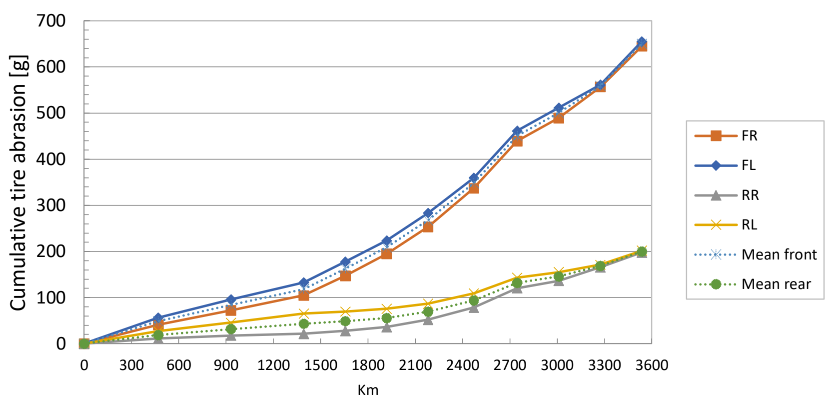


Figure 58. Abrasion - LingLong #3

In Table 21 we can see the average abrasion of the tyres on the front axle per tyre and on the rear axle per tyre.

Table 21. Average tyre abrasion rate – LingLong #3.

		Tyre Abrasion Rate [mg/km]	
		Run-in	Test
LL#3 Modified	Av. Front per tyre	84.9	247.1
	Av. Rear per tyre	31.1	69.9

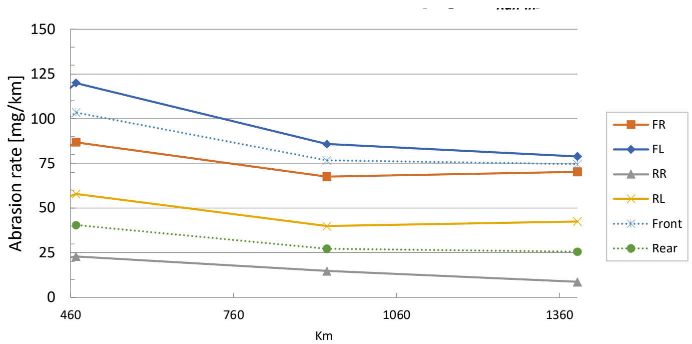


Figure 59. Run-in tyre abrasion rate - LingLong #3

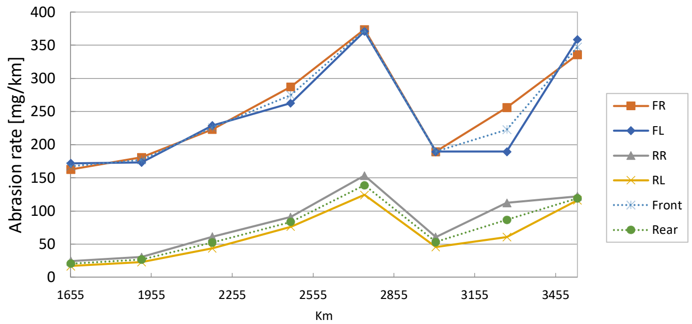


Figure 60. Tyre abrasion rate - LingLong #3

5.6.3.3. Other parameters

The tyres had a total life (mm) approximately 5.9 mm. We calculated these values in each tyre using the first tread depth minus 1.6 mm which is the minimum depth that a tyre should have [Total fife = first tread depth – 1.6 mm].

At the end of the abrasion test the front tyres loss between 2.28 mm and 2.44 mm and the rear tyres loss between 0.94 mm and 1.06 mm.

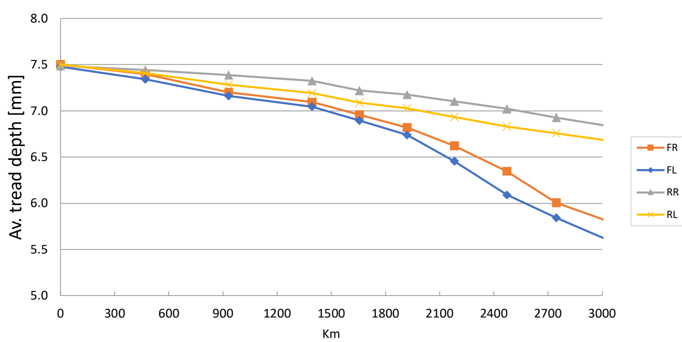


Figure 61. Tyre average tread depth - LingLong #3

Table 22. Calculated tyre life – LingLong #3.

	Total loss [mm]	Total Life [mm]	Loss [%]	Life [%]
FR set#1	2.28	5.90	38.6%	61.4%
FL set#1	2.44	5.88	41.4%	58.6%
RR set#1	0.94	5.89	16.0%	84.0%
RL set#1	1.06	5.90	18.0%	82.0%

The shore A hardness measurements were very sensitive to the point at which the measurement was made, so the results were not precise enough to see the change in the shore A hardness after each test. But it helped us to see that the initial shore A hardness was quite high between 64 and 63 and at the end of the abrasion test it was stabilized between 61 and 59.5 and had no significant variations during the abrasion test.

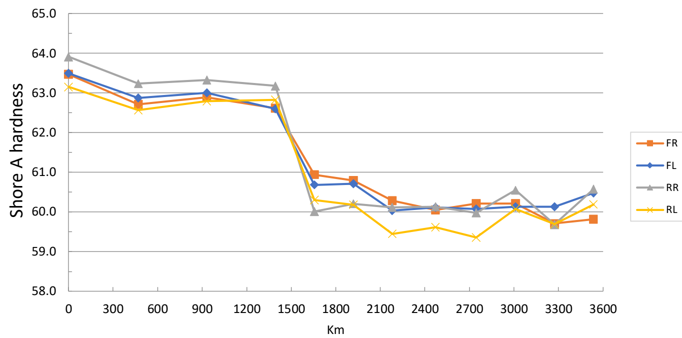


Figure 62. Tyre average shore A hardness - LingLong #3

5.6.4. LingLong #4

LingLong #4 Batman A50 SUV ATLAS M+S was tested. In the run-in we used the standard load and in the tyre wear cycle we used the standard load with high temperatures.

Standard load → Lightly loaded.

- Full fuel tank
- Added weight: 150 kg
  - Instrumentation
  - 1st row load → 150kg
- Weight
  - Front axel
    - Left tyre → 490 kg
    - Right tyre → 460 kg
  - Rear axel
    - Left tyre → 361 kg
    - Right tyre → 333 kg
  - Total weight → 1644 kg
- Tyre pressure → 240 kPa

5.6.4.1. Ambient, asphalt and tyre temperature

Since the run-in and tyre wear cycle was performed on different dates, we analysed temperatures separately.

Ambient temperatures during the abrasion test were:

- Run-in:
  - Maximum → 12.5 ºC.
  - Minimum → 6.1 ºC
  - Average → 9.4 ºC

- Tyre wear cycle:
  - Maximum → 37.2 ºC.
  - Minimum → 24.2 ºC
  - Average → 28.5 ºC

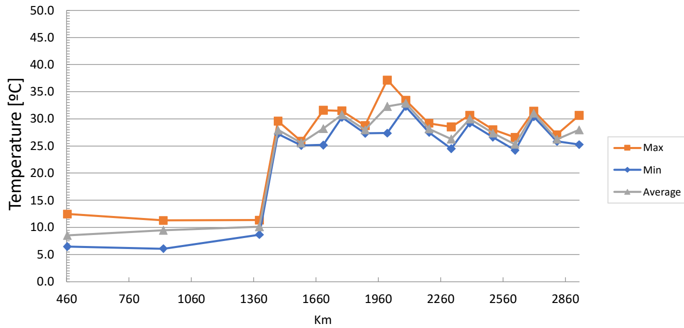


Figure 63. Ambient temperature – LingLong #4

Asphalt temperatures during the abrasion test were:

- Run-in:
  - Maximum → 23.3 ºC.
  - Minimum → 7.9 ºC
  - Average → 16.5 ºC

- Tyre wear cycle:
  - Maximum → 48.8 ºC.
  - Minimum → 31.6 ºC
  - Average → 40.1 ºC

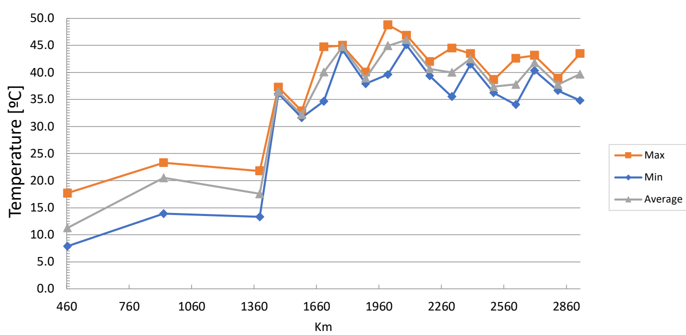


Figure 64. Asphalt temperature – LingLong #4

Tyre temperatures during the abrasion test were:

- Run-in:
  - Maximum → 26.7 ºC.
  - Minimum → 14.5 ºC
  - Average → 22.6 ºC

- Tyre wear cycle:
  - Maximum → 50.4 ºC.
  - Minimum → 24.9 ºC
  - Average → 39.2 ºC

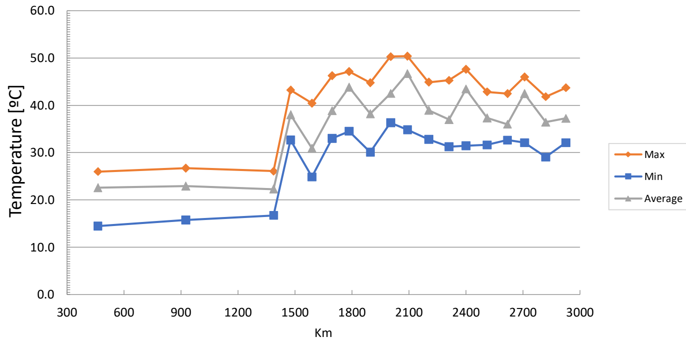


Figure 65. Tyres temperature – LingLong #4

5.6.4.2. Tyre abrasion

The LingLong #4 tyres had an abrasion mean of 1125 grams on the front tyres and 220 grams on the rear tyres.

The following figure presents the evolution of the tyre abrasion (grams) during the test defined in Table 6. That is,

- Run-in 1 to 3 → From 0 to 1380 km
- Tyre wear sequence 1 to 5: rural, motorway and urban → From 1380 to 2914 km

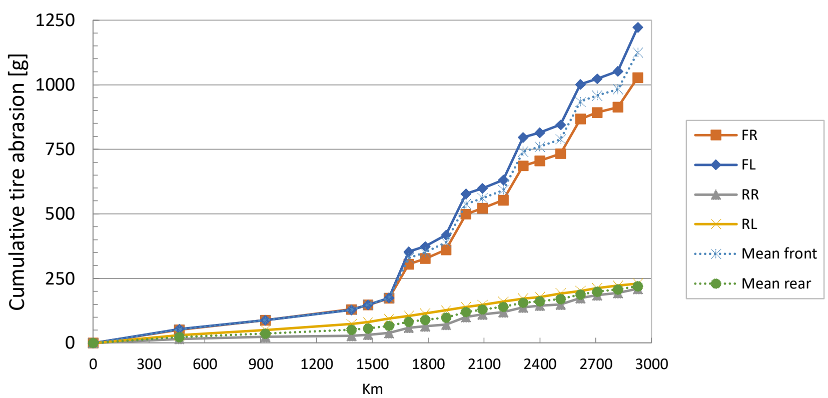


Figure 66. Abrasion - LingLong #4

Table 23 plots the average abrasion of the tyres on the front axle per tyre and on the rear axle per tyre.

Table 23. Average tyre abrasion rate – LingLong #4.

		Tyre Abrasion Rate [mg/km]				
		Run-in	Tyre wear test			
			Rural	Motorway	Urban	Av. Test
LL#4 High temp	Av. front per tyre	93.0	234.9	269.4	1 389.5	631.3
	Av. rear per tyre	36.8	88.0	85.7	153.5	109.1

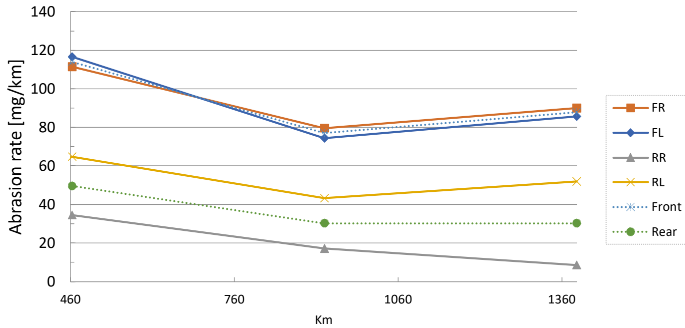


Figure 67. Run-in tyre abrasion rate - LingLong #4

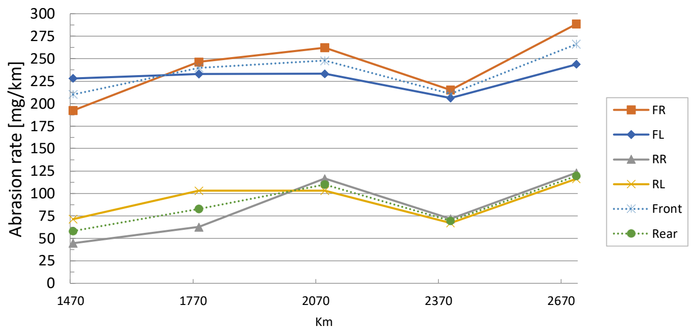


Figure 68. Rural tyre abrasion rate - LingLong #4

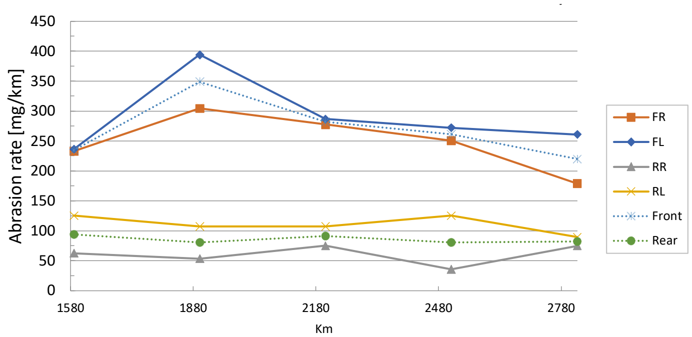


Figure 69. Motorway tyre abrasion rate - LingLong #4

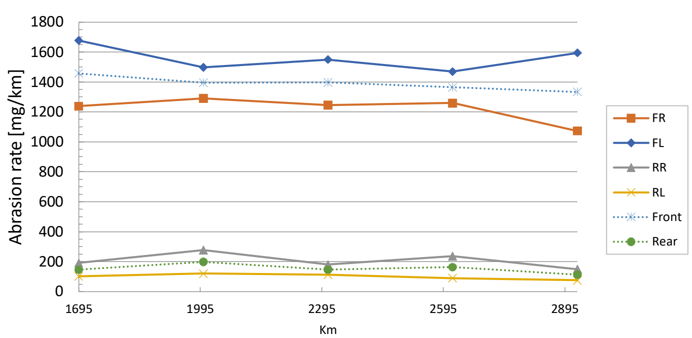


Figure 70. Urban tyre abrasion rate - LingLong #4

5.6.4.3. Other parameters

The tyres had a total life (mm) approximately 5.9 mm. We calculated these values in each tyre using the first tread depth minus 1.6 mm which is the minimum depth that a tyre should have [Total fife = first tread depth – 1.6 mm].

At the end of the abrasion test the front tyres loss between 3.15 mm and 3.91 mm and the rear tyres loss between 0.89 mm and 1.15 mm.

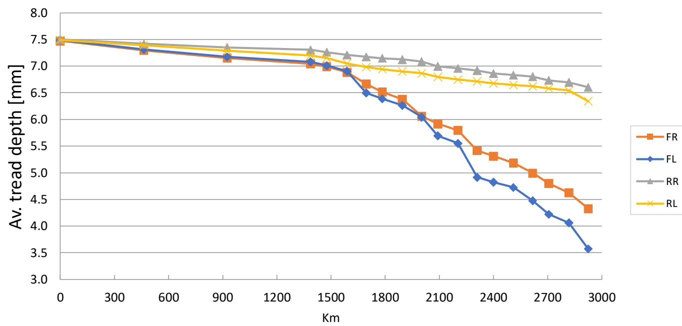


Figure 71. Tyre average tread depth - LingLong #4

Table 24. Calculated tyre life – LingLong #4.

	Total loss [mm]	Total Life [mm]	Loss [%]	Life [%]
FR set#1	3.15	5.87	53.6%	46.4%
FL set#1	3.91	5.88	66.5%	33.5%
RR set#1	0.89	5.90	15.2%	84.8%
RL set#1	1.15	5.89	19.5%	80.5%

The shore A hardness measurements were very sensitive to the point at which the measurement was made, so the results were not precise enough to see the change in the shore A hardness after each test. But it helped us to see that the initial shore A hardness is quite high between 64 and 63 and at the end of the abrasion test it was stabilized between 61 and 59.5 and had no significant variations during the abrasion test.

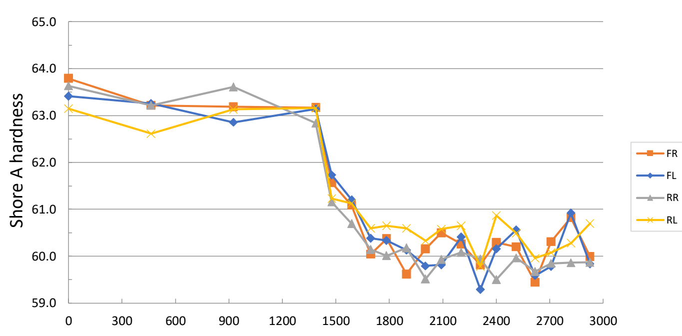


Figure 72. Tyre average shore A hardness - LingLong #4

5.6.5. Michelin

Michelin PILOT SPORT 4 SUV was tested.
Standard load → Lightly loaded.

- Full fuel tank

- Added weight: 150 kg
    - Instrumentation
    - 1st row load → 150kg
- Weight
    - Front axel
        - Left tyre → 490 kg
        - Right tyre → 460 kg
    - Rear axel
        - Left tyre → 361 kg
        - Right tyre → 333 kg
    - Total weight → 1644 kg
- Tyre pressure → 240 kPa

5.6.5.1. Ambient, asphalt and tyre temperature

Ambient temperatures during the abrasion test were:

- Maximum → 23.3 ºC.
- Minimum → 9.7 ºC
- Average → 15.2 ºC

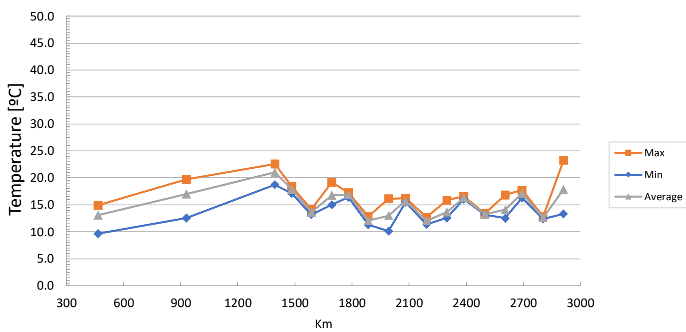


Figure 73. Ambient temperature – Michelin

Asphalt temperatures during the abrasion test were:

- Maximum → 35.1 ºC.
- Minimum → 11.5 ºC
- Average → 23.3 ºC

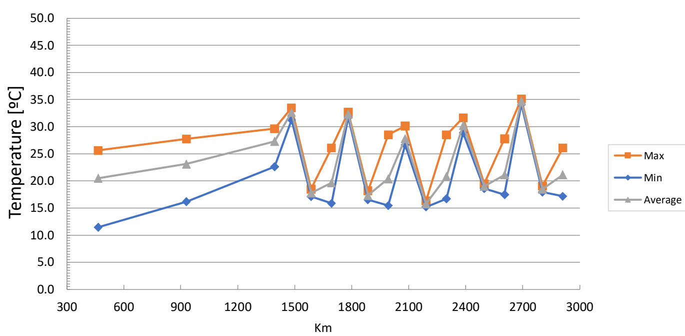


Figure 74. Asphalt temperature – Michelin

Tyre temperatures during the abrasion test were:

- Maximum → 39.9 ºC.
- Minimum → 16 ºC
- Average → 28.9 ºC

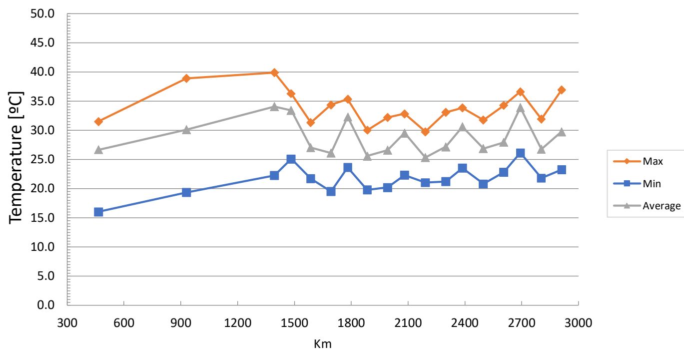


Figure 75. Tyres temperature – Michelin

5.6.5.2. Tyre abrasion

The Michelin tyres had an abrasion mean of 473.2 grams on the front tyres and 134.2 grams on the rear tyres.

The following figure presents the evolution of the tyre abrasion (grams) during the test defined in Table 6. That is,

- Run-in 1 to 3 → From 0 to 1380 km
- Tyre wear sequence 1 to 5: rural, motorway and urban → From 1380 to 2914 km

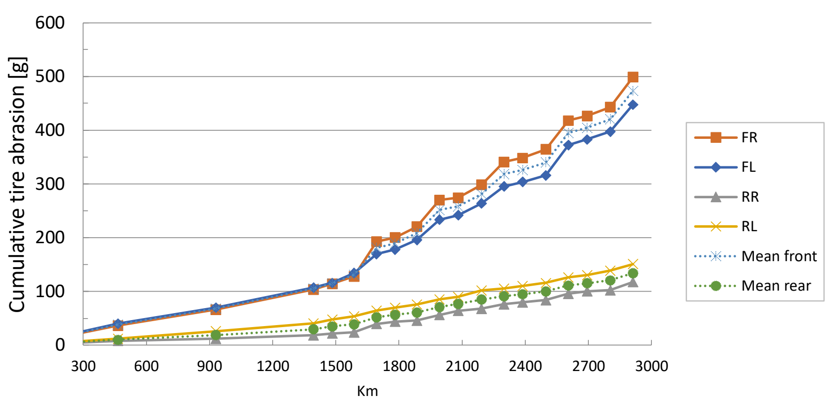


Figure 76. Abrasion - Michelin

Table 25 plots the average abrasion of the tyres on the front axle per tyre and on the rear axle per tyre.

Table 25. Average tyre abrasion rate – Michelin.

		Tyre Abrasion Rate [mg/km]				
		Run-in	Tyre wear test			
			Rural	Motorway	Urban	Av. Test
Michelin	Av. front per tyre	75.6	94.6	162.8	444.8	234.1
	Av. rear per tyre	21.2	55.7	48.0	100.7	68.1

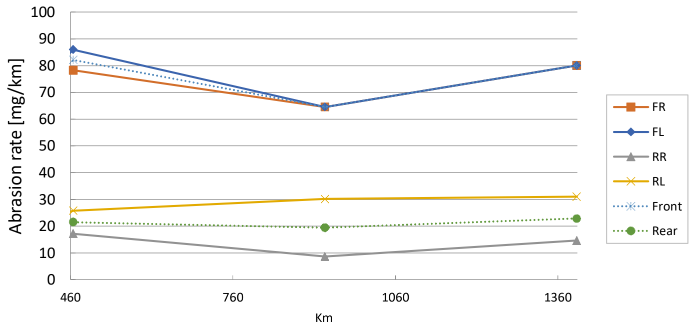


Figure 77. Run-in tyre abrasion rate - Michelin

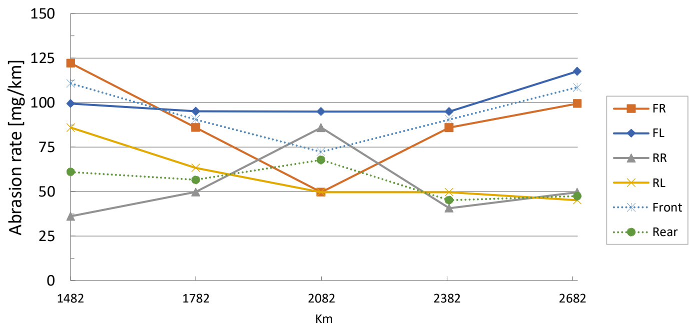


Figure 78. Rural tyre abrasion rate - Michelin

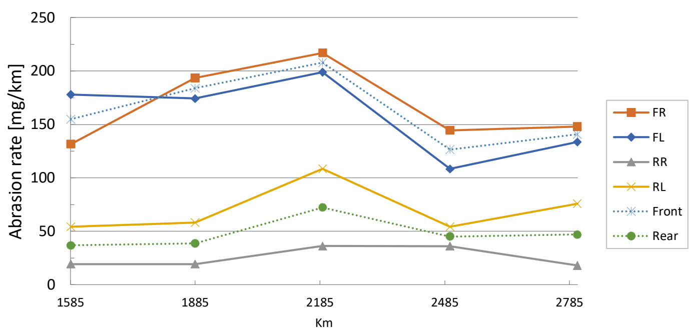


Figure 79. Motorway tyre abrasion rate - Michelin

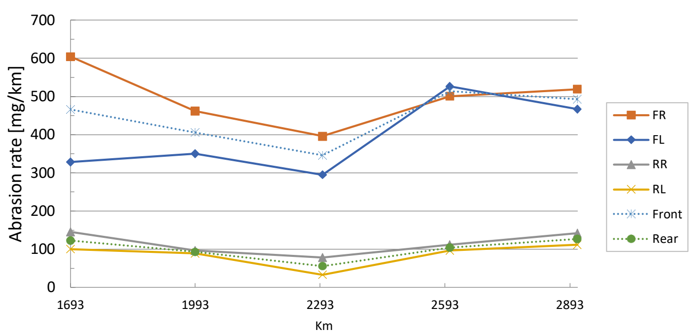


Figure 80. Urban tyre abrasion rate - Michelin

5.6.5.3. Other parameters

The tyres had a total life (mm) approximately 5.8 mm. We calculated these values in each tyre using the first tread depth minus 1.6 mm which is the minimum depth that a tyre should have [Total fife = first tread depth – 1.6 mm].

At the end of the abrasion test the front tyres loss between 1.76 mm and 1.68 mm and the rear tyres loss between 0.83 mm and 0.92 mm.

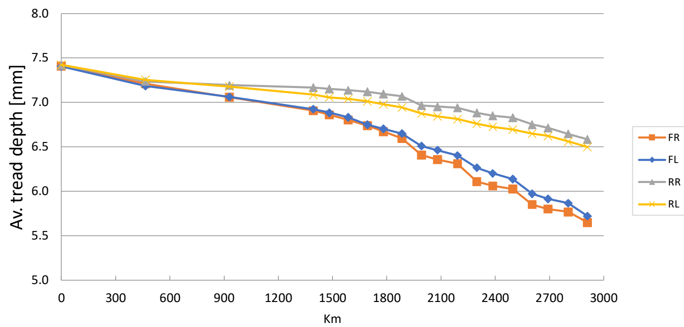


Figure 81. Tyre average tread depth - Michelin.

Table 26. Calculated tyre life – Michelin.

	Total loss [mm]	Total Life [mm]	Loss [%]	Life [%]
FR	1.76	5.81	30.3%	69.7%
FL	1.68	5.80	29.0%	71.0%
RR	0.83	5.82	14.3%	85.7%
RL	0.92	5.82	15.9%	84.1%

The shore A hardness measurements were very sensitive to the point at which the measurement was made, so the results were not precise enough to see the change in the shore A hardness after each test. But it helped us to see that the initial shore A hardness was quite high between 64 and 62 and at the end of the abrasion test it was stabilized between 58 and 57 and had no significant variations during the abrasion test.

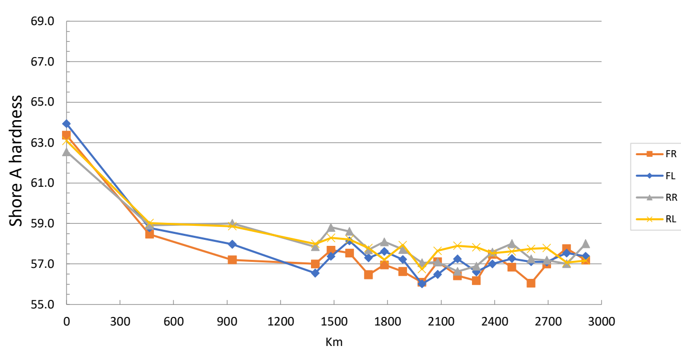


Figure 82. Tyre average shore A hardness - Michelin

5.6.6. Goodyear

Goodyear EFFICIENTGRIP SUV M+S was tested.

Standard load → Lightly loaded.

- Full fuel tank
- Added weight: 150 kg
  - Instrumentation
  - 1st row load → 150kg
- Weight
  - Front axel
    - Left tyre → 490 kg
    - Right tyre → 460 kg
  - Rear axel
    - Left tyre → 361 kg
    - Right tyre → 333 kg
  - Total weight → 1644 kg
- Tyre pressure → 240 kPa

5.6.6.1. Ambient, asphalt and tyre temperature

Ambient temperatures during the abrasion test were:

- Maximum → 27.3 ºC.
- Minimum → 11.5 ºC
- Average → 18 ºC

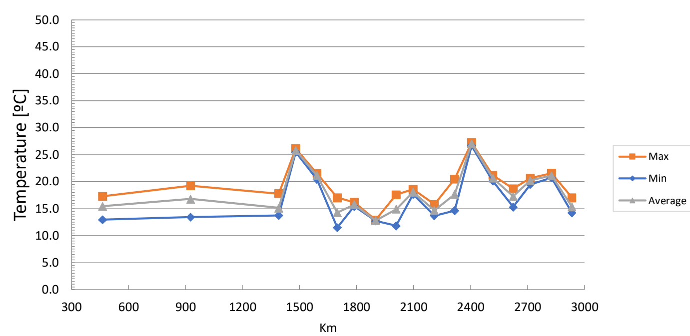


Figure 83. Ambient temperature – Goodyear

Asphalt temperatures during the abrasion test were:

- Maximum → 41.2 ºC.
- Minimum → 18.1 ºC
- Average → 28.4 ºC

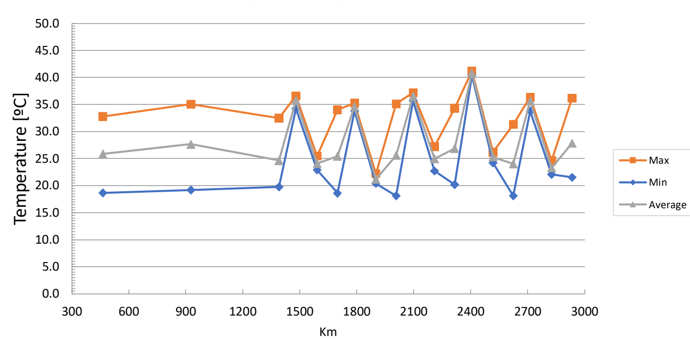


Figure 84. Asphalt temperature – Goodyear

Tyre temperatures during the abrasion test were:

- Maximum → 45.2 ºC.
- Minimum → 18.5 ºC
- Average → 31 ºC

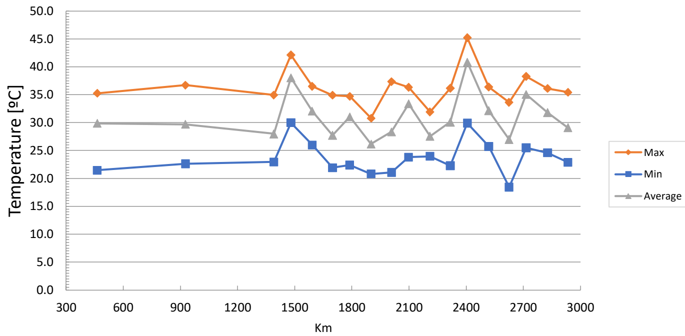


Figure 85. Tyres temperature – Goodyear

5.6.6.2. Tyre abrasion

The Goodyear tyres had an abrasion mean of 567.8 grams on the front tyres and 136.2 grams on the rear tyres.

The following figure plots the evolution of the tyre abrasion (grams) during the test defined in Table 6. That is,

- Run-in 1 to 3 → From 0 to 1380 km
- Tyre wear sequence 1 to 5: rural, motorway and urban → From 1380 to 2914 km

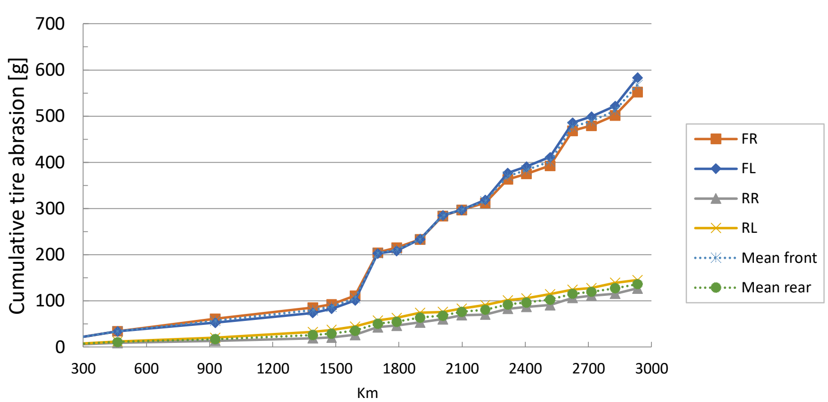


Figure 86. Abrasion - Goodyear

Table 27 plots the average abrasion of the tyres on the front axle per tyre and on the rear axle per tyre.

Table 27. Average tyre abrasion rate – Goodyear.

		Tyre Abrasion Rate [mg/km]				
		Run-in	Tyre wear test			
			Rural	Motorway	Urban	Av. Test
Goodyear	Av. front per tyre	57.3	118.9	179.4	625.2	307.8
	Av. rear per tyre	18.7	54.1	60.3	97.6	70.7

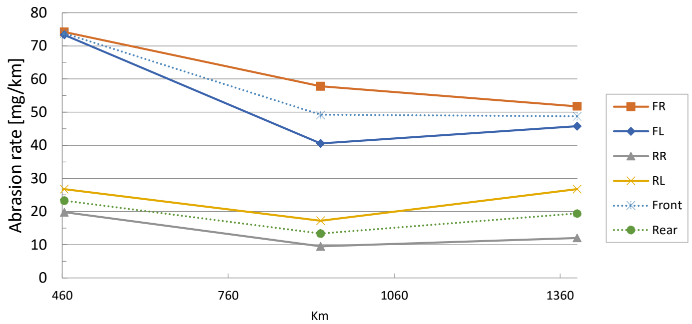


Figure 87. Run-in tyre abrasion rate - Goodyear

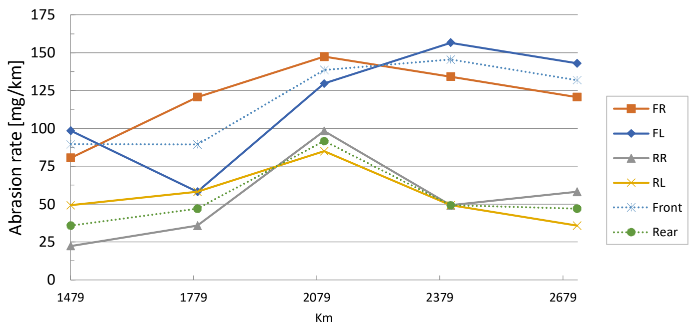


Figure 88. Rural tyre abrasion rate - Goodyear

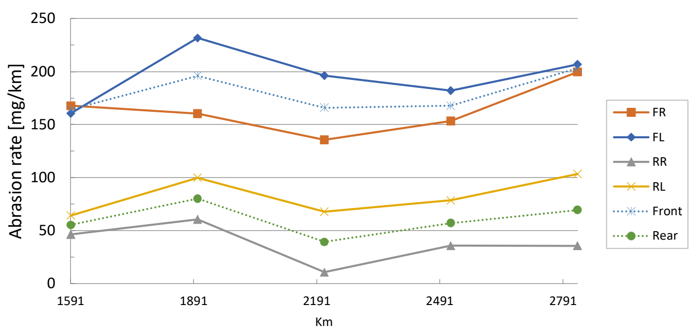


Figure 89. Motorway tyre abrasion rate - Goodyear

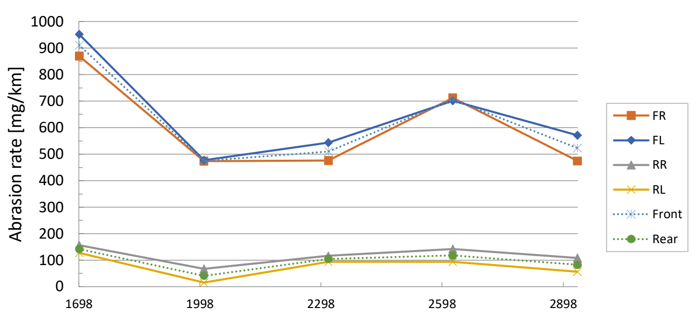


Figure 90. Urban tyre abrasion rate - Goodyear

5.6.6.3. Other parameters

The tyres had a total life (mm) approximately 6 mm. We calculated these values in each tyre using the first tread depth minus 1.6 mm which is the minimum depth that a tyre should have [Total fife = first tread depth – 1.6 mm].

At the end of the abrasion test the front tyres loss between 1.82 mm and 1.95 mm and the rear tyres loss between 0.71 mm and 0.83 mm.

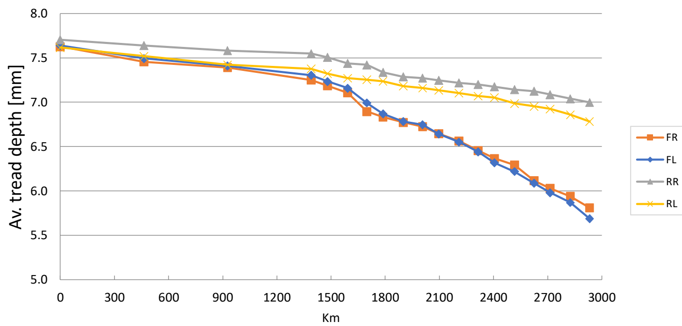


Figure 91. Tyre average tread depth – Goodyear

Table 28. Calculated tyre life – Goodyear.

	Total loss [mm]	Total Life [mm]	Loss [%]	Life [%]
FR set#1	1.82	6.03	30.1%	69.9%
FL set#1	1.95	6.04	32.3%	67.7%
RR set#1	0.71	6.11	11.6%	88.4%
RL set#1	0.83	6.02	13.8%	86.2%

The shore A hardness measurements were very sensitive to the point at which the measurement was made, so the results were not precise enough to see the change in the shore A hardness after each test. But it helped us to see that the initial shore A hardness was quite high between 65 and 59 and at the end of the abrasion test it was stabilized between 58 and 56 and had no significant variations during the abrasion test.

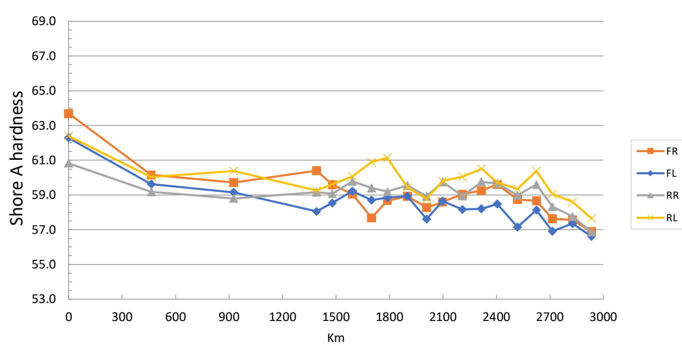


Figure 92. Tyre average shore A hardness - Goodyear

5.6.7. Dunlop

Standard test with the Dunlop GRANDTREK ST30 M+S was tested.
Standard load → Lightly loaded.

- Full fuel tank

- Added weight: 150 kg
  - Instrumentation
  - 1st row load → 150kg
- Weight
  - Front axel
    - Left tyre → 490 kg
    - Right tyre → 460 kg
  - Rear axel
    - Left tyre → 361 kg
    - Right tyre → 333 kg
  - Total weight → 1644 kg
- Tyre pressure → 240 kPa

5.6.7.1. Ambient, asphalt and tyre temperature

Ambient temperatures during the abrasion test were:

- Maximum → 26 ºC.
- Minimum → 14.9 ºC
- Average → 20.8 ºC

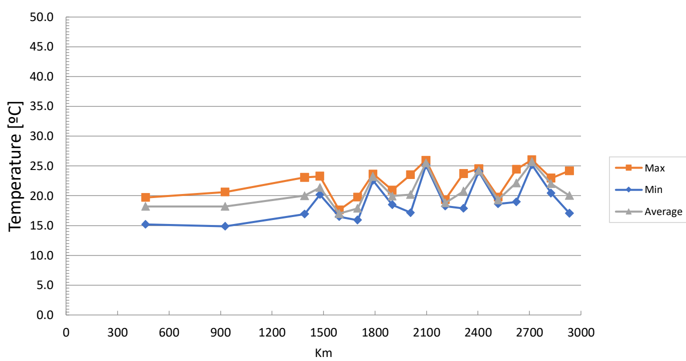


Figure 93. Ambient temperature – Dunlop

Asphalt temperatures during the abrasion test were:

- Maximum → 48.3 ºC.
- Minimum → 21.4 ºC
- Average → 35.5 ºC

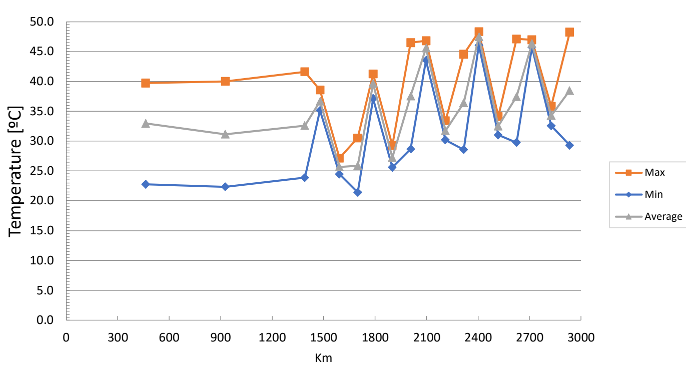


Figure 94. Asphalt temperature – Dunlop

Tyre temperatures during the abrasion test were:

- Maximum → 43.7 ºC.

- Minimum → 24.1 ºC
- Average → 33.7 ºC

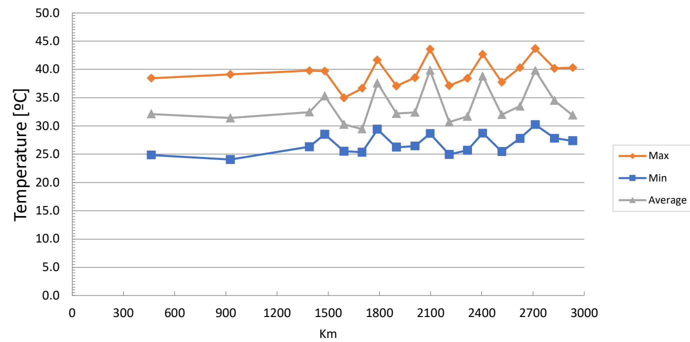


Figure 95. Tyres temperature – Dunlop

5.6.7.2. Tyre abrasion

The Dunlop tyres had an abrasion mean of 630.2 grams on the front tyres and 128.8 grams on the rear tyres.

The following figure presents the evolution of the tyre abrasion (grams) during the test defined in Table 6. That is,

- Run-in 1 to 3 → From 0 to 1380 km
- Tyre wear sequence 1 to 5: rural, motorway and urban → From 1380 to 2914 km

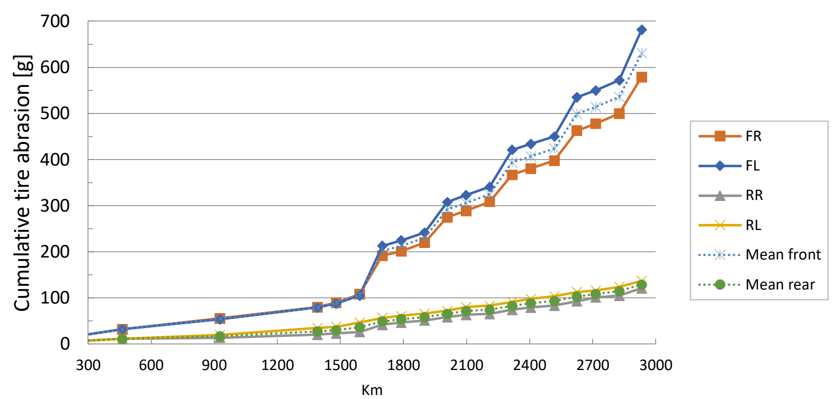


Figure 96. Abrasion - Dunlop

Table 29 plots the average abrasion of the tyres on the front axle per tyre and on the rear axle per tyre.

Table 29. Average tyre abrasion rate – Dunlop.

		Tyre Abrasion Rate [mg/km]				
		Run-in	Tyre wear test			
			Rural	Motorway	Urban	Av. Test
Dunlop	Av. front per tyre	57.3	140	167.5	741.2	349.6
	Av. rear per tyre	19.8	56.1	44.1	97.1	65.8

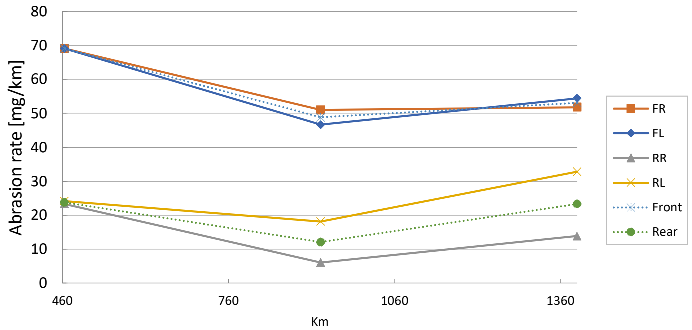


Figure 97. Run-in tyre abrasion rate - Dunlop

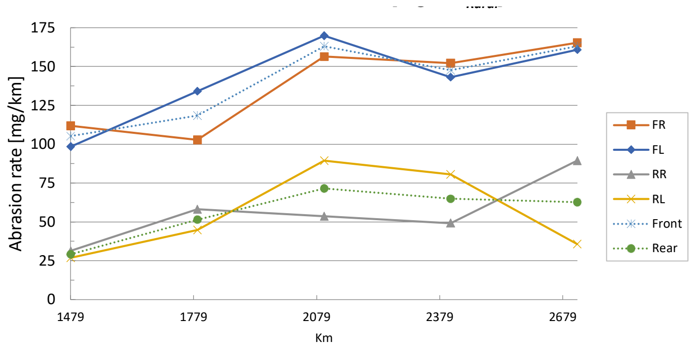


Figure 98. Rural tyre abrasion rate - Dunlop

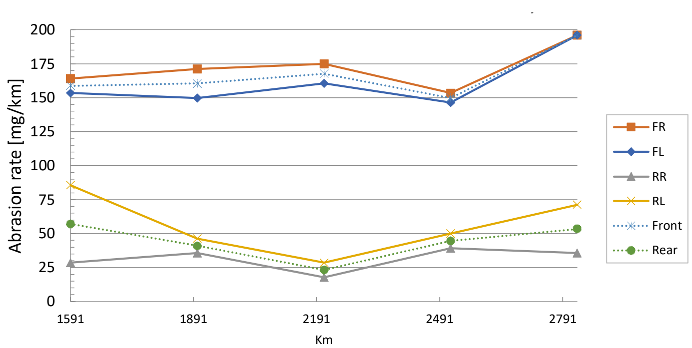


Figure 99. Motorway tyre abrasion rate - Dunlop

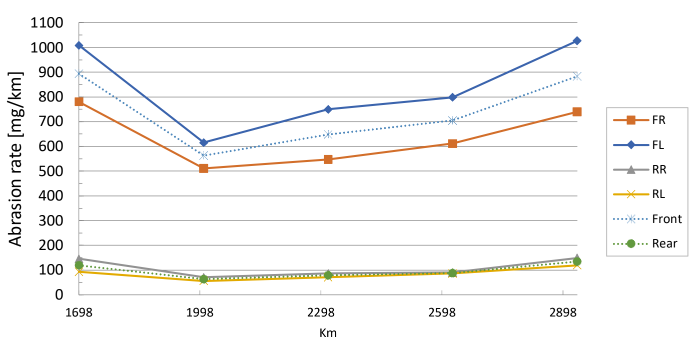


Figure 100. Urban tyre abrasion rate - Dunlop

5.6.7.3. Other parameters

The tyres had a total life (mm) approximately 5.9 mm. We calculated these values in each tyre using the first tread depth minus 1.6 mm which is the minimum depth that a tyre should have [Total fife = first tread depth – 1.6 mm].

At the end of the abrasion test the front tyres loss between 1.77 mm and 2.15 mm and the rear tyres loss between 0.85 mm and 0.84 mm.

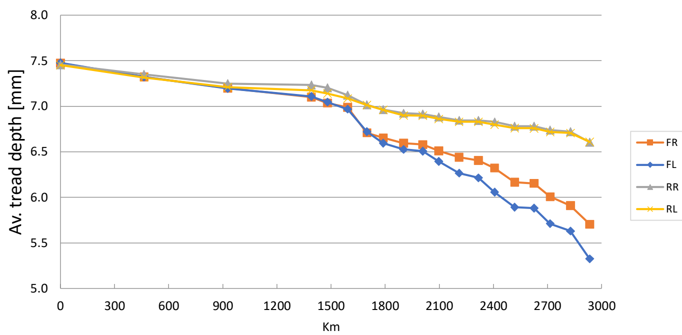


Figure 101. Tyre average tread depth - Dunlop

Table 30. Calculated tyre life – Dunlop.

	Total loss [mm]	Total Life [mm]	Loss [%]	Life [%]
FR set#1	1.77	5.87	30.1%	69.9%
FL set#1	2.15	5.88	36.6%	63.4%
RR set#1	0.85	5.86	14.5%	85.5%
RL set#1	0.84	5.85	14.4%	85.6%

The shore A hardness measurements were very sensitive to the point at which the measurement was made, so the results were not precise enough to see the change in the shore A hardness after each test. But it helped us to see that the initial shore A hardness was quite high between 64 and 60 and at the end of the abrasion test it was stabilized between 59 and 57 and had no significant variations during the abrasion test.

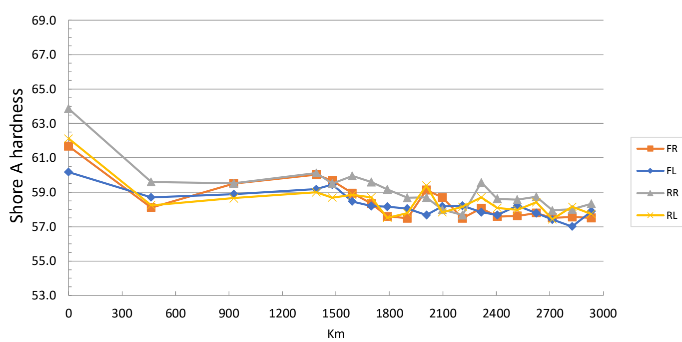


Figure 102. Tyre average shore A hardness - Dunlop

5.6.8. *Pirelli*

Standard test with the Pirelli SCORPION VERDE was tested.

Standard load → Lightly loaded.

- Full fuel tank
- Added weight: 150 kg
  - Instrumentation
  - 1st row load → 150kg
- Weight
  - Front axel
    - Left tyre → 490 kg
    - Right tyre → 460 kg
  - Rear axel
    - Left tyre → 361 kg
    - Right tyre → 333 kg
  - Total weight → 1644 kg
- Tyre pressure → 240 kPa

5.6.8.1. Ambient, asphalt and tyre temperature

Ambient temperatures during the abrasion test were:

- Maximum → 20 ºC.
- Minimum → 18 ºC
- Average → 23.4 ºC

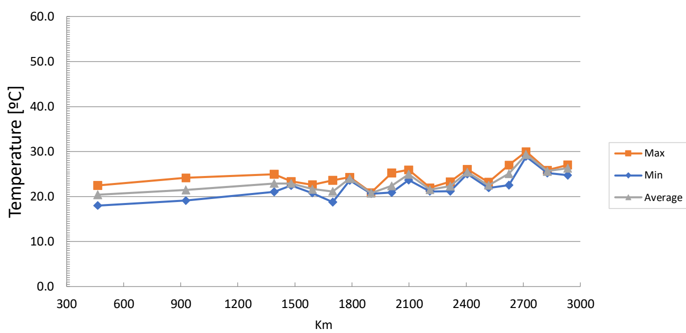


Figure 103. Ambient temperature – Pirelli

Asphalt temperatures during the abrasion test were:

- Maximum → 51.2 ºC.
- Minimum → 25.6 ºC
- Average → 37.4 ºC

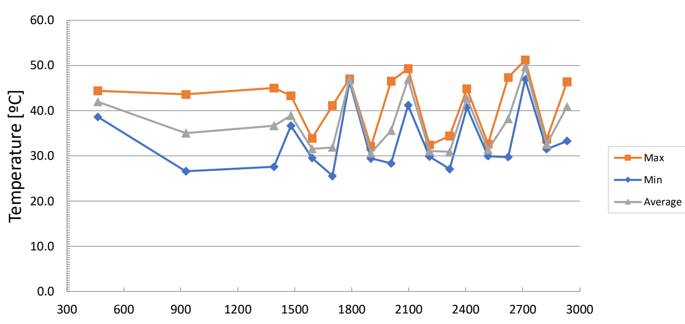


Figure 104. Asphalt temperature – Pirelli

Tyre temperatures during the abrasion test were:

- Maximum → 47.9 ºC

- Minimum → 27.2 ºC
- Average → 37.2 ºC

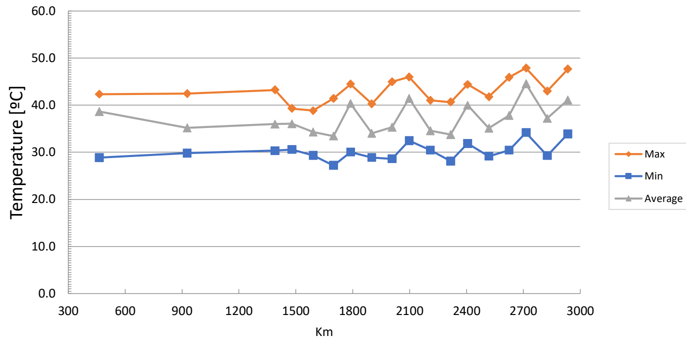


Figure 105. Tyres temperature – Pirelli

5.6.8.2. Tyre abrasion

The Pirelli tyres had an abrasion mean of 766.8 grams on the front tyres and 209.6 grams on the rear tyres.

The following figure presents the evolution of the tyre abrasion (grams) during the test defined in Table 6. That is,

- Run-in 1 to 3 → From 0 to 1380 km
- Tyre wear sequence 1 to 5: rural, motorway and urban → From 1380 to 2914 km

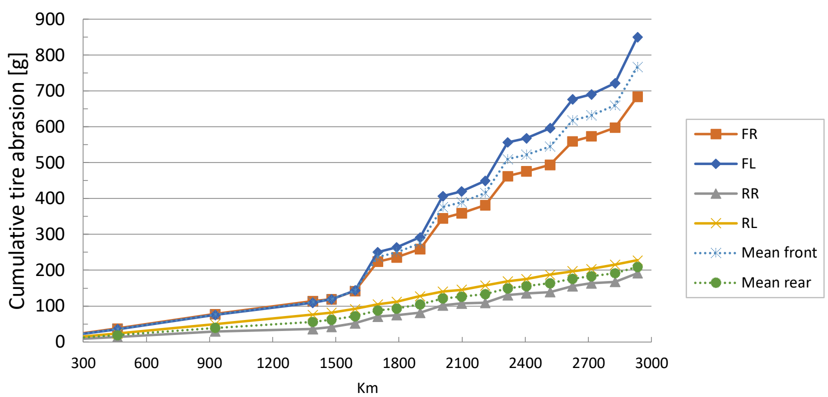


Figure 106. Abrasion - Pirelli

Table 31 plots the average abrasion of the tyres on the front axle per tyre and on the rear axle per tyre.

Table 31. Average tyre abrasion rate – Pirelli.

		Tyre Abrasion Rate [mg/km]				
		Run-in	Tyre wear test			
			Rural	Motorway	Urban	Av. Test
Pirelli	Av. front per tyre	79.8	136.8	227.3	878.5	414.2
	Av. Rear per tyre	40.1	67.3	78.9	150	98.7

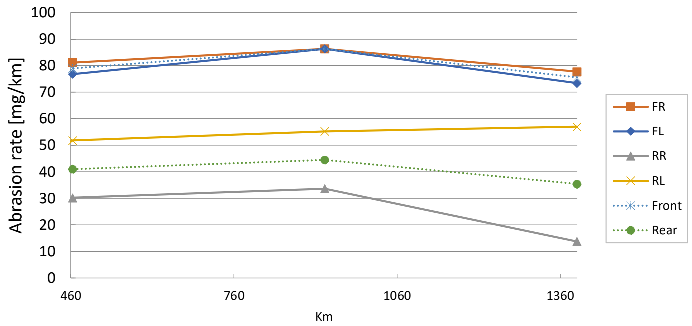


Figure 107. Run-in tyre abrasion rate - Pirelli

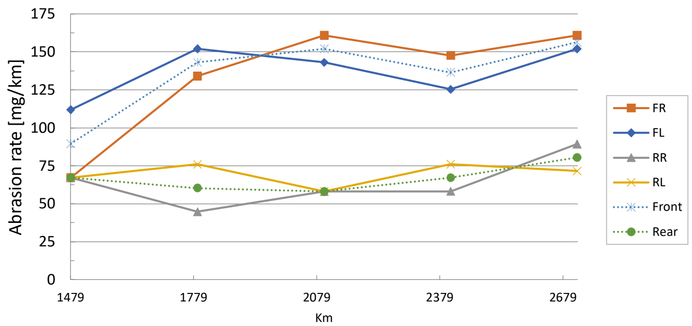


Figure 108. Rural tyre abrasion rate - Pirelli

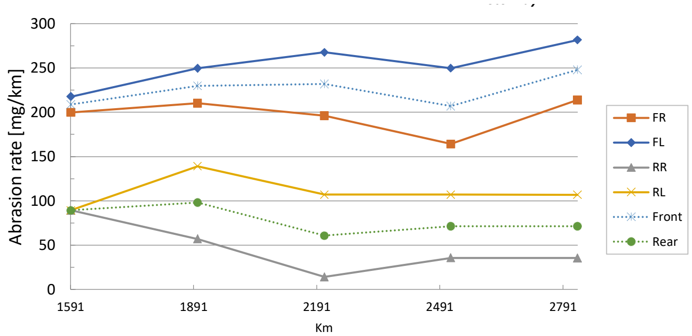


Figure 109. Motorway tyre abrasion rate - Pirelli

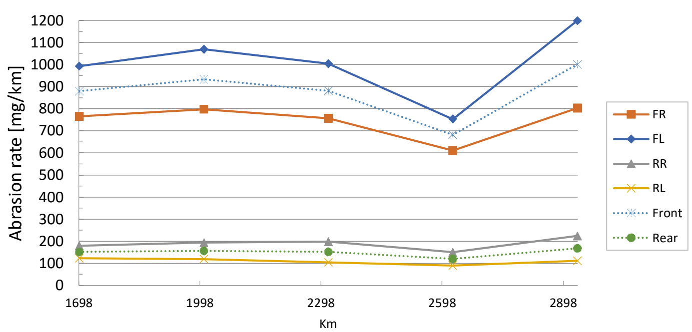


Figure 110. Urban tyre abrasion rate - Pirelli

5.6.8.3. Other parameters

The tyres had a total life (mm) approximately 6.4 mm. We calculated these values in each tyre using the first tread depth minus 1.6 mm which is the minimum depth that a tyre should have [Total fife = first tread depth – 1.6 mm].

At the end of the abrasion test the front tyres loss between 2.2 mm and 2.69 mm and the rear tyres loss between 1.06 mm and 1.08 mm.

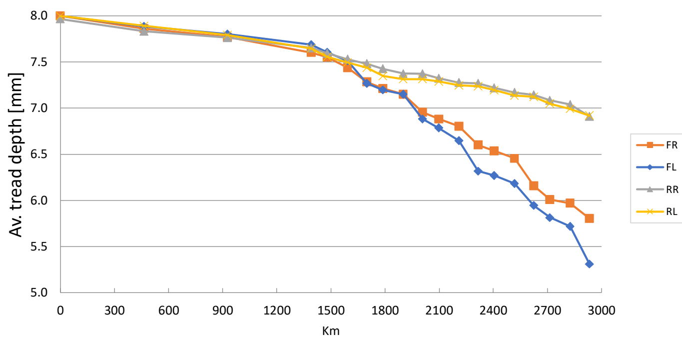


Figure 111. Tyre average tread depth – Pirelli

Table 32. Calculated tyre life – Pirelli.

	Total loss [mm]	Total Life [mm]	Loss [%]	Life [%]
FR set#1	2.20	6.40	34.3%	65.7%
FL set#1	2.69	6.40	42.1%	57.9%
RR set#1	1.06	6.37	16.6%	83.4%
RL set#1	1.08	6.40	16.9%	83.1%

The shore A hardness measurements were very sensitive to the point at which the measurement was made, so the results were not precise enough to see the change in the shore A hardness after each test. But it helped us to see that the initial shore A hardness was quite high between 63 and 61 and at the end of the abrasion test it was stabilized between 59 and 57 and had no significant variations during the abrasion test.

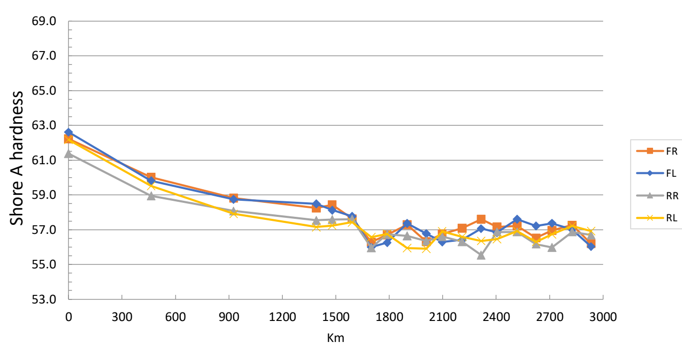


Figure 112. Tyre average shore A hardness - Pirelli

5.6.9. Comparison of tyres

5.6.9.1. Evolution of tyre abrasion

Figure 113 shows the evolution of the total vehicle abrasion curve of the different types of tyres. The values of each type of tyre are the sum of the 4 tyres. Figure is marked with number from 1 to 6, number 1 show three run-in parts and the number 2 to 6 show: rural part 1 to 5, motorway part 1 to 5, urban part 1 to 5.

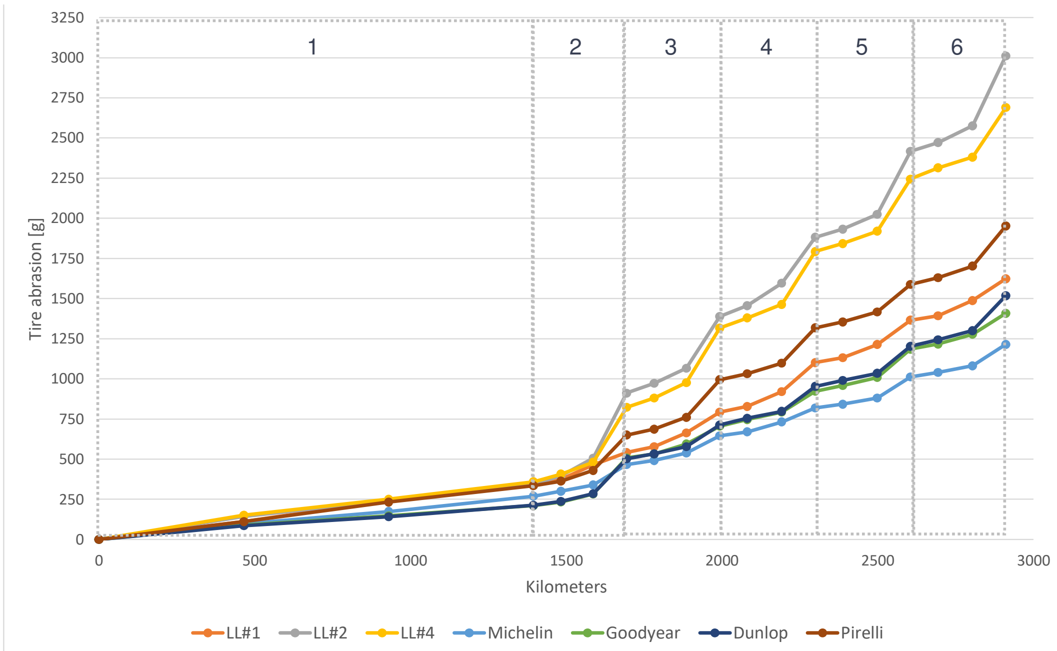


Figure 113. Total vehicle (4 tyres) tyre abrasion comparison

It shows that although the abrasion rate results are different for each tyre, the trend was very similar in all of them. Also shows that extreme conditions of temperature and load (LL#2 and LL#4), the increase was higher. This will be discussed in more details in the following paragraphs.

5.6.9.2. Tyre Abrasion Rate comparison

The results of the different types of tyres are presented in the following Table 33 and in Figure 114:

Total vehicle abrasion ratio [mg/km] of the 4 tyres are presented in the following table:

Table 33. Total abrasion rate per vehicle (4 tyres) for the different types of tyres.

	Tyre abrasion rate [mg/km]				
	Run-in	Abrasion test			
		Rural	Motorway	Urban	Av. test
LL#1 Cold	248.8	356.6	794.3	1 255.3	802.1
LL#2 High load	248.5	641.9	967.3	3 453.7	1 687.6
LL#3 Modified	232.0				639.3
LL#4 High temp	259.5	645.9	710.3	3 085.9	1 480.7
Michelin	193.6	300.5	421.6	1 091.1	604.4
Goodyear	151.9	346.1	479.4	1 445.6	757.0
Dunlop	154.1	392.3	423.2	1 676.6	830.7
Pirelli	239.8	408.3	612.5	2 057.0	1 025.9

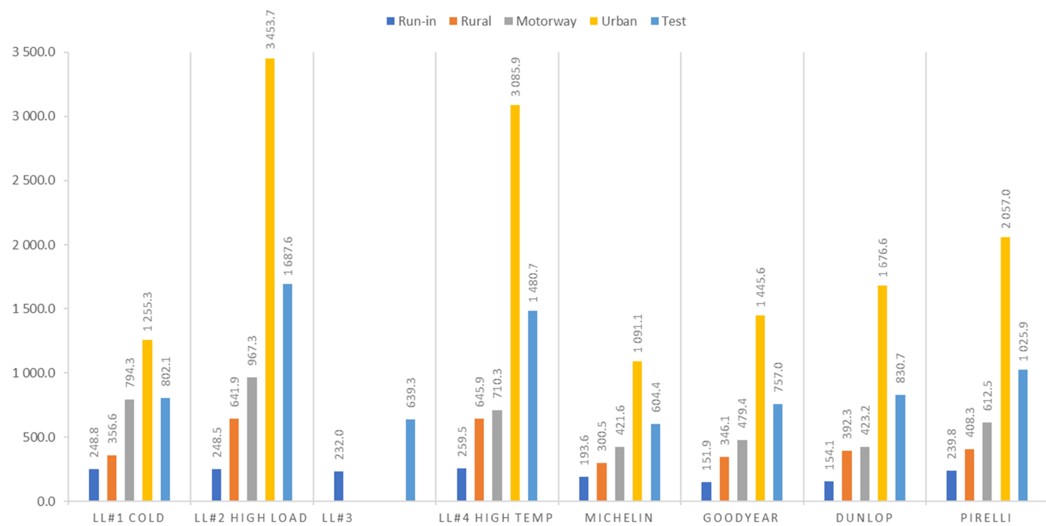


Figure 114. Tyre Abrasion Rate for the different types of tyres

From these results, some conclusions can be drawn:

Comparing different driving conditions, abrasion rate had the following trend with the same tyre: Run-in < Rural < Motorway < Urban. This trend was followed with all the different types of tyres, and with the different conditions of load and temperature. This trend was to be expected due to each driving conditions have different conditions, as the bends had also the following trend: Rural < Motorway < Urban, so it was expected that the abrasion rate increases with the increase of the amount of bends. In the case of brake events, the urban part also was the part with more number. More detailed information is shown in Table 34:

Table 34. Difference between rural, urban and motorway.

	Rural	Motorway	Urban
Speed test [km/h]	60, 70 & 80	130	20, 30 & 40
Laps	12	15	148
Total distance [km]	89.2	111	106.6
Total brake events	77	15	226
Bends	24	30	296

Furthermore, comparing the duration of the test, the rural or motorway lasted 1 hour and the urban test lasted 4 hours.

In the following figures we can see the comparison in the front and rear axle between the abrasion ratio (mg/km) per tonne applied to the axle [(mg/kg)/t] and tyre temperature (ºC). The abrasion per kilometer in each axle was calculated as the sum of the abrasion per kilometer obtained on the left and right tyre.
The figures show LingLong tyres marked with circles and Michelin, Goodyear, Dunlop and Pirelli tyres marked with triangles. The Linglong tyre was tested at low and high temperature.

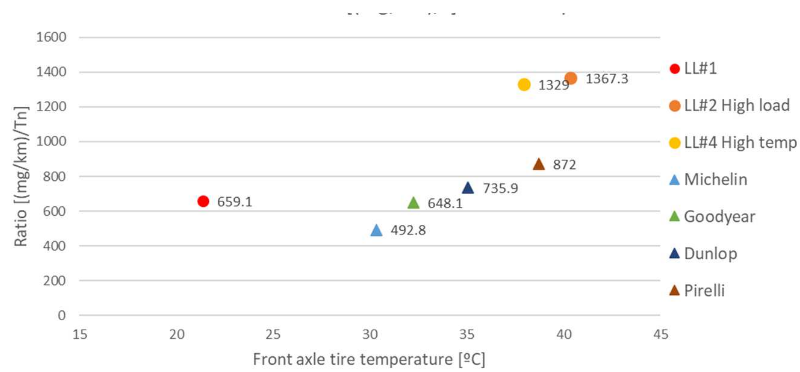


Figure 115. Front axle comparison (two wheels): (Abrasion / weight) vs tyre temperature

The figure suggests that the sensitivity of abrasion ratio per tonne with respect to tyre temperature was the same in most tyres manufactures.

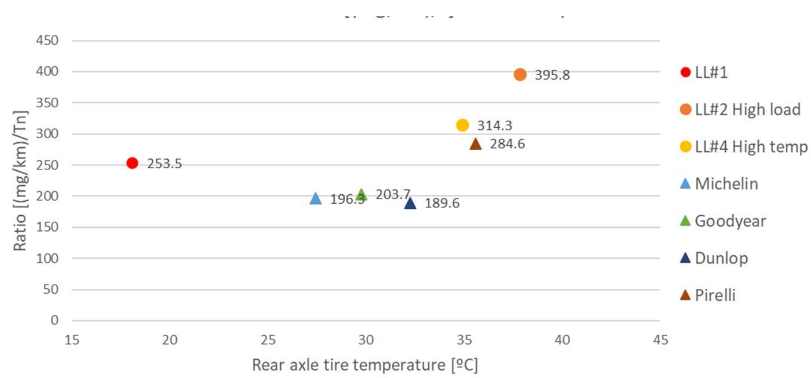


Figure 116. Rear axle comparison (two wheels): (Abrasion km / weight) vs tyre temperature

In this case the figure suggests that the sensitivity of abrasion ratio per tonne with respect to tyre temperature for the rear axle was very similar for most tyres.

5.6.9.3. Effect of temperature and load on abrasion

Table 35 and Figure 117 show the vehicle abrasion (4 tyres) results obtained from tests LL#1 and LL#4 which were carried out with the same tyres but in different temperature conditions and vehicle abrasion (4 tyres) results obtained from tests LL#2 and LL#4 which were carried out with the same tyres but with a different load.

- LingLong #1 → Cold temperature test (marked in blue)
- LingLong #4 → Hot temperature test (marked in grey)
- LingLong #2 → Hot temperature and high load test (marked in orange)

- Rural part: Table 35 and Figure 117 show that in rural part there was an increase in the tyre abrasion rate between the cold and hot temperature test with a ratio of 81% more abrasion in the hot test. We didn't find significant differences in abrasion rate between the hot test and the hot test with high load.

- Motorway part: Table 35 and Figure 117 show that in motorway part there was an unexpected slight decrease in the tyre abrasion rate between the cold and hot temperature test with a ratio of -11% less abrasion in the hot test and the tyre temperature was 21.5 ºC higher. We found an increase in the tyre abrasion rate between the hot test and hot & high load test with a ratio of 36% more abrasion in the hot & high load test.

- Urban part: Table 35 and Figure 117 show that in urban part there was an increase in the tyre abrasion rate between the cold and hot temperature test with a ratio of 146% more abrasion in the hot test. We found an increase in the tyre abrasion rate between the hot test and hot & high load test with a ratio of 12% more abrasion in the hot & high load test.

Table 35. Tyre abrasion rate (4 tyres) – effect of temperature and load on abrasion

		Rural	Motorway	Urban
LL#1 Cold temperature	Vehicle abrasion [mg/km]	356.6	794.3	1 255.3
	Av. tyre temperature [ºC]	18.3	20.2	20.3
LL#4 Hot temperature	Vehicle abrasion [mg/km]	645.9	710.3	3 085.9
	Av. tyre temperature [ºC]	38.0	41.7	37.9
LL#2 Hot temperature & high load	Vehicle abrasion [mg/km]	641.9	967.3	3 453.7
	Av. tyre temperature [ºC]	41.5	43.4	41.2

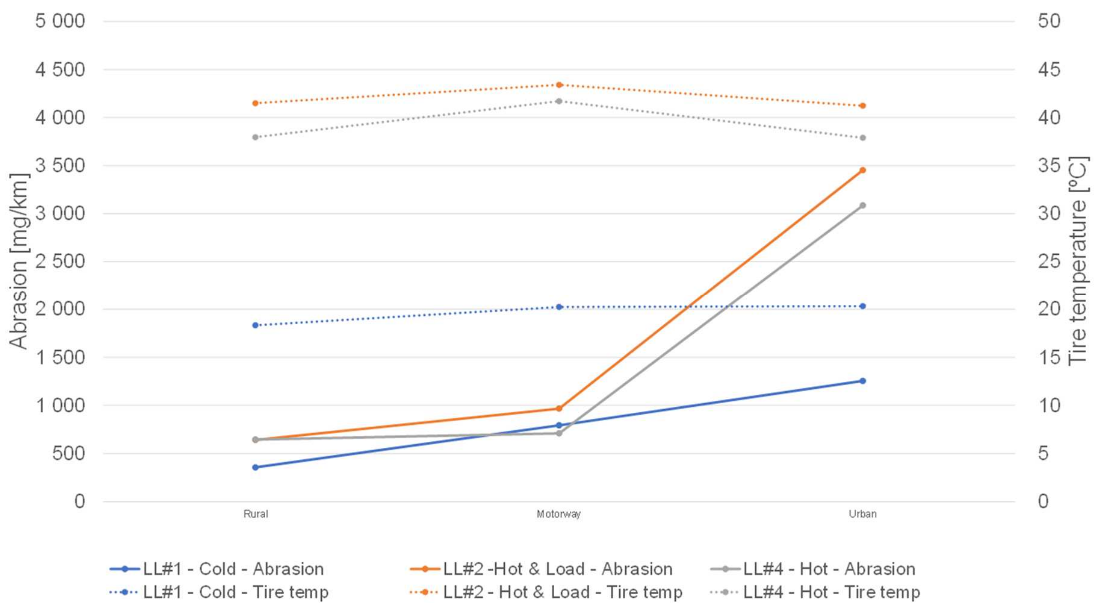


Figure 117. Effect of temperature and load on abrasion

5.6.9.4. Evolution of tyre shore A hardness

Figure 118 shows the average shore A hardness (4 tyres) evolution of the different type of tyres.

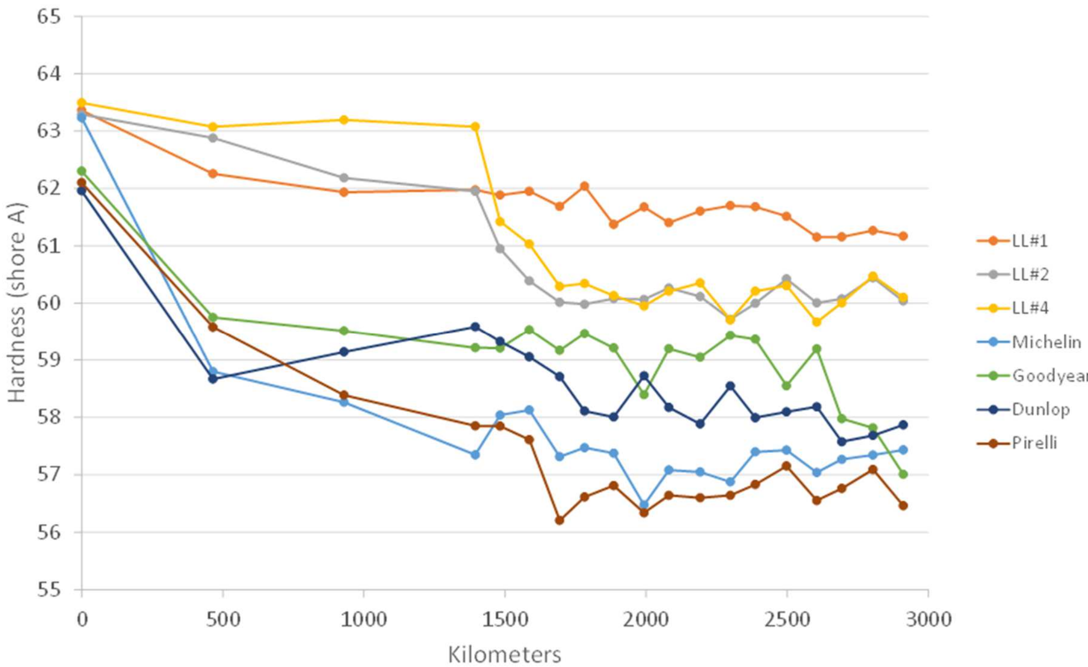


Figure 118. Average shore A hardness (4 tyres) comparison

Figure 118 shows that the initial hardness of the tyres was usually between 3 and 5 points above the value at which they stabilize during the tyre abrasion test.

6. On-road tests (IDIADA)

The on-road tests took place at the IDIADA premises in June 2024. They consisted of a run-in phase, rural, urban, and motorway (or sometimes called highway) parts. The vehicle was the one used for the accelerated tests. The tyre was the LingLong #1 Batman A50 SUV ATLAS M+S, which had been used in the accelerated abrasion tests.

6.1. Abrasion test

The abrasion tyre wear cycle had two different sections (procedures): run-in and tyre wear cycle. The run-in was 500 km driving at motorway conditions (loops of 250 km in one day) (see Table 36). The tyre wear cycle consisted of three separate parts in this order: urban (500 km, loops of 20 km in 3 days), rural (1000 km, loops of 120 km in 3 days) and motorway (1000 km, loops of 250 km in 2 days) parts. The total mileage for the abrasion test is the sum of run-in and tyre wear cycles, 3000 km. Some of the characteristics of these cycles are presented in the following Table 36.

Table 36. Abrasion test. 3000 km per tyre consisting of separate 500 km motorway run-in, 500 km urban, 1000 km rural and 1000 km motorway parts.

	Urban	**Rural**	**Motorway**
Distance (km)	500	1000	1000
Average speed (km/h)	29	60	105
Long std. dev. acc. (m/s^2)	0.68	0.63	0.41
Lat std. dev. acc. (m/s^2)	0.68	0.98	0.54
DSN long	36.4	30.4	3.6
DSN lat	36.2	42.3	28.7

- Run-in → 534 km in 1 day

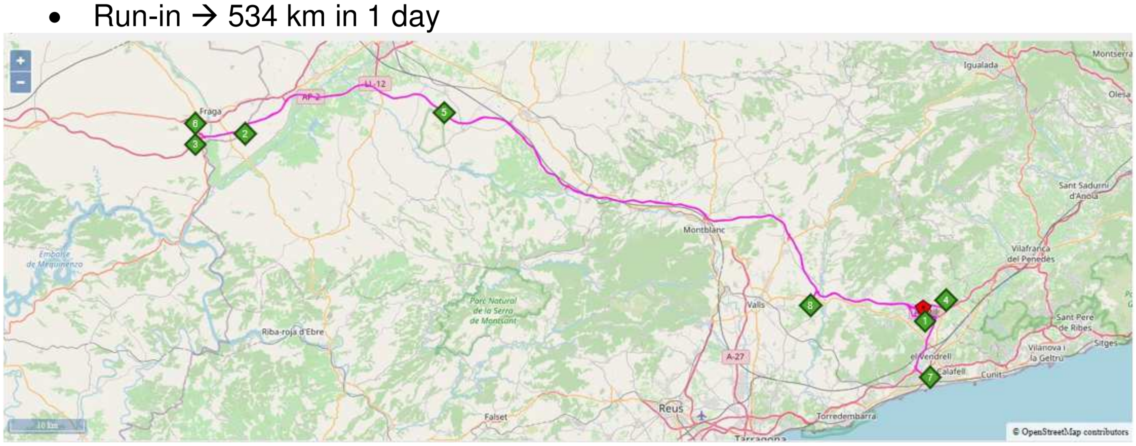


Figure 119. Run-in route

- Urban → 505.7 km in 3 days

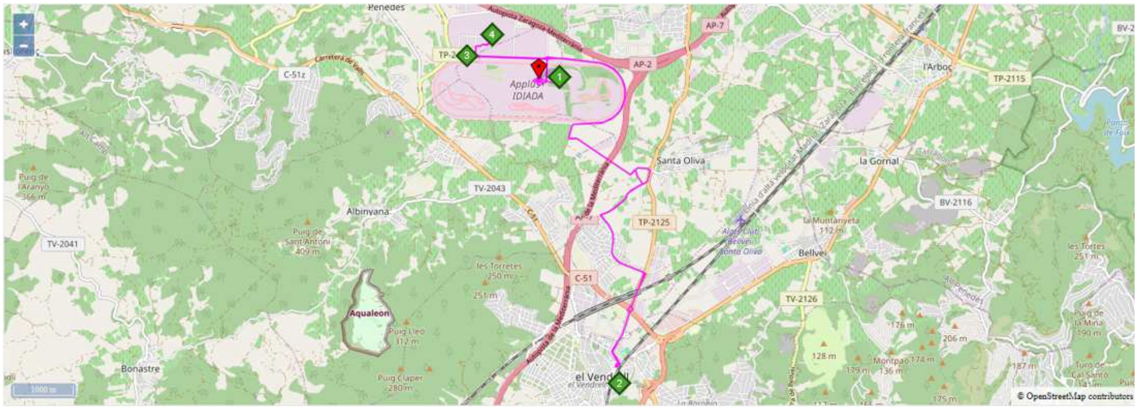


Figure 120. Urban route

- Rural → 1080.9 km in 3 days

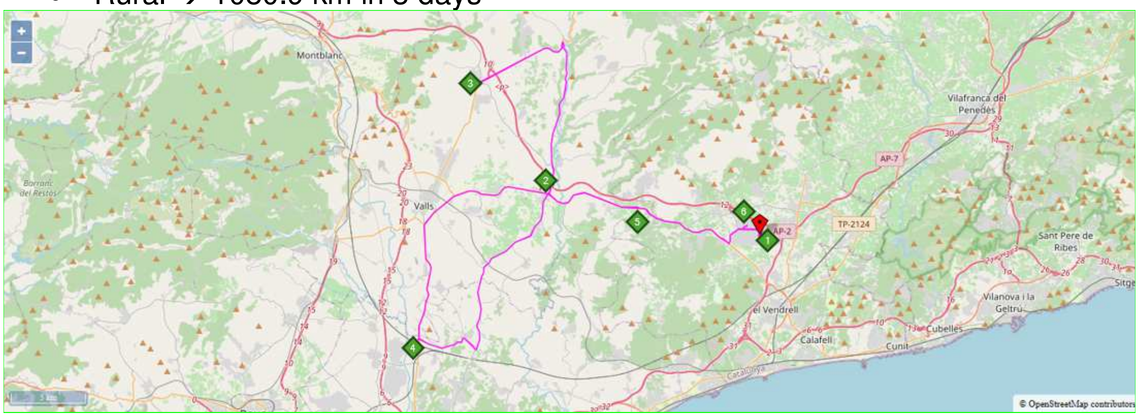


Figure 121. rural route

- Motorway → 1014 km in 2 days

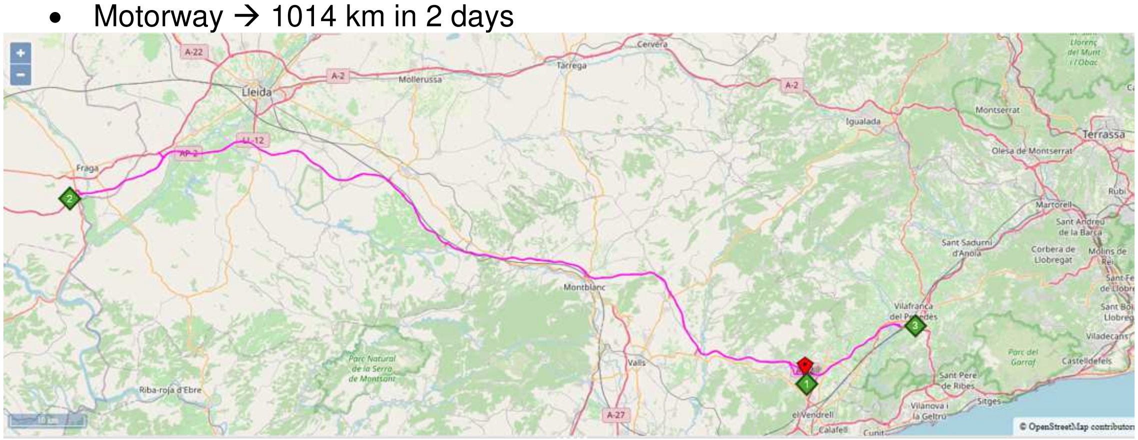
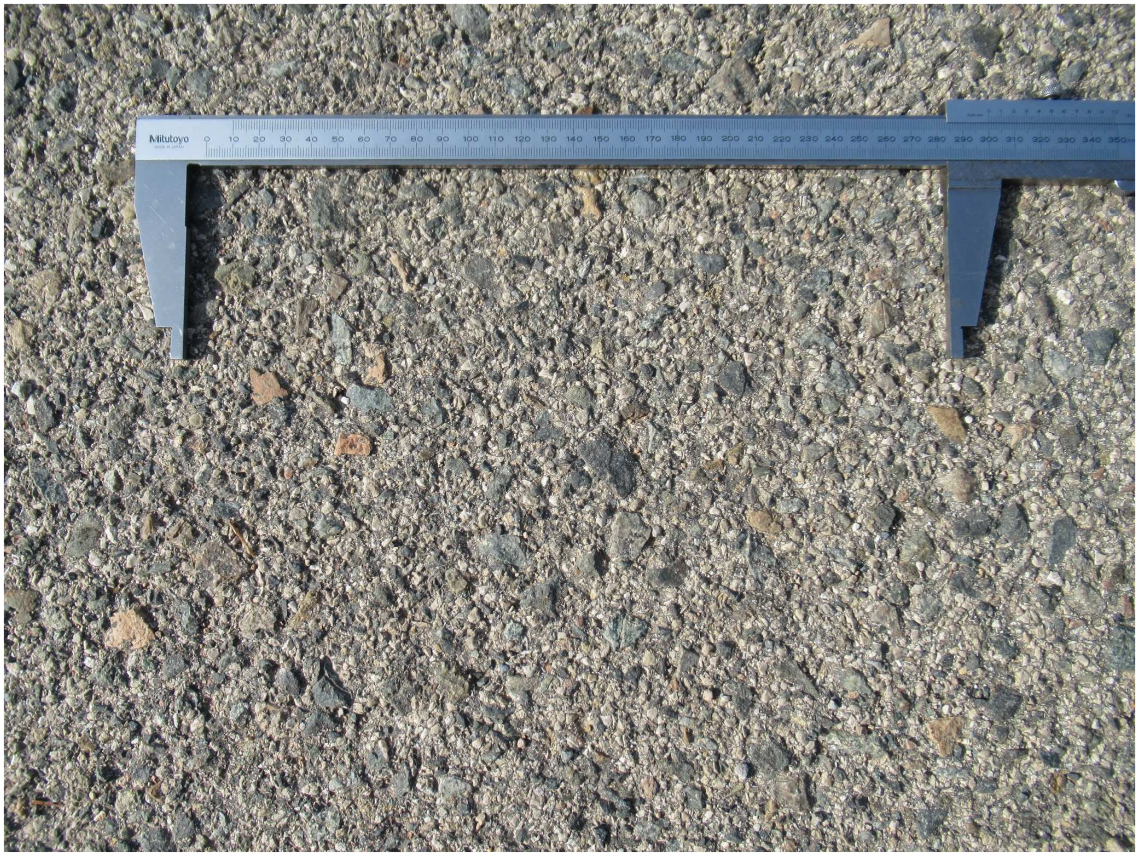


Figure 122. Motorway route

Examples of road surface are given in Figure 123.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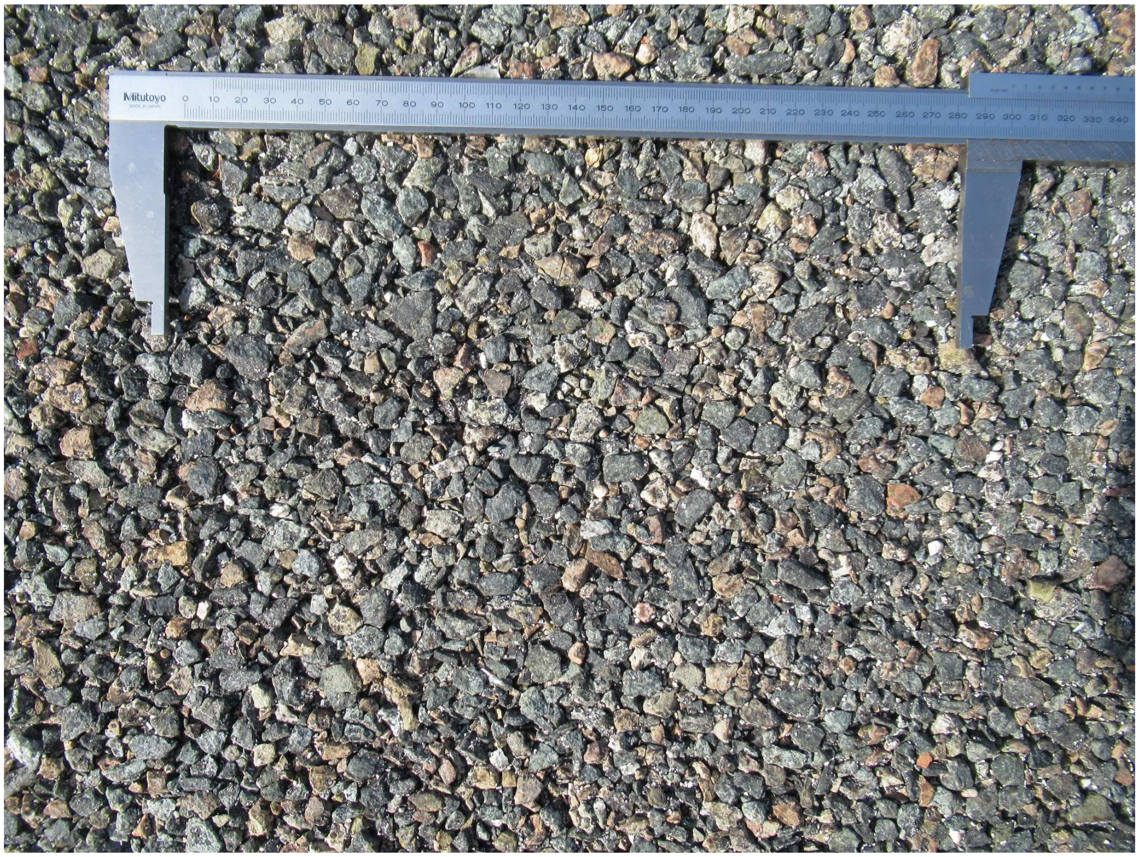
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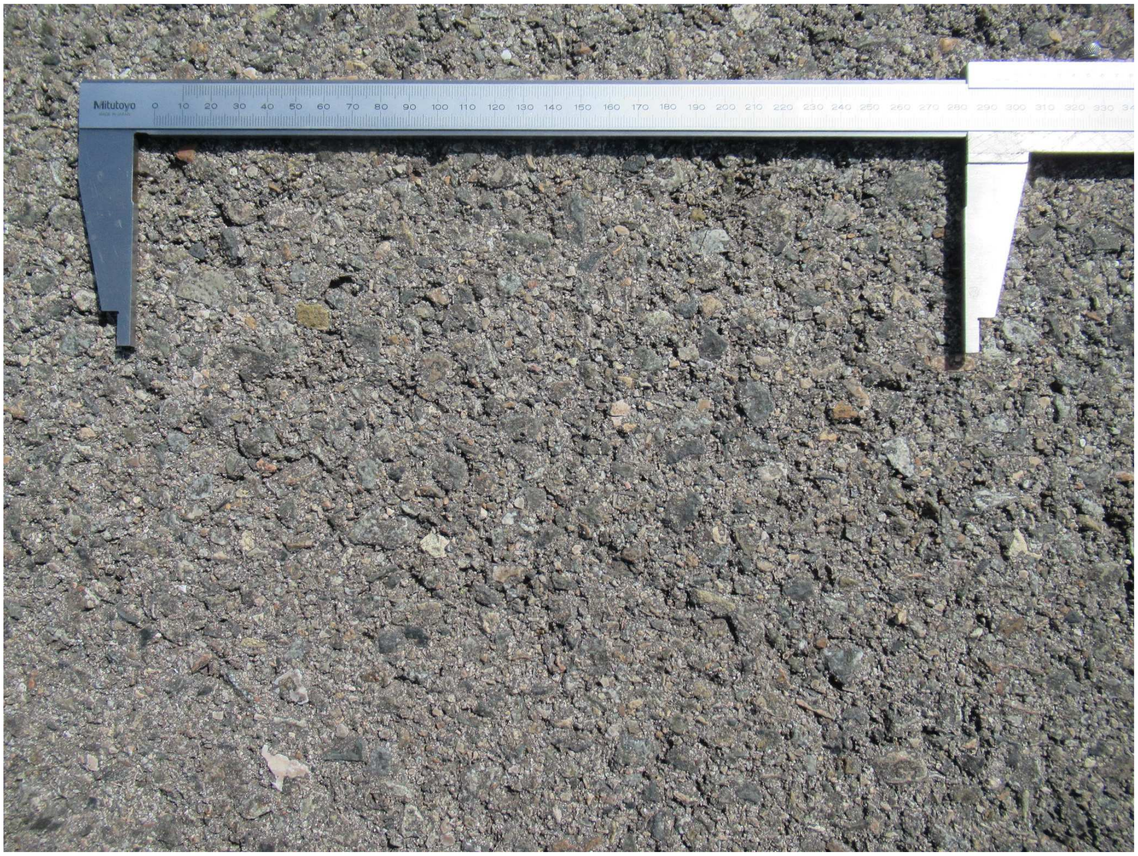


Figure 123. Examples of urban (upper), rural (lid) and motorway (lower panel) road surfaces

6.2. Test procedures

Mass and tread depth measurements were taken at the end of each loop. The instrumentation was identical with the one used for the accelerated proving ground tests.
The vehicle was also the same that was used for the proving ground tests fitted with four LinglLong 225/60R18 100V Batman A50 SUV tyres. The tyres were those that were used for test LL#1 in order to reduce the need of a run-in period. Nevertheless a run-in period of 500 km was done.
The standard (light) load was applied to the tyres. The weight at the front wheels was approximately 475 kg and at the rear wheels around 350 kg, with a total weight of 1644 kg. The tyre pressure was set to 240 kPa.

Standard load → Lightly loaded.

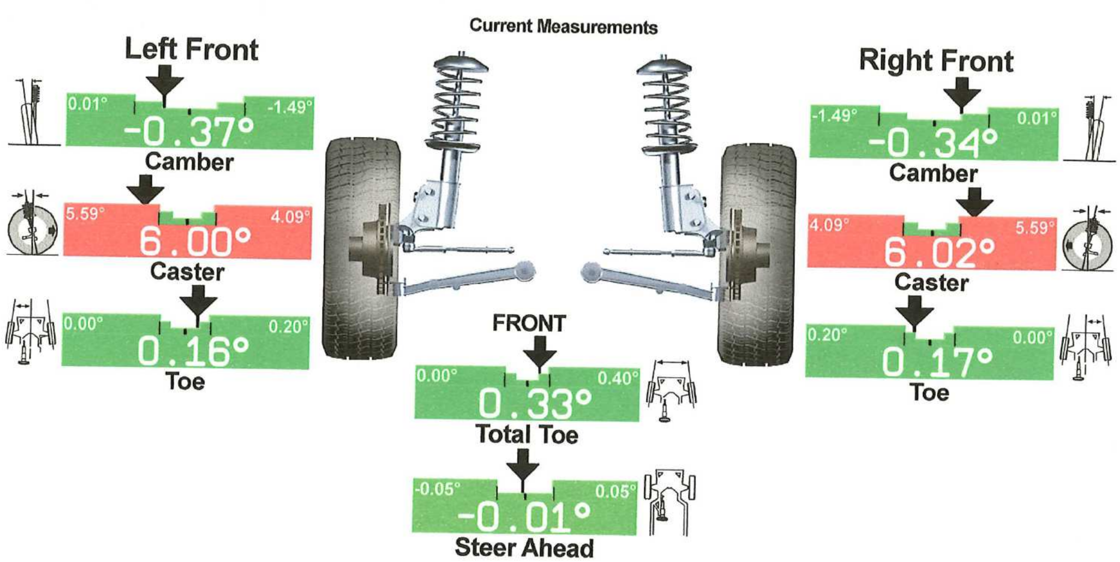
- Full fuel tank
- Added weight: 150 kg
  - Instrumentation
  - 1st row load → 150kg
- Weight
  - Front axel
    - Left tyre → 490 kg
    - Right tyre → 460 kg
  - Rear axel

  - Left tyre → 361 kg
  - Right tyre → 333 kg
- Total weight → 1644 kg

Tyre pressure → 240 kPa

Table 37. Vehicle alignment values.

		Target	**Measured**
Front axle			
Camber	Left	-0.74° (±0.75°)	-0.37°
	Right	-0.74° (±0.75°)	-0.34°
	Cross	0.00° (±0.75°)	0.04°
Toe	Left	0.10° (±0.10°)	0.15°
	Right	0.10° (±0.10°)	0.17°
	Total	0.20° (±0.20°)	0.33°
Caster	Left	4.84° (±0.75°)	*6.00*°
	Right	4.84° (±0.75°)	*6.02*°
	Cross	0.00° (±0.75°)	0.02°
Rear axle			
Camber	Left	-1.22° (±0.75°)	-1.41°
	Right	-1.22° (±0.75°)	-1.46°
	Cross	0.00°	0.06°
Toe	Left	0.19° (±0.20°)	0.16°
	Right	0.19° (±0.20°)	0.06°
	Total	0.38° (±0.20°)	0.22°
Geometrical driving axis		0.00° (±0.50°)	0.05°



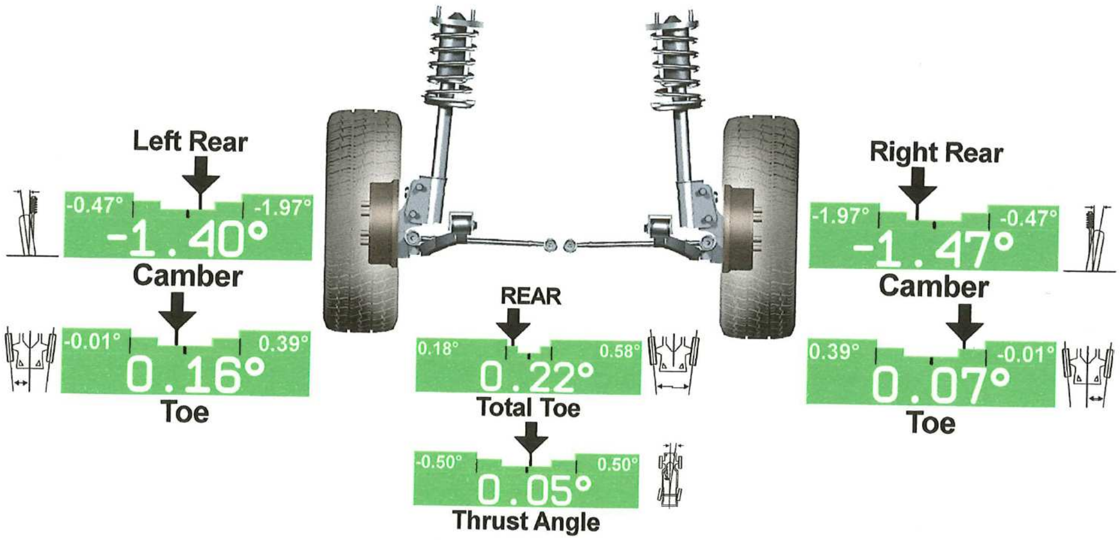


Figure 124. Vehicle alignment.

The accelerations were measured with PCAN GPS IPEH-002110 for Automotive (PEAK-System Technik GmbH) installed in the middle of the vehicle. The tyre temperatures were measured with sensors IRTS-120-V2 and IRTS-120-V3 from IZZE Racing (USA). The asphalt temperature was measured with an optical temperature sensor installed in the back of the vehicle. The ambient temperature was measured with a thermocouple installed on the top and right side of the vehicle. All the sensors are activated and start measuring when vehicle key is ON.

6.3. Results (on-road IDIADA)

The results with the LingLong Batman A50 SUV ATLAS M+S tyre with standard (light) load are presented in the following.

6.3.1. Ambient, asphalt and tyre temperature

Ambient temperatures during the abrasion test were:

- Maximum → 35.9 ºC.
- Minimum → 15.5 ºC
- Average → 24.4 ºC

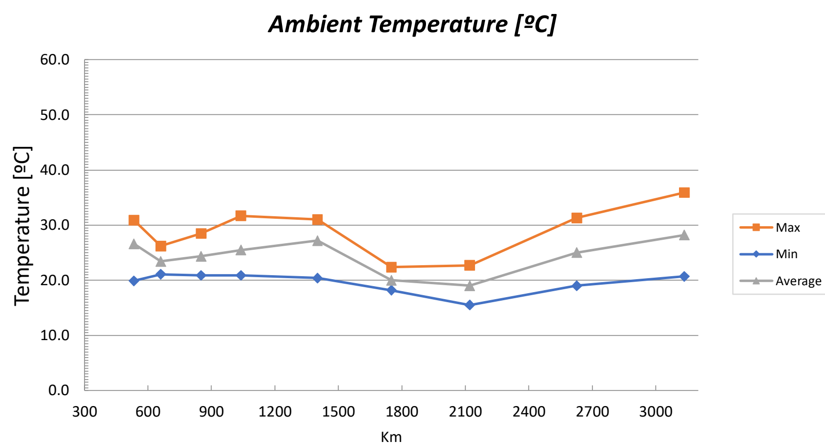


Figure 125. Ambient temperature – LingLong #1 tyre (on-road)

Asphalt temperatures during the abrasion test were:

- Maximum → 55.3 ºC.
- Minimum → 12.4 ºC
- Average → 34.7 ºC

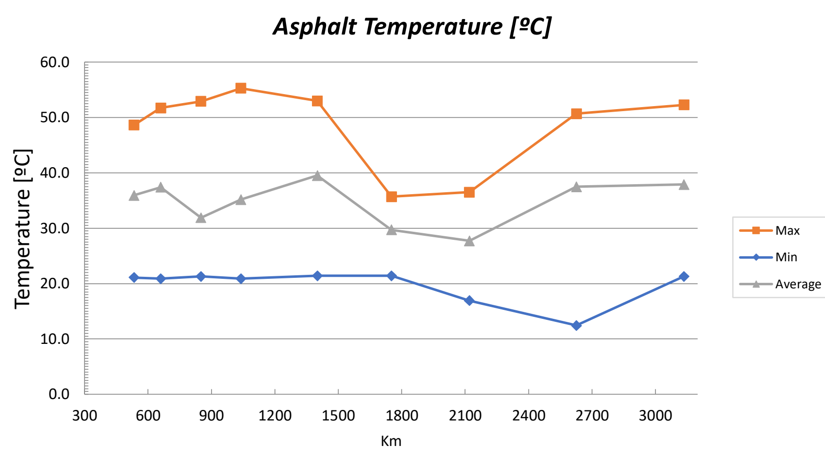


Figure 126. Asphalt temperature – LingLong #1 tyre (on-road)

Tyre tyres temperatures during the abrasion test were:

- Maximum → 52.0 ºC.
- Minimum → 15.4 ºC
- Average → 33.5 ºC

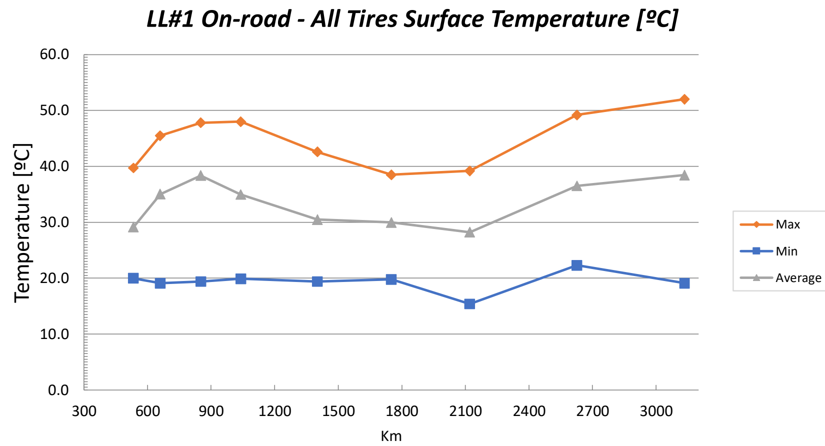


Figure 127. Tyres temperature – LingLong #1 tyre (on-road)

6.3.2. *Cumulative tyre abrasion*

The following figure plots the evolution of the tyre abrasion (grams) during the on-road test. That is,

- Run-in (534 km)
- Urban (until 1040 km)
- Rural (until 2121 km)
- Motorway (until 3135 km)

The LingLong tyre abrasion (Figure 128) was on average 62.6 g for the front wheels and 35.6 g for the rear wheels.

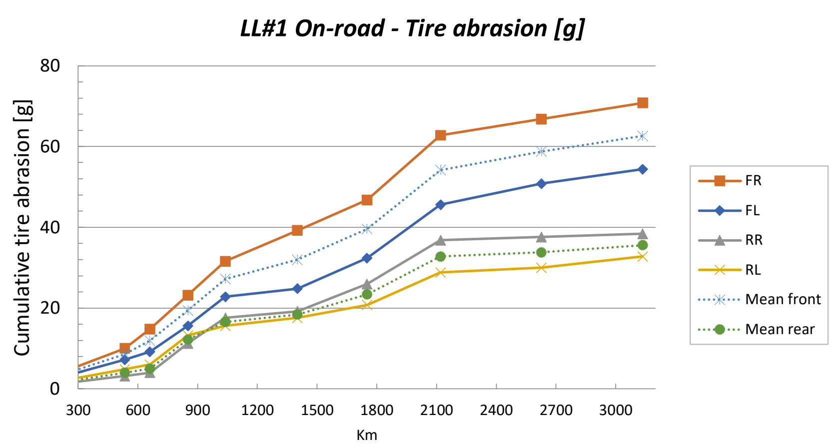


Figure 128. Tyre abrasion – LingLong tyre (on-road)

		Tyre Abrasion [g]		
		Left tire	Right tire	Mean
LL#1 On-road	Front axel	54.4	70.8	62.6
	Rear axel	32.8	38.4	35.6

Table 38. Tyre abrasion – LingLong #1 (on-road)

The tyre abrasion rate (Figure 129) was around 20 mg/km for the front wheels and 11.5 mg/km for the rear wheels.

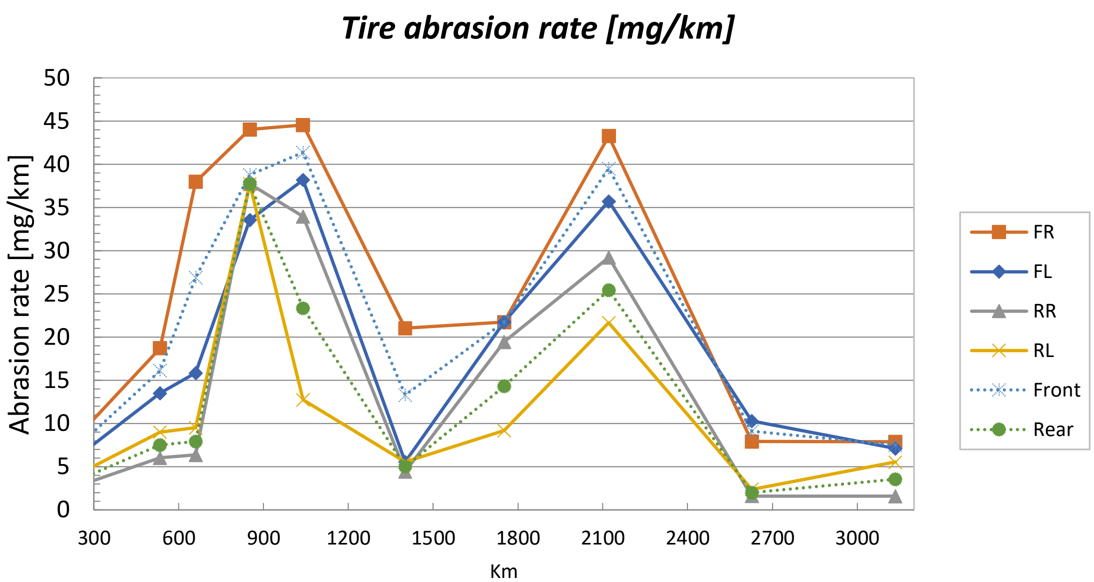


Figure 129. Tyre abrasion rate – LingLong #1 tyre (on-road)

	Tire Abrasion Rate [mg/km]								
	R1	T1-Ur	T2-Ur	T3-Ur	T1-Rur	T2-Rur	T3-Rur	T1-Mot	T2-Mot
Km	534.0	660.4	851.2	1039.7	1401.2	1751.0	2120.6	2626.6	3134.6
FR	18.7	38.0	44.0	44.6	21.0	21.7	43.3	7.9	7.9
FL	13.5	15.8	33.5	38.2	5.5	21.7	35.7	10.3	7.1
RR	6.0	6.3	37.7	34.0	4.4	19.4	29.2	1.6	1.6
RL	9.0	9.5	37.7	12.7	5.5	9.1	21.6	2.4	5.5
Mean Front	16.1	26.9	38.8	41.4	13.3	21.7	39.5	9.1	7.5
Mean Rear	7.5	7.9	37.7	23.3	5.0	14.3	25.4	2.0	3.5

Table 39. Tyre abrasion rate – LingLong #1 (on-road)

6.3.3. Other parameters

The tyres lost on average 0.2 mm tread after 3145 km. For a total available tread of 3.86 to 5.23 mm (until the legal 1.6 mm) this loss translates to an average total life of 75,000 km under such driving conditions, road and ambient temperatures.

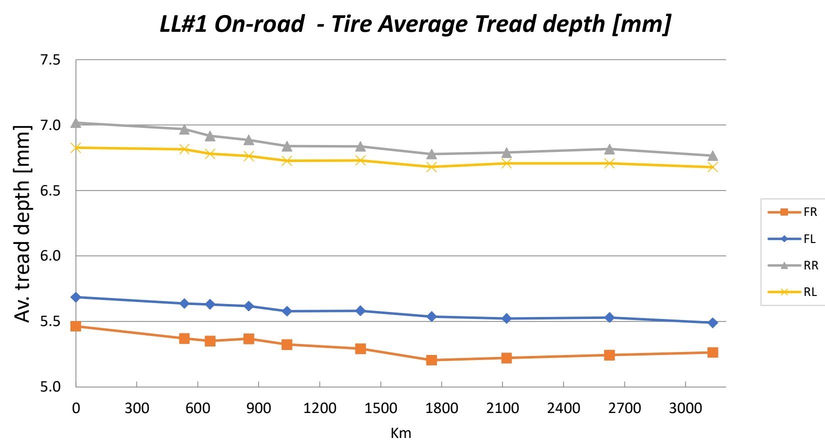


Figure 130. Tyre average tread depth – LingLong #1 (on-road)

	Total loss [mm]	Total Life [mm]	Loss [%]
FR set#1	0.20	3.86	5.2%
FL set#1	0.20	4.09	4.8%
RR set#1	0.25	5.42	4.7%
RL set#1	0.15	5.23	2.8%

Table 40. Tread depth reduction and remaining life – LingLong #1 (on-road)

The front tyres initial shore A hardness was around 58.5 and at the end of the abrasion test it was around 58. They had no significant variations during the abrasion test, as they were not new. For the rear tyres it started and remained at around 57.

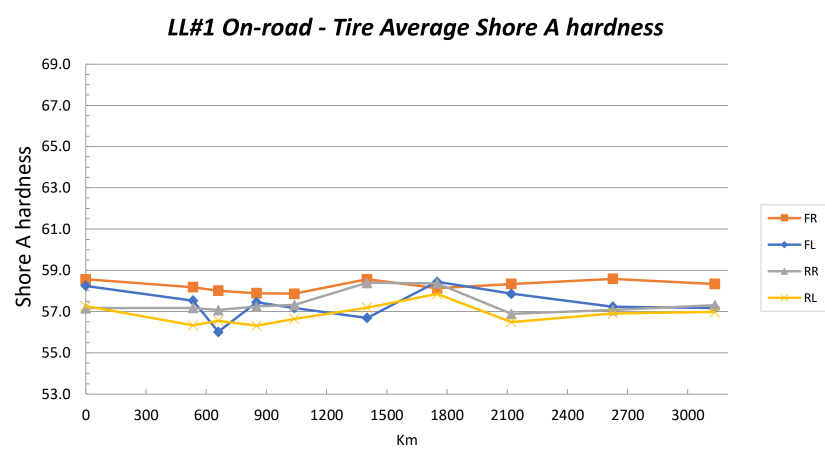


Figure 131. Tyre average shore A hardness – LingLong #1 (on-road)

7. On-road tests (LINGLONG)

The on-road tests at LINGLONG took place at Zhaoyuan city (China) at the end of March 2024. They consisted of a run-in phase, rural, urban, and motorway (or highway) parts. The vehicle was of similar characteristics as the one used by IDIADA.

7.1. Abrasion test

The abrasion tyre wear cycle had two different sections (procedures): run-in and tyre wear cycle. The run-in was 1000 km driving at motorway conditions (4 loops of 250 km) (see Table 41). The tyre wear cycle consisted of three separate parts in this order: rural (1000 km, 8 loops of 125 km), urban (1000 km, 25 loops of 40 km) and motorway (1000 km, 4 loops of 250 km) parts. The total mileage for the abrasion test is the sum of run-in and tyre wear cycles, 4500 km. Some of the characteristics of these cycles are presented in the following Table 41.

Table 41. Abrasion test. 4500 km per tyre: 1500 km motorway run-in and 1000 km tyre wear cycle consisting of separate urban, rural and motorway parts. The route from LingLong follows closely the requirements of ISO 18511-1.

Item / Road type			highway	Rural	Urban
Total mileage km			2500	1000	1000
Route					
Road surface			 	 	 
Mileage per loop km			250	125	40
Speed km/h		Max	120	80	60
		average	96	61	49
ISO 18511-1	STDEV. ay m/s^2	Range	[0.15, 0.80]	[0.70, 1.80]	[0.40, 1.20]
		Value	**0.38**	**0.70**	**0.56**
	STDEV. ax m/s^2	Range	[0.15, 0.55]	[0.20, 0.75]	[0.40, 0.90]
		Value	**0.27**	**0.46**	**0.86**

Figure 132. Road surface characteristics (urban, rural, motorway).

7.2. Tyre measurement procedures

Before starting each test and after finishing it, measurements were performed in order to characterise the evolution of mass loss and tread depth reduction of the tyres.

7.2.1. Instruments accuracy

The accelerations were measured with Drift-Box from Racelogic installed in the middle of the vehicle. The tyre and asphalt temperatures were measured with a temperature gun (Fluke, USA). Tyre shore A hardness test with BAREISS (Germany). The wheel alignment was checked with Hunter (USA) device.
The accuracy of the measuring instruments (see Figure 133) were the following:

- Tyre mass loss: The complete wheel and tyre weight was measured with an accuracy scale of ± 1 g.
- Tyre groove depth: Tread depth reduction was measured with depth gauge with accuracy of ± 0,1 mm.
- Tyre inflation pressure: Tyre inflation pressure was measured using a manometer with accuracy of ± 5 kPa.
- Tyre shore A hardness: Tyre shore A hardness was measured using a shore A hardness durometer with accuracy of ± 5.
- Air temperature and surface temperature: The temperature measuring devices was accurate within ± 1 °C.
- Tyre temperature: Tyre temperature was measured using a sensor with accuracy of ± 1 °C.
- Vehicle motion information: Accelerometer biaxial measuring lateral and longitudinal forces.
- Wheel alignment: Toe/Camber 0.02° and Caster 0.05°

Figure 133. Measurement instruments.

7.2.1. *Measurements procedures description*

7.2.1.1. Tyre weight measurement procedure

The steps to carry out the tyre weighing and tread depth measurements followed the procedure described at the accelerated test (Chapter 5). An overview is given in the below (Figure 134).

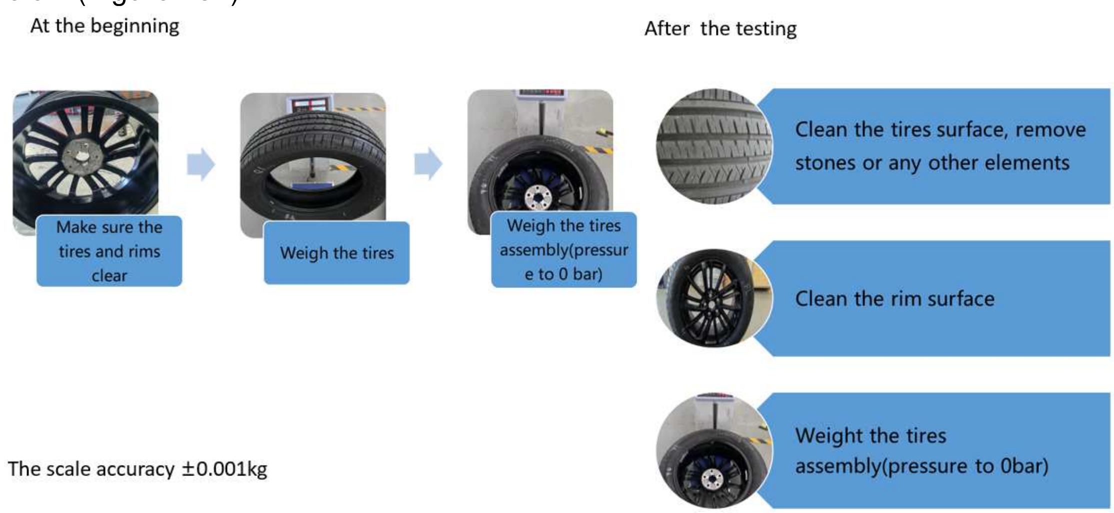


Figure 134. Tyres weighing procedure.

Tread depth was measured at the four main grooves along four equally spaced positions around the wheel Figure 135).

Figure 135. Tread depth measurements.

7.1. Tyre abrasion test plan

7.1.1. Test matrix

The complete test matrix and procedure is depicted below (Figure 136).

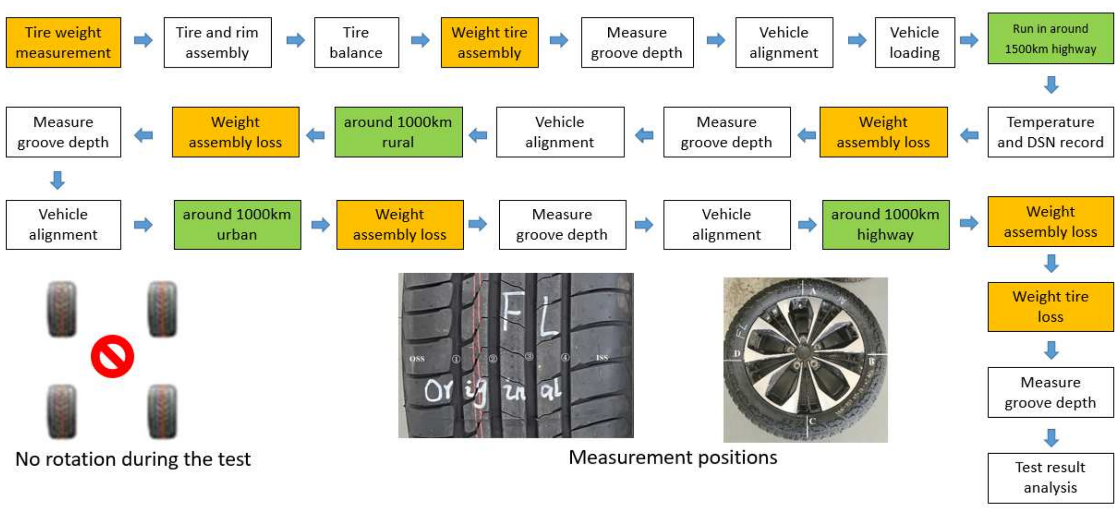


Figure 136. Test protocol.

7.1.2. Vehicle

The vehicle used for the tests was a front-wheel driven (FWD) SUV Geely Lynk&Co 06 fitted with four LinglLong 225/60R18 100V Batman A50 SUV tyres (Figure 137).

Figure 137. Vehicle: Geely Lynk&Co 06

Characteristics:

- Gasoline
- 1.5L in-line
- Front wheel drive (FWD)

Table 42. Vehicle alignment values

	Position	Target	Tolerance	Measure
Front axle				
Camber	Left	-0.58	±0.65	-0.65
	Right	-0.58	±0.65	-0.88
	Cross	0.00	±0.65	0.23
Toe	Left	0.05	±0.03	0.05
	Right	0.05	±0.03	0.05
	Total	0.10	±0.06	0.10
Rear axle				
Camber	Left	-0.45	±0.65	-0.95
	Right	-0.45	±0.65	-1.00
	Cross	0.00	±0.65	0.05
Toe	Left	0.05	±0.03	0.06
	Right	0.05	±0.03	0.06
	Total	0.10	±0.06	0.12

7.1.3. Vehicle load conditions

The standard (light) load was applied to the tyres. The weight at the front wheels was approximately 475 kg and at the rear wheels around 350 kg, with a total weight of 1654 kg (Table 43). The tyre pressure was set to 240 kPa.

Table 43. Load applied to the wheels

Load kg	FL	FR	RL	RR	Total
LINGLONG	496	457	364	337	1654

7.2. Results (on-road LINGLONG)

The results with the LingLong Batman A50 SUV ATLAS M+S tyre with standard (light) load are presented in the following.

7.2.1. Ambient, asphalt and tyre temperature

Ambient temperatures during the abrasion test were:

- Maximum → 22 ºC.
- Minimum → 4 ºC
- Average → 12.5 ºC

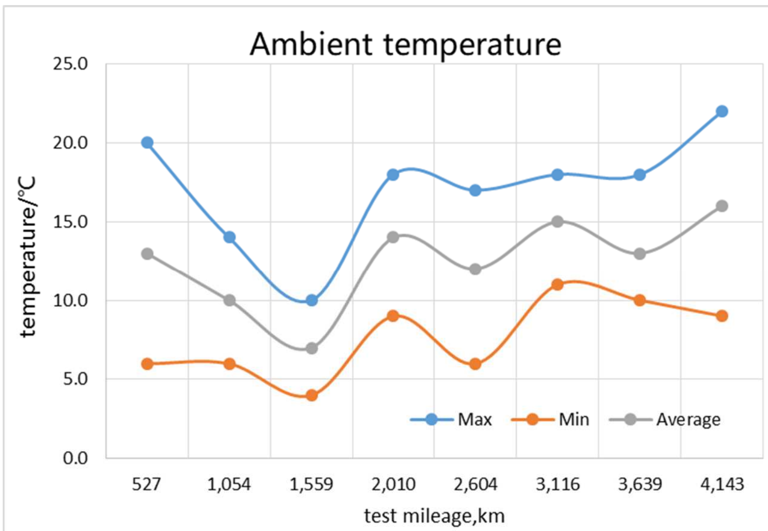


Figure 138. Ambient temperature – LingLong (on-road)

Asphalt temperatures during the abrasion test were:

- Maximum → 30 ºC.
- Minimum → 5 ºC
- Average → 15.4 ºC

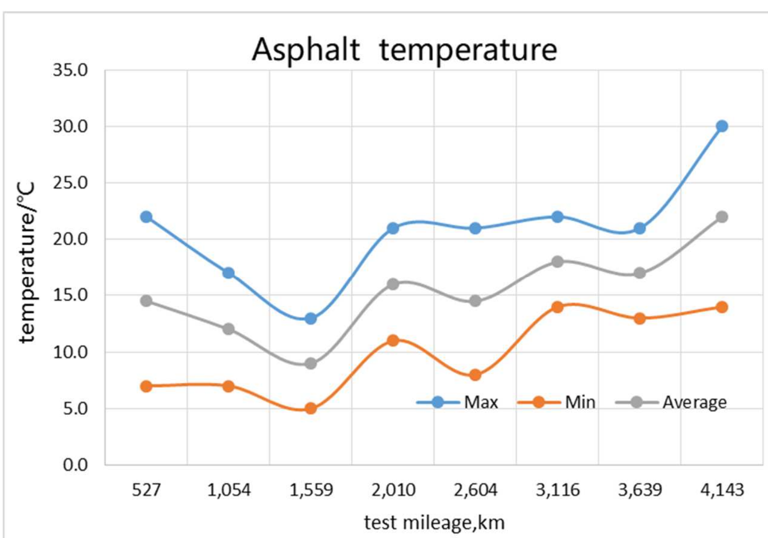


Figure 139. Asphalt temperature – LingLong (on-road)

Tyre tyres temperatures during the abrasion test were:

- Maximum → 32.5 ºC.
- Minimum → 5.3 ºC
- Average → 19.8 ºC

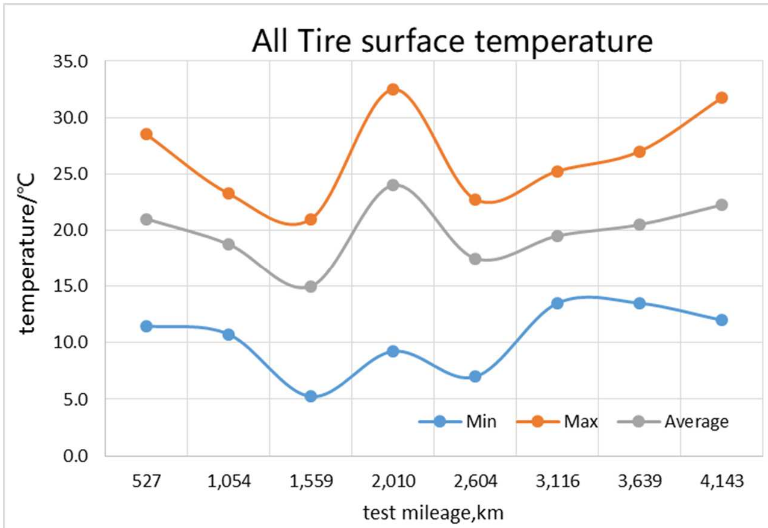


Figure 140. Tyres temperature – LingLong (on-road)

7.2.2. *Cumulative tyre abrasion*

In the following figure you can see the evolution of the tyre abrasion (grams) during the test define in Table 41. That is,

- Run-in (1559 km)
- Rural (until 2604 km)
- Urban (until 3639 km)
- Motorway (until 4143 km)

The tyre abrasion (Figure 141) was around 60 g for the front wheels and 30 g for the rear wheels. The exact values are given in Table 44.

Table 44. Tyre abrasion – LingLong tyre (on-road). Weight difference based on the tyre and wheel assembly or only the tyre.

Position	FR	FL	F	RR	RL	R
Assembly	65	56	60.5	32	31	31.5
Tyre	64	57	60.5	31	29	30.0

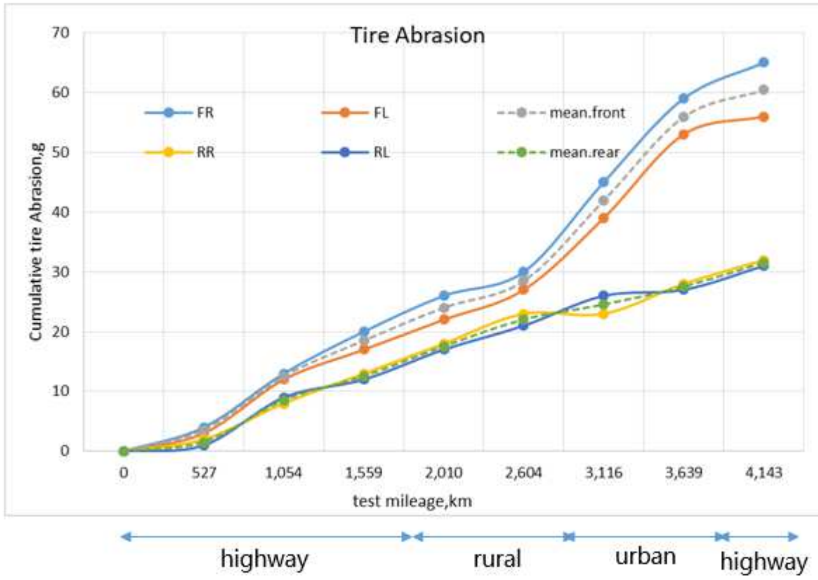


Figure 141. Tyre abrasion – LingLong tyre (on-road)

The abrasion rate per tyre (Figure 142) was around 10-15 mg/km for the front wheels for most tests except the urban part around 25-30 mg/km. For the rear tyres the abrasion rate was around 6-10 mg/km for the rear wheels. The exact values are given in Table 45.

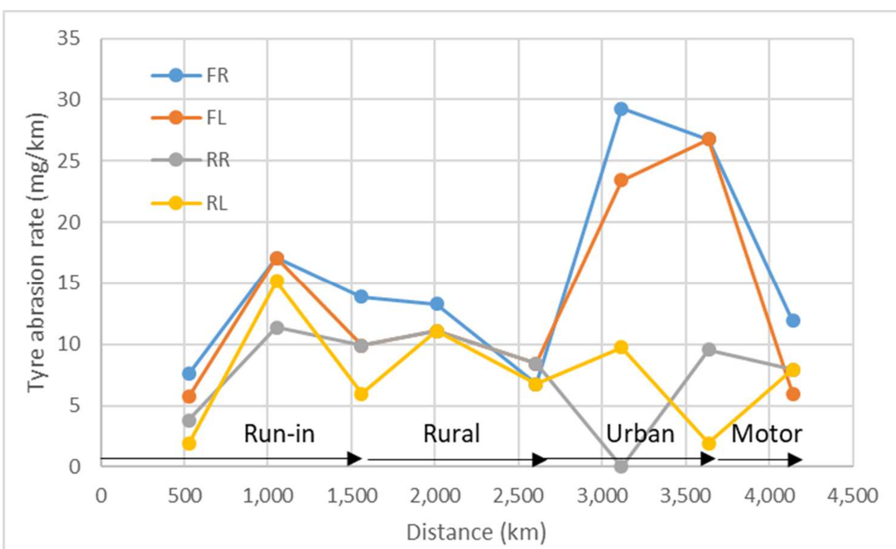


Figure 142. Tyre abrasion rate – LingLong tyre (on-road)

Table 45. Tyre abrasion rate – LingLong tyre (on-road)

position	FR	FL	Mean. front	RR	RL	Mean. rear
Abrasion rate mg/km	15.7	13.5	14.6	7.7	7.5	7.6

7.2.3. Other parameters

The tyres had a total life (mm) approximately 5.9 mm. We calculate these values in each tyre using the first tread depth minus 1.6 mm which is the minimum depth that a tyre should have [Total fife = first tread depth – 1.6 mm].

At the end of the abrasion test the front tyres loss between 2.26 mm and 2.02 mm and the rear tyres loss between 0.81 mm and 0.89 mm.

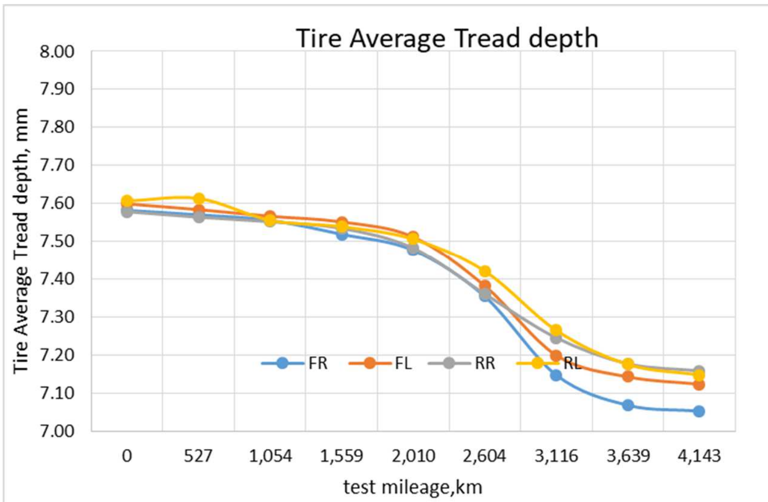


Figure 143. Tyre average tread depth - LingLong (on-road)

Table 46. Tread depth reduction and remaining life – LingLong (on-road)

position	Tread loss mm	Total life mm	Loss %	Life %
FR	0.53	5.98	8.8%	91.2%
FL	0.48	6.00	7.9%	92.1%
RR	0.42	5.98	7.0%	93.0%
RL	0.46	6.01	7.6%	92.4%

The initial shore A hardness was quite high around 65 and at the end of the abrasion test it was around 64.5 and had no significant variations during the abrasion test.

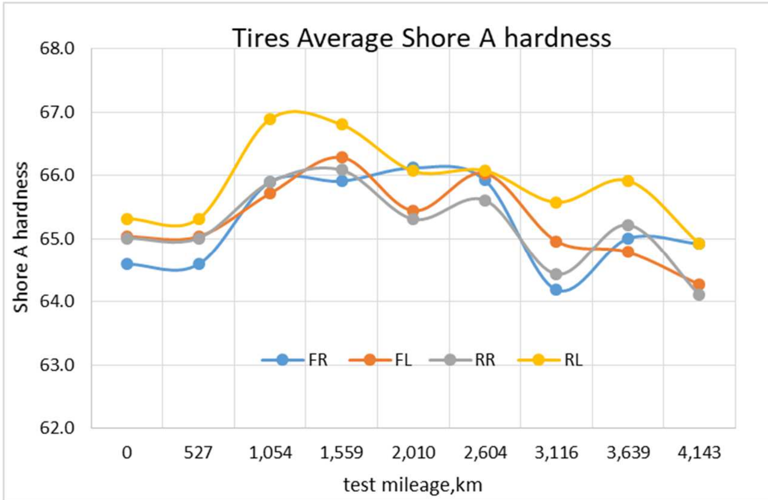


Figure 144. Tyre average shore A hardness - LingLong (on-road)

8. Run-in tests (FORD)

The run-in tests at FORD aimed in preparing the tyres for the PM/PN measurements.

8.1. Experimental (Run-in FORD)

Two different vehicles were used to run-in the tyres (Ford Transit Custom V362 and V710). On both vehicles, loads were installed to achieve the same front/rear axle weights. With a front load per corner of approximately 780 kg the relative load was 76% (LI=109) or 92% (LI=102) of the load index. There was a difference in the rear vehicle suspension design between these vehicles which was not relevant for the current project since the run-in was focusing on the front tyres.
The driving was conducted at the handling road in Lommel according to the speed limits (Figure 145). It is basically cornering all of the time. The temperatures in Lommel those days were approximately 4°C -16°C.

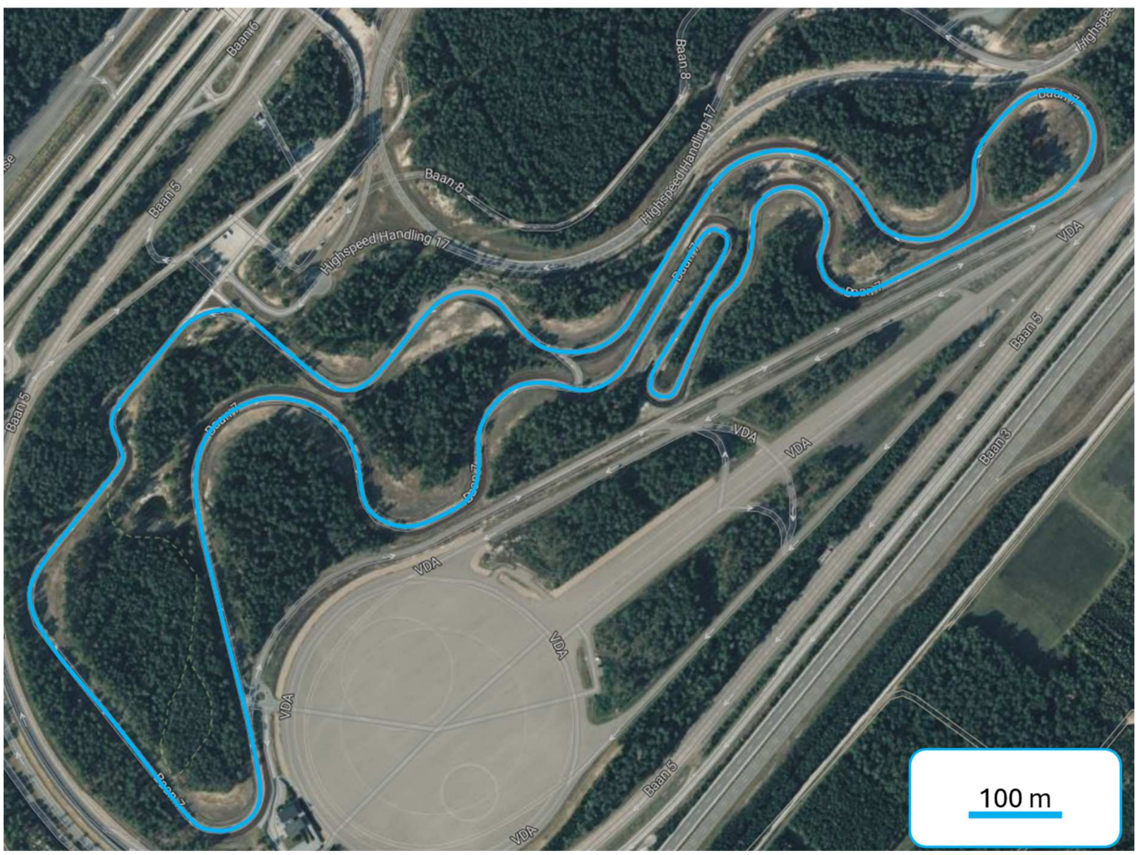


Figure 145. Handling track at Ford Lommel Proving Ground. Copyright Bing Maps/TomTom/Vecvel Imaging

Figure 146 gives an example of the road surface.

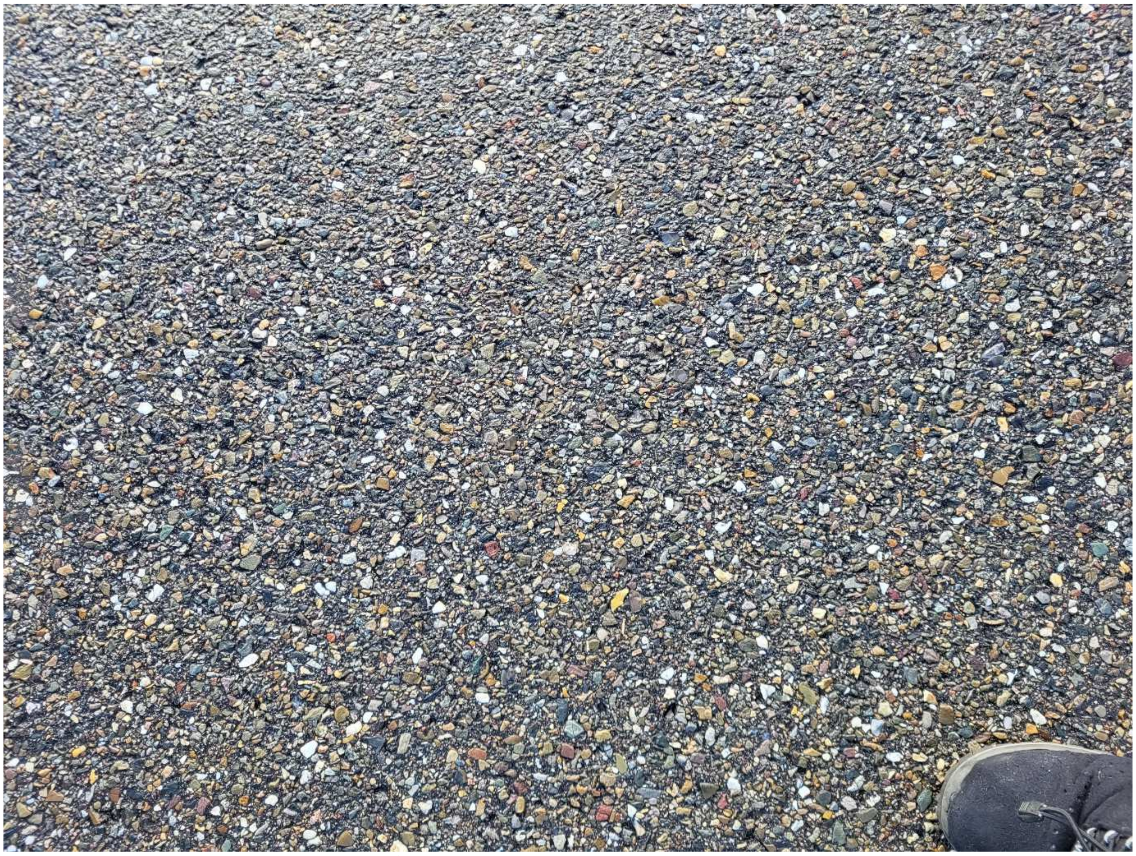


Figure 146. Example of road surface. Real dimensions approximately 88×66 cm.

The measurement procedure included measurement of tyre and rim weight and tread depth every 50 laps (around 250 km). The tread depth was measured at the three main grooves and the two tyre sides, whenever possible and four equally spaced locations around the wheel (Figure 147). The scale was a Gram Xtrem F1-30 HR with a maximum measurable weight of 30 kg at a resolution of 0.5 g. A digital tread depth meter from Vogel, Germany was used with a measurement range of 0-25 mm and a resolution of 0.01 mm.

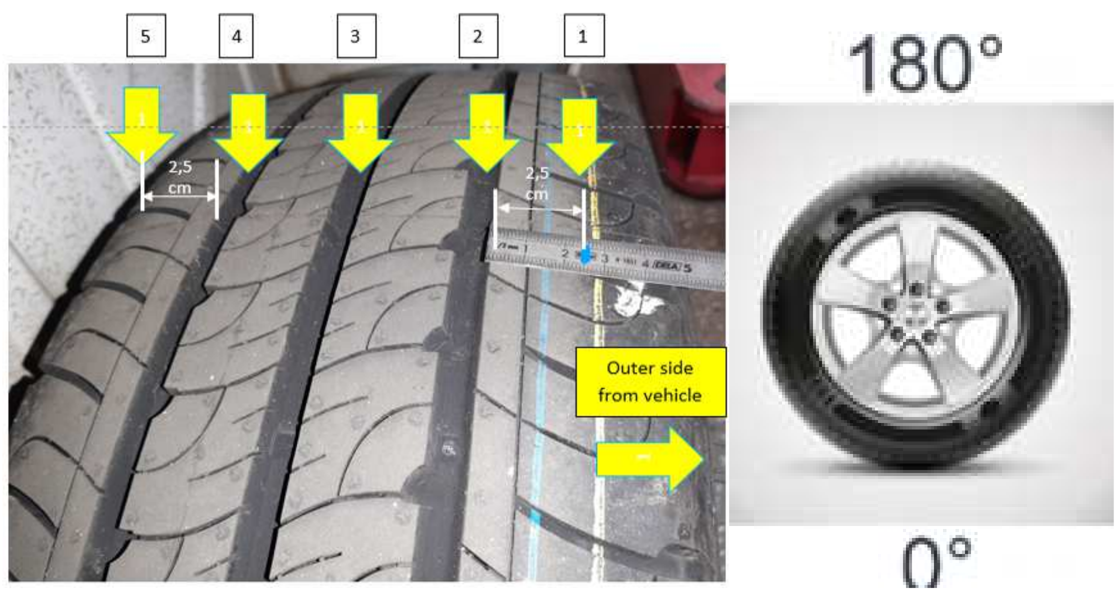


Figure 147. Tread depth measurements

8.2. Results (run-in FORD)

The results are summarised in the following tables (Table 47, Table 48), and as an example, Figure 148 plots the results of the Goodyear tyre.

Table 47. Mass loss (g) during run-in test (FORD)

	Front right	Front Left
Conti VanContact 4 Seasons (CO-V)	268	266
Conti Winter Contact (CO-W)	256	274
LingLong Green-Max (LL-G)	371	366
LingLong Tracer (LL-Tr)	302	-
Goodyear EfficientGrip (front) (GY-E)	274	255
Goodyear EfficientGrip (rear tyres)	136	108

Table 48. Tread depth reduction (mm) during run-in tests (FORD). 1=outer side from vehicle. When four values are given, they are from the four main grooves.

	Front Right					Front Left				
	1	2	3	4	5	1	2	3	4	5
CO-V	1.20	0.68	0.94	0.91	1.61	0.98	0.80	1.12	1.19	1.62
CO-W	1.05	0.99	1.06	1.58		1.08	0.98	0.95	1.34	
LL-G		1.02	1.02	1.23			1.13	0.97	1.45	
LL-Tr	1.77	1.09	0.72	1.16	1.87					
GY-E	0.23	0.13	075	0.52	0.31	0.37	0.48	0.91	0.64	0.53
(rear)	-0.14	0.32	0.37	0.27	0.32	0.55	0.48	0.67	0.60	0.33

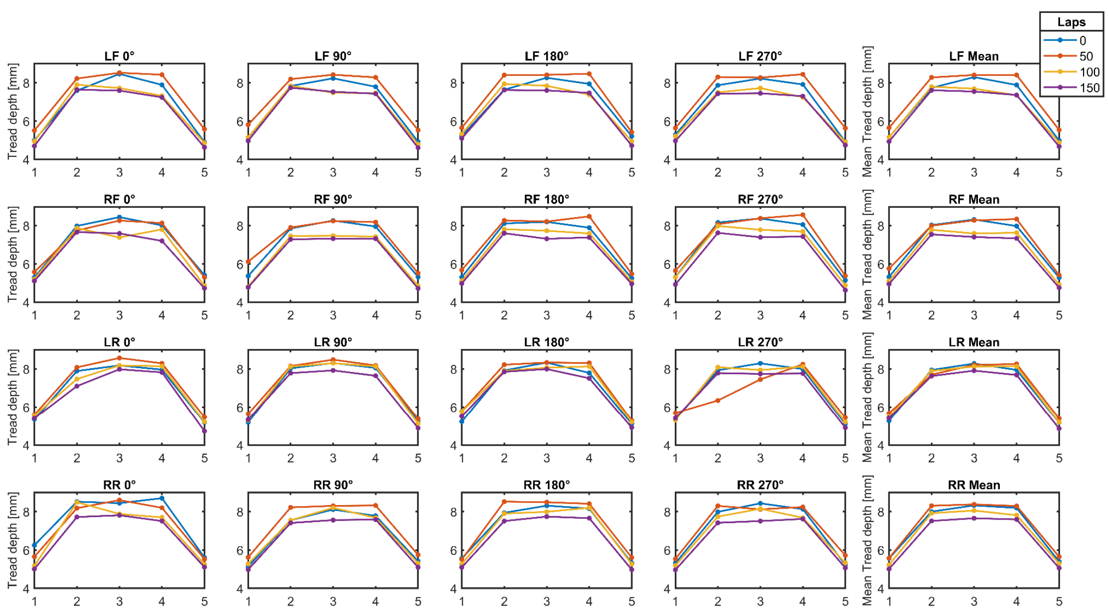


Figure 148. Example of tread depth measurements results (Goodyear).

9. Road simulator (VTI)

The tests at VTI aimed at characterising the PM/PN emissions of the tyres at different conditions (ambient temperature, dry/wet). Details can be found in **Deliverable 2.2**. Here only the basic information for mass loss and tread depth measurements will be presented.

9.1. Experimental (road simulator VTI)

The test were conducted at the road simulator of VTI. Mass loss and tread depth measurements were taken for the tyres of Table 5.
The road simulator consists of four wheels that run along a circular track with a diameter of 5.3 m as shown in Figure 149. A separate motor is driving each wheel and the speed can be varied up to 70 km/h. At 50 km/h an eccentric movement of the vertical centre axis is started to slowly undulate the tyres over the pavement track.
For the tests a cement concrete pavement ring was used. The ring was composed of 28 slabs with 7 different cement concrete mixes (four slabs each). The rock ballast had a maximum aggregate size fraction consisting of 11–16 mm rocks from three different quarries. The pavement macrotexture, expressed as mean profile depth (MPD), i.e. mean value of two peak values along a 100 mm distance, according to ISO 13473-1:1997(E), was between 0.5 mm and 0.85 mm for the 28 slabs, with a mean close to 0.7 mm.
During the test time the simulator hall was not ventilated. However due to the sampling instruments some air exchange was taking place (around 10% per hour). An internal air-cooling system was used to temperate the simulator hall.

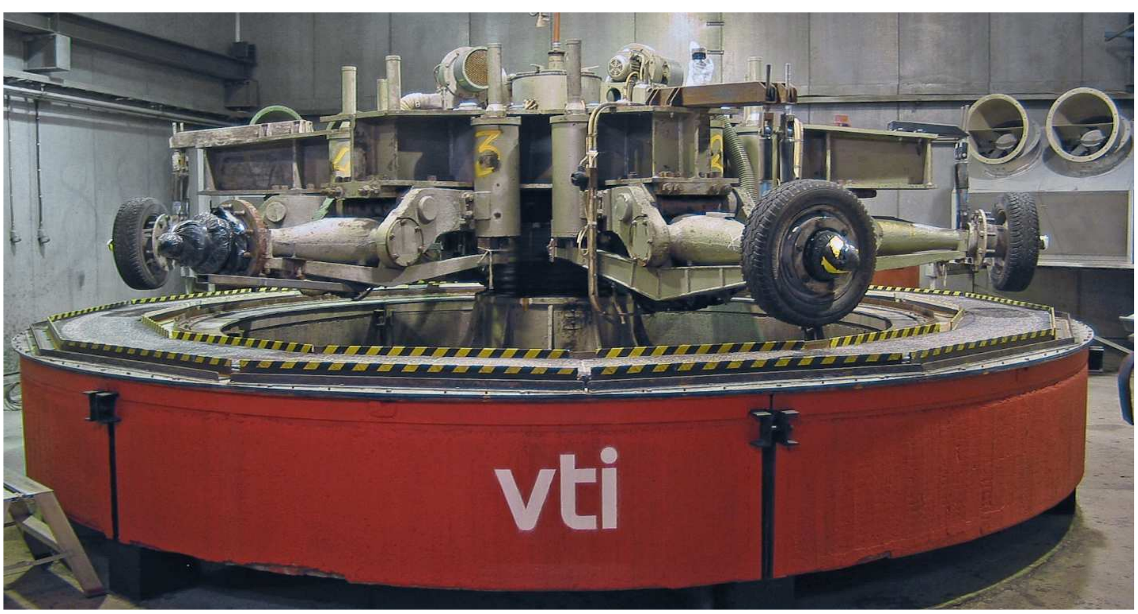


Figure 149. The road simulator of VTI.

Figure 150. Example of slabs surface.

9.1.1. Mass loss

The tyres were weighed according to the IDIADA protocol (Chapter 5) using a scale KERN 572 (linearity 0.3 g) (Figure 151 left). The air was removed from the tyres before weighing. Tyres were weighed both mounted and unmounted on rim. Unmounted tyres were weighed five times and a mean value was used. The rims were also weighed separately before tests.

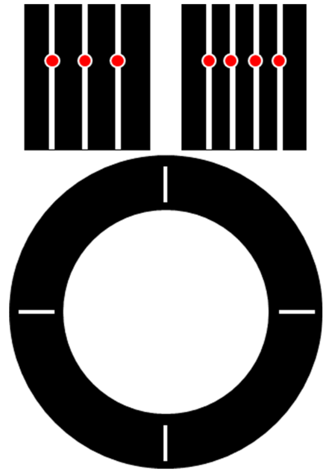


Figure 151. Right: Weighing of tyre with rim. Left: Tread depth measurement positions on the tyre and on the tread depending on 3 or 4 longitudinal grooves.

9.1.2. *Tyre tread depth*

Tyre tread depth was measured with a digimatic indicator (Mitutoyo IDU25). Tread depth was measured in four transects on each tyre. Depending on the number of longitudinal grooves, three of four measurements were used in each transect, resulting in 12 or 16 values per tyre (Figure 151 right).

9.1.3. *Tyre rubber hardness*

Tyre rubber hardness was measured using a Bareiss HPE III Basic device at four positions on the tyre. At each position, measurements were made in one point on the outer rib and one on an inner rib. Four values in each point were taken. Measurements were made before tests at a temperature of 18–20 °C.

9.2. Results (road simulator VTI)

The mass loss and tread depth reduction of all tests are summarized in Figure 152. There is no obvious correlation between mass loss and tread depth reduction. However, it should be emphasized that the reduction were very small and difficult to distinguish from experimental uncertainty.

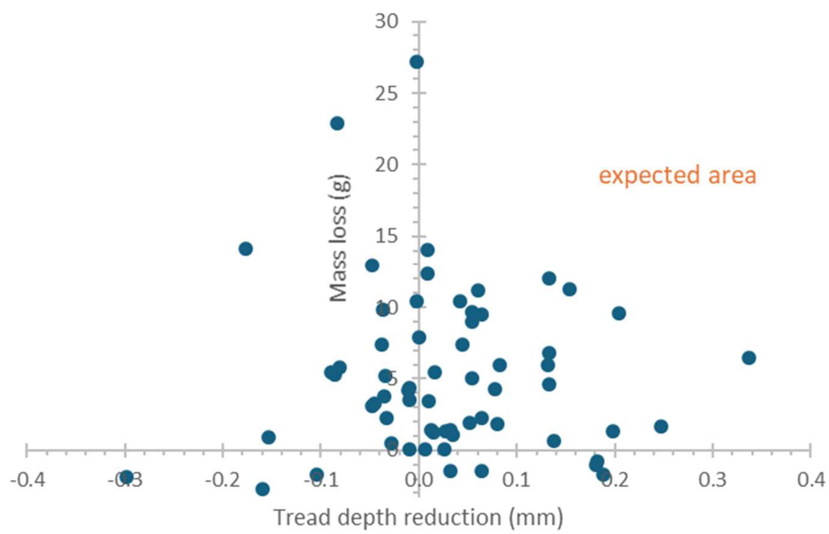


Figure 152. Mass loss versus tread depth reduction.

The influence of temperature on abrasion of the tyre sets, support that higher temperature results in more abrasion and higher mass loss (Figure 153). Also in these results it can be seen that tyres mounted on axles 2 and 4 abrades more than tyres mounted on axles 1 and 3. Within the tested temperature interval between -5 °C and +25 °C, mass loss of the tested winter tyre seems more sensitive to temperature changes than the summer tyre.

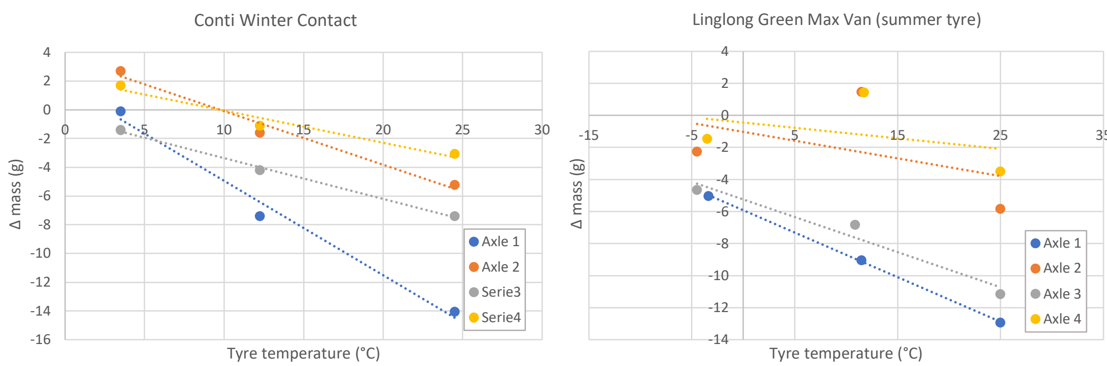


Figure 153. Δ mass loss for tyres on all road simulators axles as function of tyre surface temperature during temperature tests using the Continental winter tyres (left) and Linglong summer tyres (right).

10. Discussion

This chapter will combine the results of the previous tests at different laboratories.

10.1. Tyre hardness impact on abrasion

In general, softer rubber results in higher abrasion. Figure 154 plots tyre hardness measurements and tyre abrasion. The tyre hardness measurements were conducted at a temperature of around 20°C but the abrasion tests at different temperatures (10°C at the VTI road simulator and 9-29°C at IDIADA's accelerated tests). As the tests were different in terms of duration, severity and temperature range, the mass loss results were normalised to the mass loss of the least abrating tyre at each location. Furthermore, the proving ground abrasion results were normalised to the same temperature (20°C). Thus, abrasion ratio 1 means that the tyre has the same abrasion rate with the tyre that had the minimum abrasion of the specific set of tyres. There is no evident correlation between hardness and abrasion rate indicating that for different tyres other parameters are of high importance, as well.

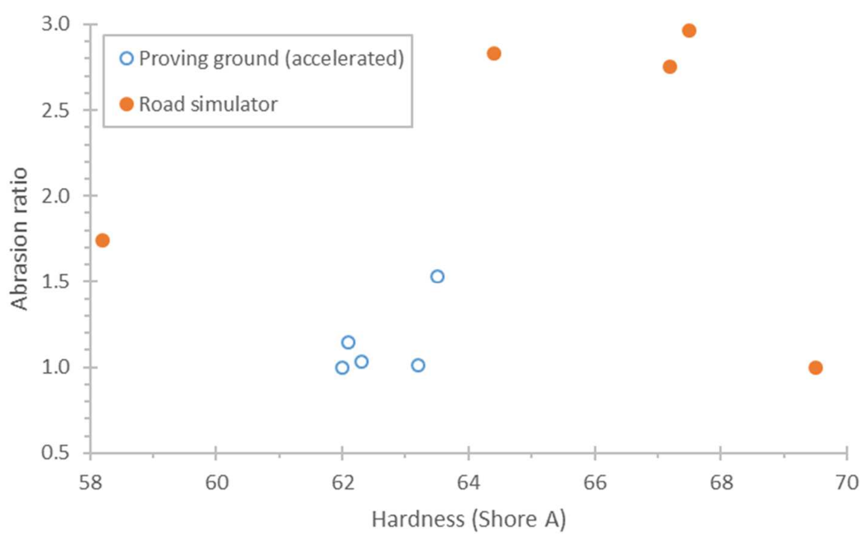


Figure 154. Tyre hardness and abrasion. Abrasion rates normalised to lowest emitting tyre per group: Accelerated tests at proving ground (tyres of Table 3) and road simulator (tyres of Table 5).

10.2. Load impact on abrasion

The impact of temperature on tyre abrasion was investigated on the proving ground (IDIADA). The two conditions are summarised in Table 49. It should be emphasized that also the tyre pressure changed from 2.4 bar at standard load to 2.5 bar at high load. This might have also influenced the mass loss due to different contact area. Nevertheless, the results indicate a linear relationship between load and mass loss. It should be added that the load was approximately 60% of the Load Index (LI) for the front axle tyres and 40% for the rear axle tyres.

Table 49. Overview of load tests (proving ground IDIADA).

	Standard	High	Load ratio	Mass loss ratio
Tyres pressure	2.4 bar	2.5 bar	-	-
Front axle	950 kg	976 kg	1.03	1.06
Rear axle	694 kg	892 kg	1.29	1.45
Vehicle	1644 kg	1868 kg	1.14	1.12

10.3. Temperature impact on abrasion

The impact of temperature on tyre abrasion was investigated on the road simulator (VTI) and the proving ground (IDIADA). As the tests were different in terms of duration, severity and temperature range, the mass loss results were normalised to the mass loss at ambient temperature of 9-10°C, which was the common temperature at the two locations. The normalised results are summarised in Figure 155. There is an increasing trend of mass loss with increasing ambient temperature. For the summer and M+S tyres the mass loss increase is 30% per 10° increase of ambient temperature. For the winter tyre the increase is 55%.

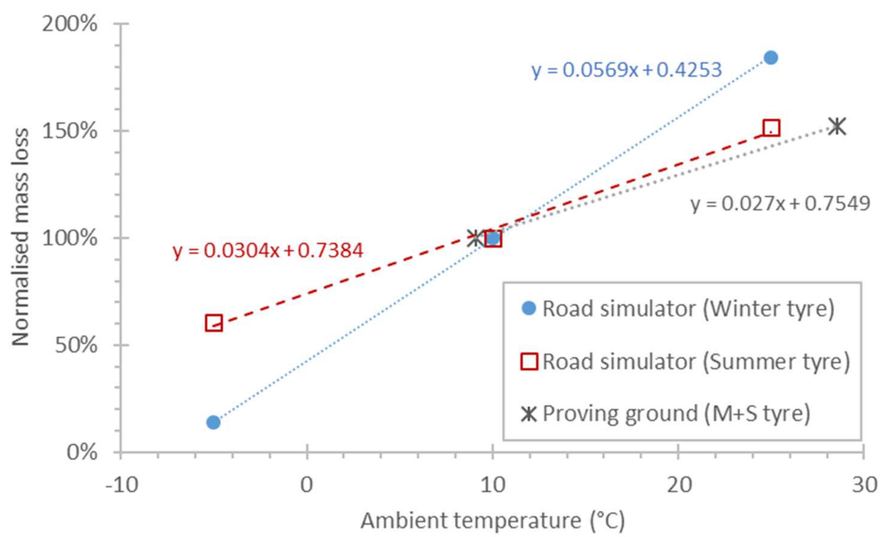


Figure 155. Impact of ambient temperature on tyre abrasion.
Tyre #1 (Winter): 215/65 R16 102H, Continental Winter Contact TS870
Tyre #2 (Summer): 215/65 R16C 109/107R, LingLong Green Max Van HP
Tyre #3: (M+S): 225/60 R18 100H, LingLong Batman A50 SUV ATLAS

Figure 156 summarises the accelerated wear results from the proving ground (left bars). As the measurements were conducted at different temperatures, the abrasion rates were normalised to 20°C, applying the impact of temperature of the LL tyre. The normalised results are plotted as right bars. The three tyres (MI, GY, DU) are near, the PI slightly higher, and LL much higher.

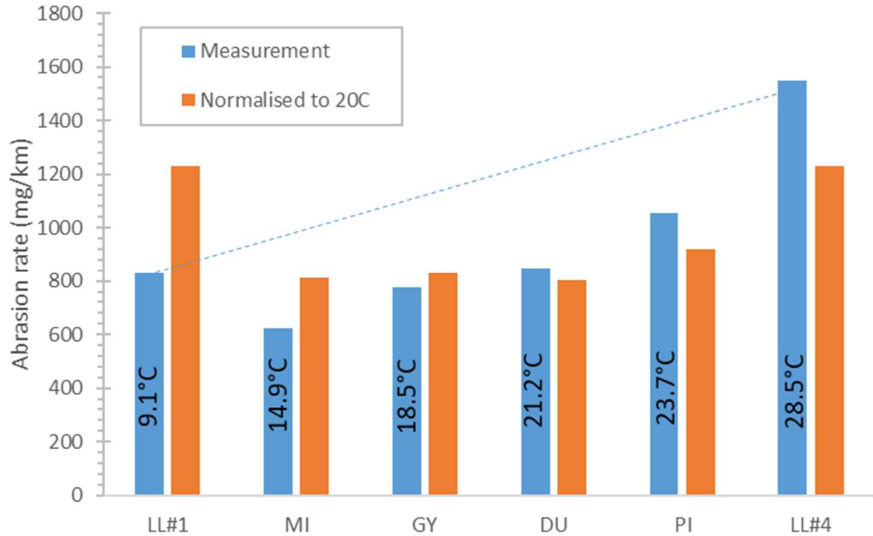


Figure 156. Impact of ambient temperature on tyre abrasion. Tests at proving ground (IDIADA). Tyres of Table 3.

With the same format the tread depth reduction is plotted in Figure 157. The normalised tread depth reduction is also given, calculated from the LingLong tyre difference.

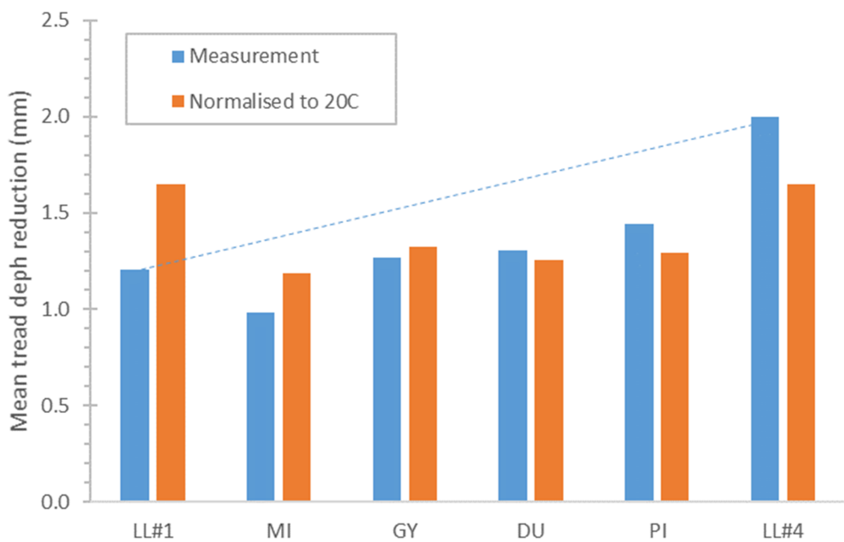


Figure 157. Impact of ambient temperature on tread depth (total distance around 3000 km). Tests at proving ground (IDIADA). Tyres of Table 3.

10.4. Wear contribution of front and rear axles

The contribution of the front wheels to the total wear is plotted in Figure 158. The front tyres contribute 65% at rural, 75% at motorway, and 85% at urban driving. The on-road tests at LINGLONG premises had percentages of 60%, 51%, and 83% respectively, while those at IDIADA 62%, 75%, and 60%.

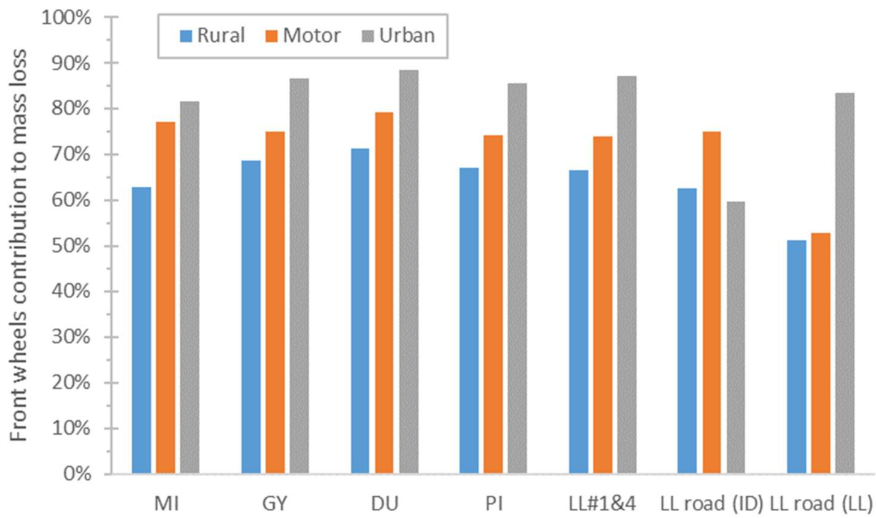


Figure 158. Contribution of front tyres to total wear Tests at proving ground (IDIADA), on-road at IDIADA and LINGLONG with the LL tyre. Tyres of Table 3.

The higher contribution of front tyres to total abrasion was also confirmed with the tread depth measurements. Figure 159 shows the results. The average percentages were around 65% for rural and motorway driving and 80% at urban roads. The on-road results at LINGLONG gave percentages of approximately 45-55%, while for IDIADA a wider range due to the very low tread depth reductions. Interestingly for some tyres (GY, DU, LL) the contribution at motorway was slightly lower than at rural, but the differences are small to draw any robust conclusions

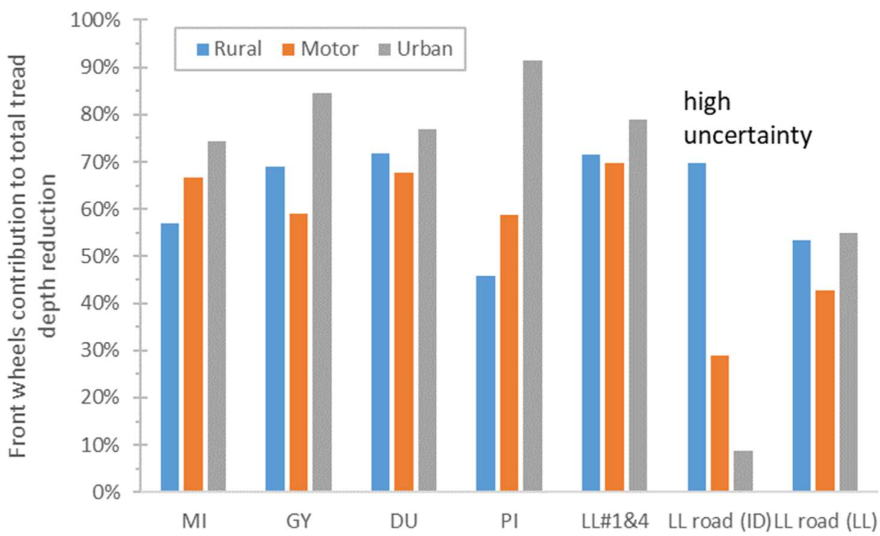


Figure 159. Contribution of front tyres to total tread depth reduction. Tests at proving ground (IDIADA) on-road at IDIADA and LINGLONG with the LL tyre. Tyres of Table 3.

10.5. Urban, rural and motorway wear

The normalised wear rate (in mg/km) of each urban, rural, and motorway parts are summarised in Figure 160 and the normalised tread depth reduction in Figure 161. For the accelerated tests the rural part had the lowest wear and was set to 1, while for the on-road tests the motorway part had the lowest wear and was set to 1. The high wear at the urban part is clear (×3.5-5 for mass, ×2-3.5 for tread) for the accelerated tests. The rural and motorway wear rates are closer to each other. It should be recalled that rural and motorway accelerated driving were conducted at the same tracks, while urban at a different with higher MPD. The on-road tests also had higher mass wear at the urban part, 2-5 times higher. For the on-road tests there is no info available for the surface of the roads. The tread wear gave extremely high values due to the very low wear of the tread at the motorway part, and thus has high uncertainty.

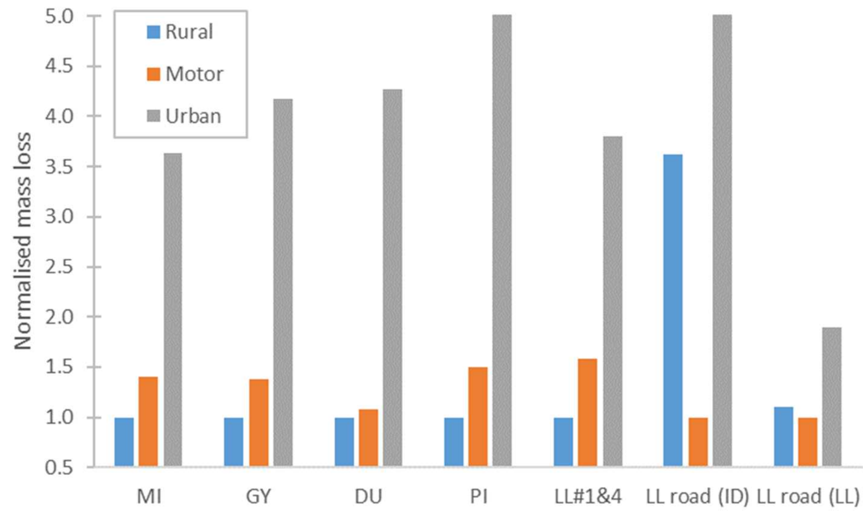


Figure 160. Normalised mass loss of the three parts: rural, motorway and urban. Tests at proving ground (IDIADA), on-road at IDIADA and LINGLONG with the LL tyre. Tyres of Table 3.

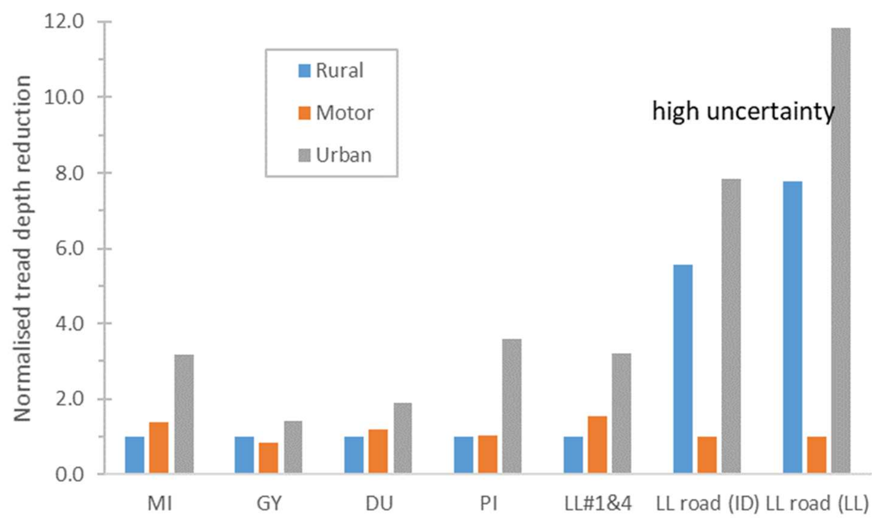


Figure 161. Normalised tread depth reduction of the three parts: rural, motorway and urban. Tests at proving ground (IDIADA), on-road at IDIADA and LINGLONG with the LL tyre. Tyres of Table 3.

10.6. Tyre life distance

The tyre life distance (M) can be estimated from the initial tread depth (T), the minimum allowed in the regulation (1.6 mm), and the tread depth reduction (R) during a test of distance (D) (see Equation 8 and Figure 162).

$$\text{tangent } \theta = D / R = M / (T - 1.6) \text{ or}$$

$$M = D / R\ (T - 1.6)$$

Equation 8. Theoretical estimation of tyre mileage based on tread depth measurements.

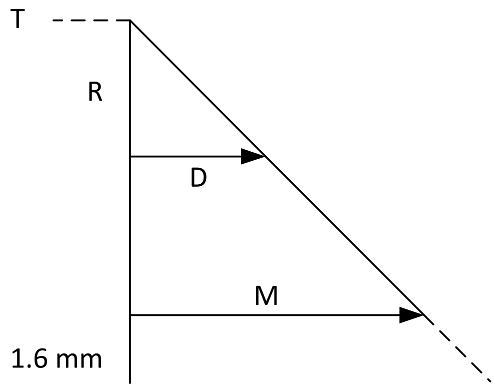


Figure 162. Theoretical estimation of tyre mileage based on tread depth measurements.

A similar approach is followed for the determination of the treadwear Uniform Tire Quality Grading (UTQG) in the United States[3]. The estimated tyre life (M) (average of the four tyres) vs treadwear Uniform Tire Quality Grading (UTQG) of the tyres tested is plotted in Figure 163. It should be mentioned that the estimated distance is low because it is based on the accelerated wear method. For example, the LL tyre had estimated distance of 12,000 km in the proving ground but 53,000 to 94,000 km on the road. There is no obvious correlation between the two methods.

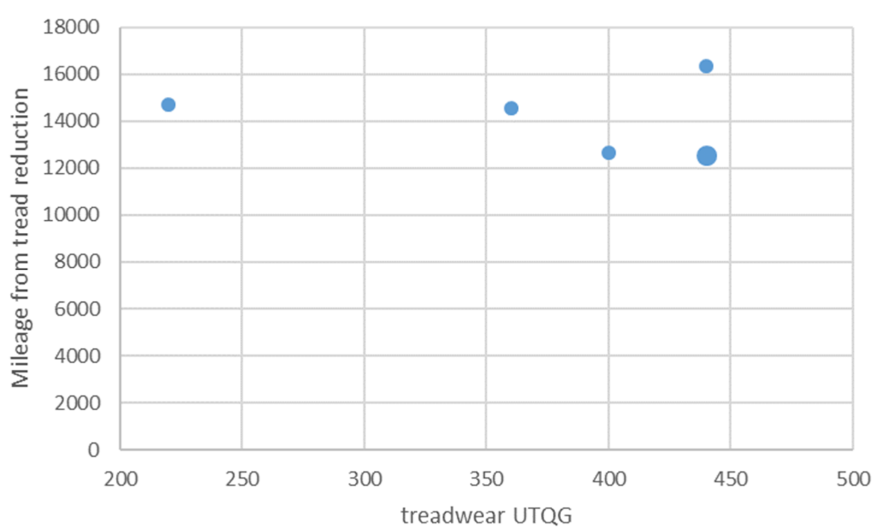


Figure 163. Theoretical estimation of tyre mileage based on tread depth measurements of accelerated tests vs treadwear Uniform Tire Quality Grading (UTQG). The large circle is the average of the LL tyre (#1, #3, #4).

[3] CFR (Code of Federal Regulations) 49 CFR § 575.104 - Uniform Tire Quality Grading Standards. Available on Line at: https://www.law.cornell.edu/cfr/text/49/575.104

10.7. Tread depth reduction

The tread usually wears equally at the main groves. To assess the normality the variation (one standard deviation) from the mean tread depth reduction of the three or four main grooves was calculated and is plotted in Figure 164. The variation is typically 5-15% with a mean around 10%. Higher values were measured with one tyre at the accelerated tests at the proving ground (left panel) and with most tyres of the run-in tests (right panel). There was no particular trend of which groove was wearing more (internal side or external side of the vehicle). Very high values (35%) were measured at the on-road tests at IDIADA due to the low tread depth that was reduced during the tests.

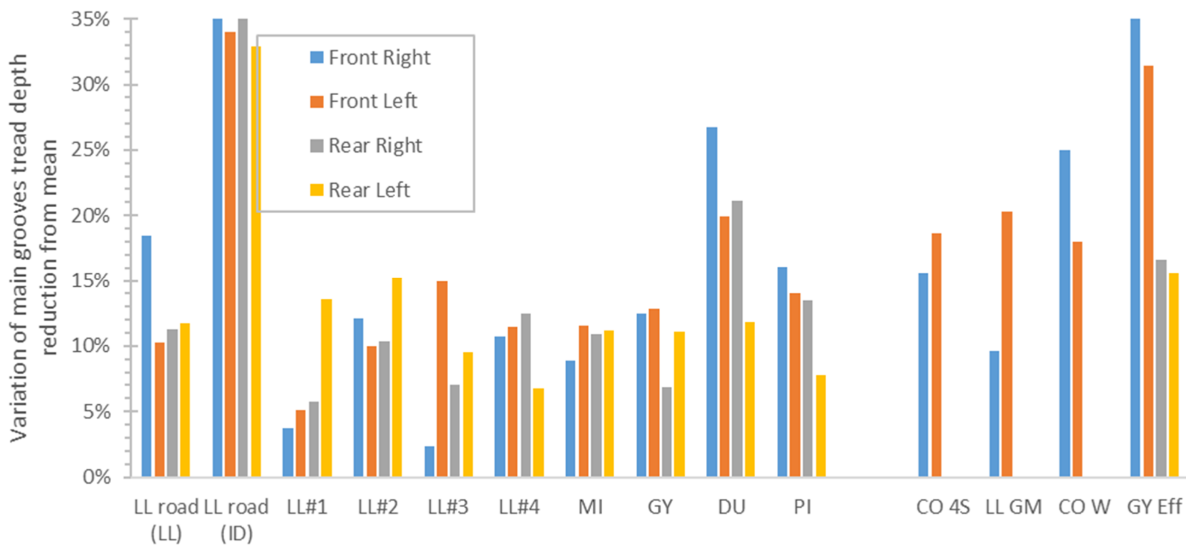


Figure 164. Variation from mean (coefficient of variance) of the three or four main grooves tread depth reduction. Tyres of Table 3 on the left tested on-road and at the proving ground (accelerated tests) (IDIADA) and tyres of Table 5 on the right tested at the handling road during run-in tests (FORD).

For the proving ground, the average tread wear ratio of right to left tyre was 0.92 for both front and rear axles. The higher tread wear of the left tyre can be attributed to the direction of the tests. For the run-in tests the ratio was also similar (results available mainly for the front axle).

10.8. Tread wear reduction vs. mass loss

Figure 165 plots mass loss versus tread depth reduction for each tyre of the 225/60 R18 LingLong Batman A50 SUV Atlas (Table 3). The slope of each trendline gives the mass loss per mm of tread depth reduction. The front tyres lose around 300 g/mm, while the rear tyres 200-250 g/mm. The load at the rear tyres was around 40% of the max load, while for the front tyres around 60%. The different load might have impacted the contact area, and thus the material lost per mm.

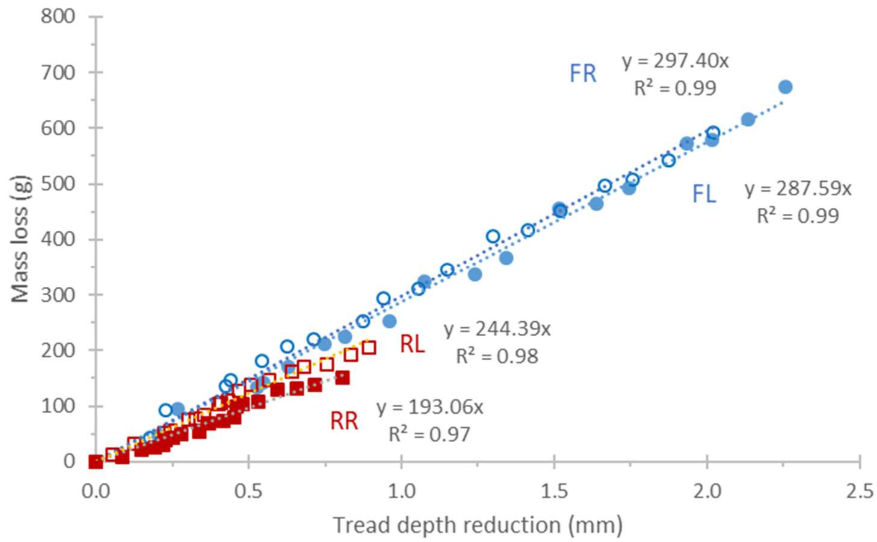


Figure 165. Correlation of tread depth reduction and mass loss per tyre. Example of 225/60 R18 LingLong Batman A50 SUV Atlas.

Another example is given in Figure 166 (225/60 R18 Michelin Pilot Sport 4 SUV). The wear rates are around 260 g/mm for the front tyres and 150 g/mm for the rear tyres. In addition to the front-rear tyres difference, there are differences between the two brands. Parameters such as contact area, void area, tread density affect the results. For the specific tyre, the difference between run-in (around 0.6 mm) and the subsequent testing is evident.

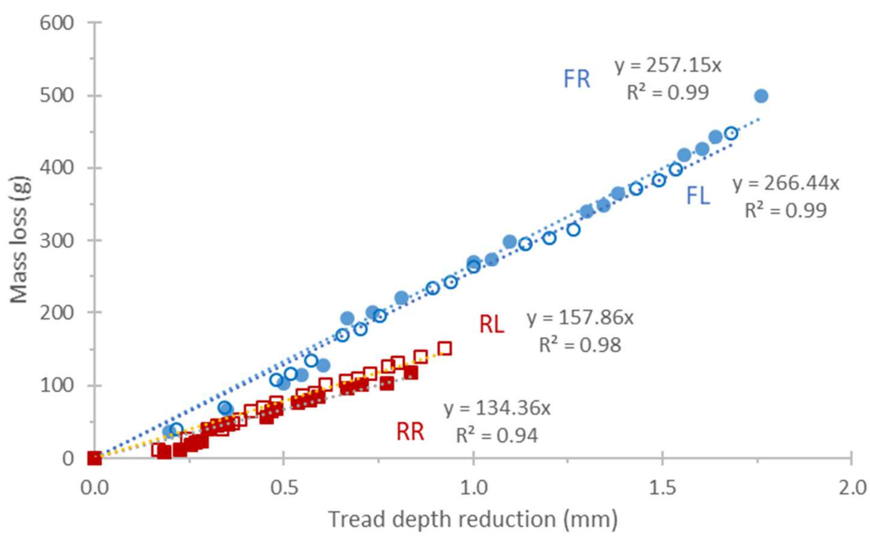


Figure 166. Correlation of tread depth reduction and mass loss per tyre. Example of 225/60 R18 Michelin Pilot Sport 4 SUV

Table 50 summarises the proving ground accelerated wear results for all tyres. The average wear loss is 306 mg/mm for the front tyres and 198 mg/mm for the rear tyres. The on-road wear rate with the LingLong tyre was 120 g/mm and 72 g/mm respectively at LINGLONG and 317 g/mm and 187 g/mm respectively at IDIADA.

Table 50. Mass loss per mm of tread reduction. Accelerated method with tyres of Table 3.

	FR	FL	RR	RL
Linglong #1	298	293	188	230
Linglong #2	364	328	309	260
Linglong #3	283	269	210	189
Linglong #4	327	313	234	201
Michelin	284	266	141	163
Goodyear	304	299	180	174
Dunlop	327	316	142	162
)0388 Pirelli	311	316	181	211
LL on-road (LL)	123	118	76	68
LL on-road (ID)	354	279	152	221

10.9. Abrasion rates

Table 51 gives an overview of the tests and conditions regarding mass loss and tread depth reduction.
Although not investigated in detail, the first 500 km seem to have different behaviour compared to the rest. This is based on the on-road tests with the LL tyre at LINGLONG and IDIADA, where the wear rate seemed more stable after 500 km and comparable with the last 500 km driving at the same roads.

Table 51. Wear levels of tyres under different protocols.

Lab	Location	Test	Ch.	Tyres	MPD [2]
IDIADA	Proving ground	Accelerated tests	5	Table 3	0.54-0.87 mm
IDIADA	Proving ground	Accelerated tests	5	LL [1]	0.54-0.87 mm
IDIADA	On-road	Normal driving	6	LL [1]	n/a
LINGLONG	On-road	Normal driving	7	LL [1]	n/a
FORD	Handling road	Cornering (run-in)	8	Table 5	n/a
VTI	Road simulator	70 km/h	9	Table 5	0.7 mm

[1] From Table 3.
[2] Mean profile depth (MPD)

Location	% of Load Index	Temp	DSN	Tread reduct. (mm_T/1000km)	Mass (mg_V/km) RI/U/R/M
Proving gr.	43-60%	15-24	20-122	0.44-0.60	185/1567/362/484
Proving gr.	43-60%	9-29	20-122	0.51-0.79	254/2170/557/752
On-road	43-60%	24	4-42	0.114	47/123/80/22
On-road	43-60%	14	5-17	0.063	40/64/37/34
Handling	76-92%	4-16	n/a	0.68-1.52	1000-1400 (run-in)[1]
Road sim.	53-65%	-5-25	n/a	0.056 [2]	31 [1,2]

[1] assuming 70% contribution of front tyres.
[2] Average of all tests

The normalised abrasion rates to the wear index reported in tyre reviews web site[4] is plotted in Figure 167. The tests data are based on Tyrereviews.com, ADAC, Autobild and Auto Zeitung testing, however the details are not disclosed. Higher percentage

[4] www.tyrereviews.com

indicates lower wear and longer tyre life. There is some correlation, but rather poor. It should be emphasised that the wear indices were sometime average of similar types of tyres as the exact models were not always available.

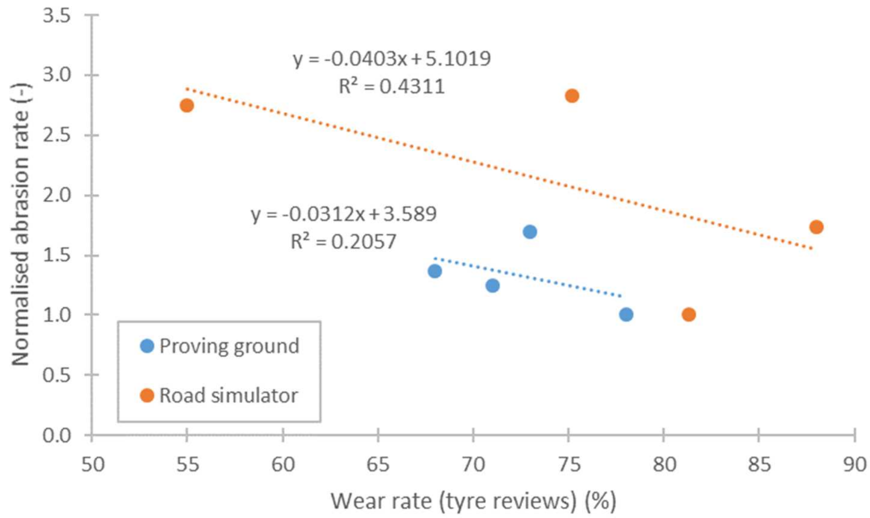


Figure 167. Correlation of normalised abrasion rate with wear index of tyre review web site. Note that high wear index corresponds to less wearing tyre.

Figure 168 plots the abrasion rate for the LL tyre of Table 3 measured at the proving ground with the accelerated method, and on the road at the IDIADA and LINGLONG premises (Spain and China respectively). The same tyre had values from 20 mg/km up to 120 mg/km on the road but 10 times higher with the accelerated method. The higher the DSN, the higher the abrasion rates, but the correlation is not so good. The road surface plays also an important role. The accelerated tests are much higher even with similar DSN in some cases.

These findings do not support an accelerated method to estimate real world abrasion rates. Furthermore, in order to have comparable results between different locations, a reference tyre is necessary.

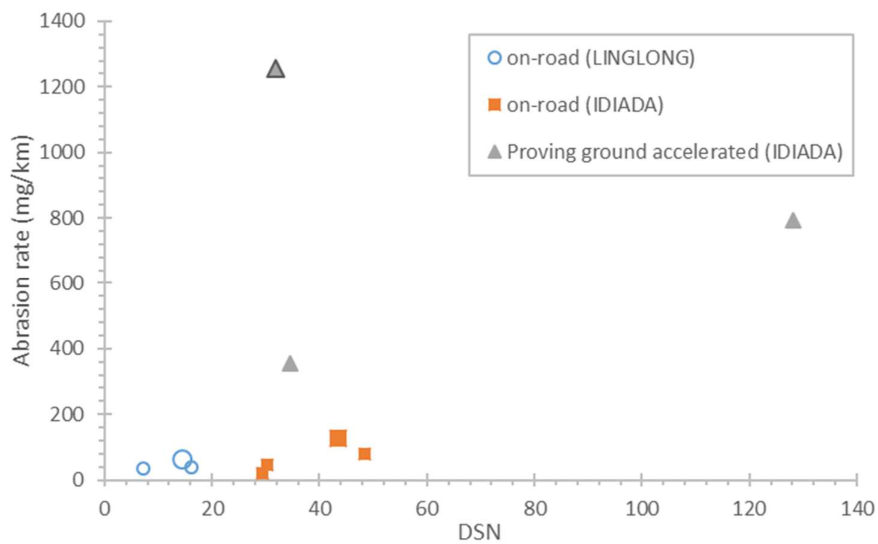


Figure 168. Abrasion rate in function of DSN at tests on the proving ground (accelerated) and on-road at IDIADA and LINGLONG. The tyres in all tests were the LL (Table 3). Larger symbols indicate urban driving.

11. Conclusions

The methodology of on-board vehicle particle sampling, the physical characterisation of particles on-road and in the laboratory have been described in two confidential deliverables (**Deliverable 2.1** and **Deliverable 2.2**). **Deliverable 2.4** summarises results from the comparison of tyre tread wear and related particle emissions. Two key elements impacted the outcomes of **Deliverable 2.4**: (i) During the project it was made clear that the vehicle on-board measurement of tyres is extremely difficult and uncertain for regulatory purposes; (ii) the activities at UNECE level defined a regulatory methodology for measurement of tyre abrasion. Furthermore, in the European Union, there is an interest to include a 'durability' index at the tyre labelling. The tread depth reduction during the tyre abrasion test could be a possible approach.

In order to assess mass loss and tread depth reduction various tests were conducted. IDIADA tested five tyres on the proving ground with an accelerated wear method. The vehicle was front-wheel driven with a weight of 1650 kg. One of the tyres (from LingLong) was also tested on the road under normal driving conditions at both IDIADA and LINGLONG. Under the PM/PN testing, VTI (at a road simulator) and FORD (at a handling road) measured mass loss and tread depth with a different set of five tyres.

The results demonstrated a clear impact of the ambient temperature and tyre load on the abrasion rate. For the summer and M+S tyres the mass loss increase was 30% per 10° increase of ambient temperature. For the winter tyre the increase was 55%. The mass loss was almost linear to the load increase (for the same tyre).
No correlation was found between mass loss and the tyre hardness. Other factors, like differences in tread pattern contact area, might have masked any relation. All the tyres started with a higher shore A hardness and stabilised during the abrasion tests.
The accelerated wear method resulted in wear rates of 600-1500 mg/km (vehicle, sum of four tyres) and 0.5-0.6 mm per 1000 km (average per tyre), more than 10 times higher than the on-road tests. Urban driving had up to 5 times higher wear than rural and motorway driving. However, part of this difference was likely due to the different road surface. The DSN (driving severity number) on its own could not fully justify the differences between proving ground and on-road tests. For the front-wheel driven vehicle of this study the front tyres contributed 65-85% of the total wear.
The on-road tests with one of the tyres had abrasion rates of 20-120 mg/km. The urban part had higher wear 2-5 times compared to total and motorway parts.
The abrasion rates had some correlation with wear indices reported in consumers' web sites.
The tyre life estimated from the accelerated method did not have any correlation with the treadwear Uniform Tire Quality Grading (UTQG) used in the United States. More studies are needed to investigate if such correlation exists with the final regulated on-road protocol. The abrasion rates of this study had some correlation with the tyre wear rate published on the internet.
The tread depth measurement was found to have high uncertainty compared to the mass measurement. Different locations of the tyre can also have different tread depth reductions. Even though there is a correlation between tread wear reduction and mass loss, this was different for the front and rear tyres and the different tyre

manufacturers. Values of 306 g/mm for the front tyres and 198 g/mm for the rear tyres were calculated.