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LEON-T

Low particle Emissions and lOw Noise Tyres

Airless tyres – Prototypes

LEON-T Report by
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Revision history

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SUMMARY

The main purpose of WP5 is to develop and construct prototypes for an airless heavy goods vehicle (HGV) tyre with the specific performance of reducing HGV noise by 6 dB, with acceptable performance of parameters related to safety, energy and wear. The intention has been to attempt producing two prototypes, one for use on steering and trailer axles and another for use on driving axles.

The Deliverable D5.2 are actual two physical prototype tyres. As a supplement to the physical Deliverable of prototypes, this document is a supplement providing an overall description of the prototypes, including how they were developed and tested. This document does not include results of functional measurements on the physical prototypes, other than a running test on an electric truck and tests on a drum facility to make sure that durability is sufficient for making later measurements of rolling resistance, noise emission and more in a safe way.

Since 2005-2010 tyre manufacturers have presented various airless concept tyres for road vehicles at fairs and exhibitions but so far none is brought into a commercial product for road vehicles. All of the tyre manufacturers' concepts for road vehicles feature an elaborated pattern of "spokes" or honeycomb structures in composite materials which seem to be rather complicated to manufacture. Nevertheless, those constructions are less complicated than modern pneumatic tyres. Compared with the airless concept tyres by the tyre manufacturers, the design by Hansson of ETU, and used in LEON-T, stands out as unique. Both the spoke design and material are very different from the other airless concepts. Furthermore, the LEON-T tyres have a unique feature in the rubber tread, as holes are drilled radially through the tread and belt, in order to ventilate air, reduce air pressure gradients in the contact patch and drain water away from the tyre/road contact patch.

Initially, it was intended to scale up the "Composite Wheel" (CW) concept, from an earlier project for car tyres, from car to truck size using similar composite material (CFRP) for the basic construction. An HGV tyre would require about 5-8 times higher load than the car version in the earlier project. Unfortunately, LEON-T's initial calculations and simulations indicated that using the CFRP for spokes did not result in a durable HGV tyre. Instead, replacing the spokes made of CHRP with high-stress steel, showed promising results and has been the design which has been worked on in LEON-T. Nothing has indicated that the spoke design with high-strength steel was a wrong decision, given the time and budget constraints. Nevertheless, there are more advanced composite materials that might have been preferred, but project resources have not been enough to manufacture and use such advanced materials.

Developing an innovative new tyre for HGV tyres is of course a much more challenging task than to do so for car tyres. This is reflected in the fact that there are many concept

tyres of airless type presented for cars but only one known so far for trucks, and that one is not for the heavy trucks. The Commission's call for the project which LEON-T answered to, requested an HGV tyre, so consequently this is the challenge that WP5 has.

When the project is near its end, two physical prototypes have been produced. For both prototypes, different versions have been produced, with variations in belt, rubber tread and connections between spokes and belt. If an HGV tyre under test (with loads of up to 3000 kg) is substantially damaged, it may cause damages to the vehicle it is mounted on, as well as to its environment, so initial durability tests are necessary. Therefore, all airless tyre versions have been tested on a laboratory drum facility at Idiada to check that they can carry the intended loads long enough to go through advanced full-scale measurements. Then all five versions produced have failed in one way or the other. Only one, simplified, noise measurement was possible, as fully functional tyres were not available.

In all cases the connection between spokes and the belt/rubber appears to be the critical problem. Forces in this connection have been much higher than expected and have either caused belt-rubber delaminations or loosened or even broken bolts and nuts that connect the belt on the spokes.

List of abbreviations and symbols

In this Deliverable the following abbreviations or symbols are often used and below they are explained and sometimes commented on.

Abbreviation	Explanation	Comment
Partners, companies or institutions related to this project		
ETU	Euroturbine AB	Project partner
Idiada	Idiada Automotive Technology S.A.	Project partner
LDAB	Lightness by Design AB	Supplier to ETU
VTI	Swedish National Road and Transport Research Institute	Project partner, leading WP5
Abbreviations		
C1 (tyres)	Tyres intended for passenger cars	
C3 (tyres)	Tyres intended for trucks and busses (HGV:s)	
CFRP	Carbon fibre reinforced plastic	
CW	Composite wheel	Used for the airless tyre prototypes produced in Sweden previously
EV	Electric vehicle	
FE / FEM	Finite elements	Finite Elements Method
GFRP	Glass fibre reinforced plastic	
HGV	Heavy goods vehicles	
WP5	Work Package 5	In LEON-T
Measures and units		
dB	Decibel, unit for sound and noise emission	The sound pressure or intensity is always frequency weighted by the "A" weighting curve, as standardized

List of content

1. The airless HGV tyre prototypes—the essential output of WP5 of LEON-T

The main purpose of WP5 is to develop and construct prototypes for an airless HGV tyre with the specific performance of reducing HGV noise by 6 dB, with acceptable performance of parameters related to safety, energy and wear. The intention has been to attempt producing two prototypes, one for use on steering and trailer axles and another for use on driving axles. This Deliverable describes the prototypes that have been produced in the project.

2. Purpose with this Deliverable

The Deliverable D5.2 are two actual physical prototype tyres intended for steering and trailer axles. As a supplement to the physical Deliverable, this document provides an overall description of the prototypes, including how they were developed and tested.

This document does not include results of measurements on the physical prototype, other than a running test on an electric truck and tests on a drum facility to make sure that durability is sufficient for measurements of rolling resistance, noise emission and more.

3. The physical Deliverable D5.2

The Deliverable D5.2 is two physical prototype tyres intended for steering and trailer axles. A couple of photos describing the construction are shown in Figure 1.

Figure 1: The first prototype for an airless tyre, for use on steering and trailer axles of a heavy goods vehicle (HGV). The left photo also shows Mr Hansson; the inventor.

4. What is an airless tyre?

Almost all tyres on present road vehicles are inflated with air: so-called pneumatic tyres. It is a 100+ years old invention which has been successively improved and today is an extremely complicated product with excellent performance. Just looking at a pneumatic tyre it is hard to imagine that some of them include more than a hundred different materials and components. It is thus complicated to manufacture them, and they can be economical because they are made in very large quantities.

Tyres operating without the need to be inflated by air are called airless tyres. One type of airless tyres is tyres filled with flexible material that can replace high-pressure air in carrying the load. VTI tested such tyres filled with polyurethane in the 1980’s but they showed only marginal noise reduction, and they had the disadvantage of being heavy. Nevertheless, such airless tyres are frequently used in military vehicles since they cannot be punctured by normal gunshots.

In LEON-T, airless tyres are tyres not needing any inflated air to carry the load; instead the load is carried by a solid but flexible structure, utilizing materials such as steel and/or carbon-fibre-reinforced plastic (CFRP) upon which there is a belt covered with a rubber tread.

5. Inventions which have been models and precursors for the LEON-T construction

An airless tyre (with dimensions suited for cars) was designed by the Swedish inventor Mr Hans-Erik Hansson [Hansson 1990]. The patent was granted in Sweden and applications were filed in the major industrial countries (1986-88). This wheel was a non-pneumatic, highly flexible construction in composite materials giving unique characteristics. Hansson’s first idea was to provide puncture-free and easy-rolling tyres for racing bicycles and trotting sulkies. When VTI was consulted for testing, this author suggested that the design had very promising features making possible noise reduction of passenger car tyres, which resulted in Hansson constructing such a version.

This tyre concept was named the “Composite Wheel (CW)” due to its integration of rim with tyre, using a composite material of glass-fibre/polyester laminate. Hansson manufactured this prototype in his own workshop at H E Hansson AB in Finspång, Sweden, with assistance by Marströms Composite AB in Västervik, Sweden. Figure 2 shows a cross-section through the first version of the Composite Wheel designed for cars. This design includes perforation of the tread by drilled ventilation holes through the tread and belt, intended to let air and water flow through the tread and the “belt”; an invention by this author.

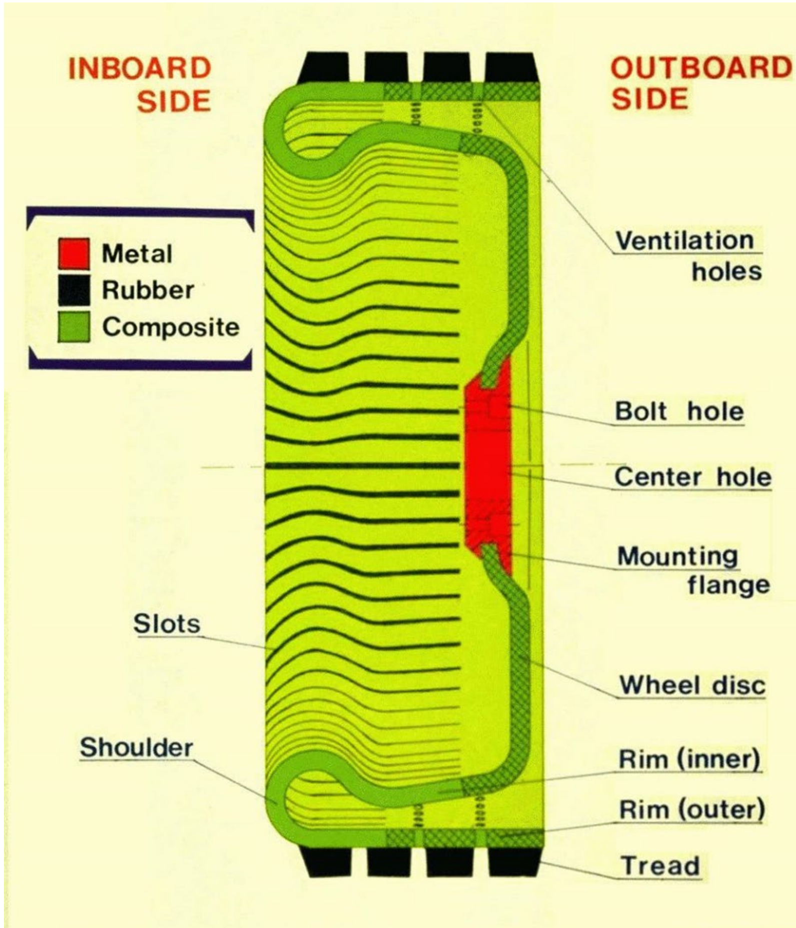


Figure 2: Cross-section of the Composite Wheel of 1989, as invented by Hansson and with ventilation holes by the author [Hansson, 1990].

With this design a noise reduction of up to 10 dB (A-weighted) was measured compared to one of the most popular quality tyres of the time (a Goodyear Eagle NCT70) [Sandberg & Ejsmont, 1990]. Also rolling resistance was measured in this first prototype, using a laboratory drum facility. It was found that the rolling resistance coefficient was 10-25 % lower than from a conventional Goodyear Eagle NCT70 passenger car tyre which was used as a high-quality reference in that case, depending on the deflection (higher deflections gave higher advantage) [Ejsmont, 1990]. This was extremely promising.

The results were presented in three papers at the International Tire/Road Noise Conference 1990, in the presence of most major tyre manufacturers [Hansson, 1990][Sandberg & Ejsmont, 1990][Ejsmont, 1990].

However, the design was not durable enough, which actually had not been the purpose with this particular design. The purpose had been to study the potential for noise reduction of the concept and not to build a fully durable tyre.

In the first years of the new century, Mr Hansson got funding from Volvo Cars for producing a new prototype intended for use on a concept car in an international exhibition. This version of the Composite Wheel is shown in Figure 3.

The version of the wheel in Figure 3 was not considered technically useful by Hansson's co-researchers, but it was the inspiration for a new project "Tyre innovations for lower noise emission" led by VTI, was a cooperation between VTI, H E Hansson AB (nowadays ETU), Chalmers University of Technology, Volvo Cars and Fighter AB in Sweden, Technical University of Gdansk (TUG) in Poland and Nokian Tyres plc in Finland. Also, Dr A.R. Williams, retired from his leading R&D position at Dunlop Tyres in the U.K. was involved as an advisor.

Figure 3: The inventor, Mr Hansson, with his wheel intended for a Volvo concept car.

In this international project [Sandberg, 2009], utilizing carbon-fibre and epoxy laminate as materials but retaining the basic principle shown in Figure 2, focus was on noise, rolling resistance, durability, and vehicle handling. In order to improve durability, some of the noise properties had to be sacrificed. Figure 5 shows the prototype samples used during the final testing session.

The result was a CW tyre resulting in about 5 dB noise reduction (A-weighted) and up to 30 % reduction in rolling resistance compared to regular air-inflated tyres such as the Michelin Energy Saver brand.

Vehicle handling and tyre dynamics on a Volvo car were judged to be satisfactory by a Volvo professional test driver and a development manager of Nokian Tires (Figure 4).

Figure 4: The Composite Wheels mounted on a Volvo car for various tests in 2008. Photo by the author.

However, when the car was driven over a "pot-hole" test lane on the Volvo test track, the deflection of the CW tyre/road contact patch exceeded the available space between the belt and part of the sidewall (see the left part of Figure 5). This resulted in mechanical contact between the two structures and in a highly non-linear behaviour, which created minor cracks in a critical bend of the structure, albeit not destructive. Had this space been designed a few mm greater, it is expected that driving on the pot-hole track would have caused no problem. Attempts to get funds for a new project to correct the problem failed. More information about the history of the "Composite Wheel" projects appears in Deliverable D5.1.

Figure 5: The airless tyre (Composite Wheel) final prototypes produced in the international project 2003-2008. The left part shows the outside of the tyre; the right part shows the inside (to be mounted towards the car chassis). Not shown here are the small holes (diameter 7 mm) drilled in the bottom of the grooves in the rubber tread.

6. Construction of the prototypes

6.1 The original project plan and its first task (5.1)

The work with airless tyres in LEON-T is carried out in Work Package 5 (WP5). The partners involved in WP5 are: VTI (leader), Idiada, Audi, Euroturbine AB (ETU), and Linglong (Shandong Linglong Tire Co Ltd). The objective of and planned construction work in WP5 are summarized below, based on parts of the project plan.

The main goal of this WP is to develop and validate an innovative HGV airless tyre concept into at least two prototypes (one for steering and trailer axles and one for drive axles) that, including advances from WP4, are capable of achieving an overall target of 6 dB(A) noise reduction (measured against an ISO 10844 reference surface), while also reducing tyre rolling resistance by 10 % compared to conventional C3 tyres, without sacrificing safety. This work package will also perform the necessary measurements to assess the performance of the innovative tyre design with respect to conventional truck tyres. The prototypes will be integrated into a heavy-duty vehicle for on-road testing and demonstration. The overall intention with this is to show the many potential environmental and safety advantages of the airless tyre concept for future road vehicles.

The first task (5.1) was to analyse and present state-of-the-art of innovative tyres; especially airless tyres, and the potential advantages and challenges these tyres may have according to researchers and tyre manufacturers. This also involved how the earlier Composite Wheel (CW) airless tyres for cars could establish a platform for the prototypes here. Based on this, integration with an HGV, and the requirements outlined in the call, realistic specifications for the two prototype CW constructions were made. For example, this includes specifications for tyre dimensions, speed and load capacity. Other considerations and decisions included the wheel’s basic shape and considering which composite materials and morphological features that can potentially achieve the specifications.

Task 5.1 is now completed and reported in Deliverable D5.1. Here we repeat the decisions about the major specifications for the prototypes:

- Dimension: 285/70R19.5
- Load capacity: Load Index (LI) of 144/146 which means to carry a mass of 3000 kg in single mounting and 2800 kg in dual mounting.

This is a dimension typically used on 15-18 tonne trucks with dual-mounted tyres on a single drive axle, making deliveries of goods in and between urban areas, and thus potentially exposing residential areas, as well as schools and health centres to tyre/road noise. However, in principle, a truck with tandem drive axles and dual mounting could carry of mass of up to 28 tonnes with such tyres. It was decided not to attempt construction of the most common HGV tyre dimension 315/70R22.5, allowing up to 33 % higher loads (up to 4000 kg per tyre), which is typically used for the heaviest long-range trucks, since this would pose too high challenges for this project, given the budget and the project duration.

It was also decided to base the design on the same principles as that of the CW tyres (Illustrated in Figure 2), but to scale up materials to carry the much higher loads. Many of the airless concept tyres presented by the industry (reported in Deliverable D5.1) have much more complicated structures which would not necessarily be better than the CW design but would be extremely complicated to manufacture without access to an advanced industrial factory.

6.2 The construction and manufacturing task (5.2)

6.2.1 Introduction

Task 5.2 is focused on the production of the airless tyre prototypes. To produce the desired prototypes, ETU has first manufactured a prototype spoke and belt sample (main components of the CW structure) based on the design and specifications provided in the first task. It has also been supplemented by rubber tread.

Advanced calculations, especially about the strength of the spokes were made by ETU, Lightness by Design and Idiada. Based on the results, ETU has manufactured a sufficient number of the spoke and belt components and integrated them into a prototype of airless tyre. Subsequently, rubber treads have been mounted on the belt and ventilation holes been drilled through the tread and belt.

6.2.2 The spoke design and materials

At first, the basic idea was to use essentially the design of the CW tyres for a Volvo car produced in the earlier project, but to scale it up to the size needed for HGV:s (dimension 285/70R19.5). ETU manufactured a tool for testing spokes in the shape used in the earlier project, manufactured some test spokes made of composite material in a “light truck” size and subjected those to the loads expected for an HGV tyre (but scaled down to the tested size). The material then was uni-directional (UD) carbon fibre reinforced plastic (CFRP) composite. Figure 6 shows the physical setup used by ETU which also gives an impression about the intended spoke construction.

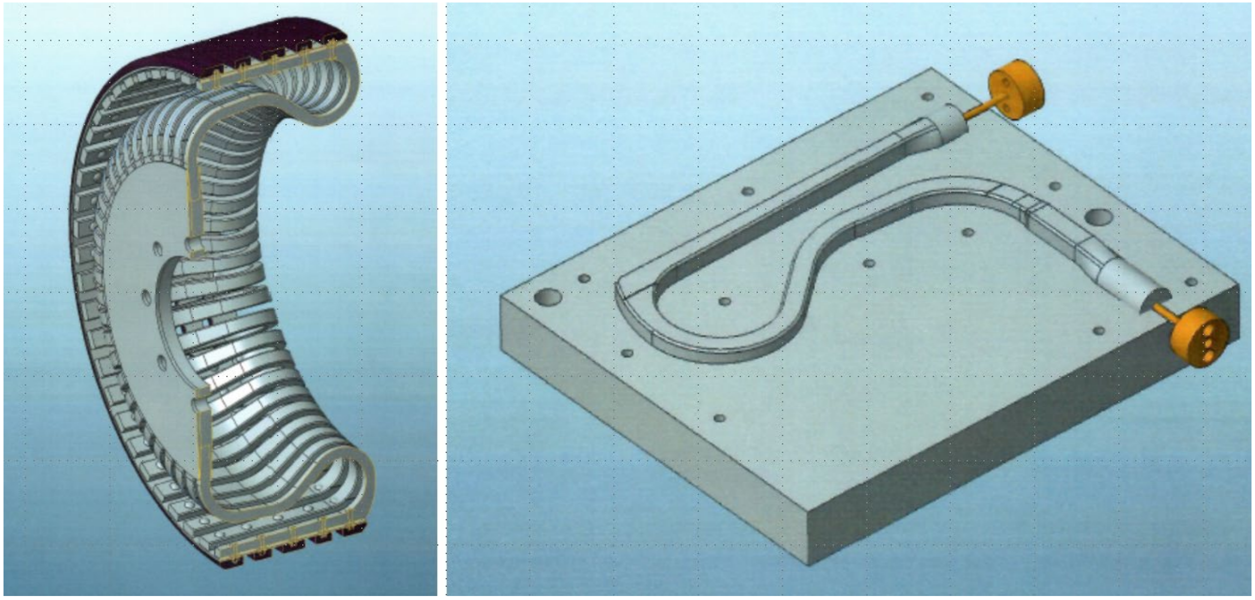


Figure 6: Initial setup to test the stresses of the spokes in the planned construction, as used by ETU. From a presentation at the first meeting of WP5.

The results were discouraging; it appeared that the spokes would have a problem to carry the load of a typical HGV tyre. To follow-up, an expert (Dr Linus Fagerberg) at ETU's subcontractor Lightness by Design AB (here denoted as LDAB), who is specialized on calculating the stresses in light materials, was engaged to supplement the test with calculations for a full-scale model. This confirmed the conclusion that the composite material of the type which would be possible to use in the project would be too weak for the task. See Figure 7.

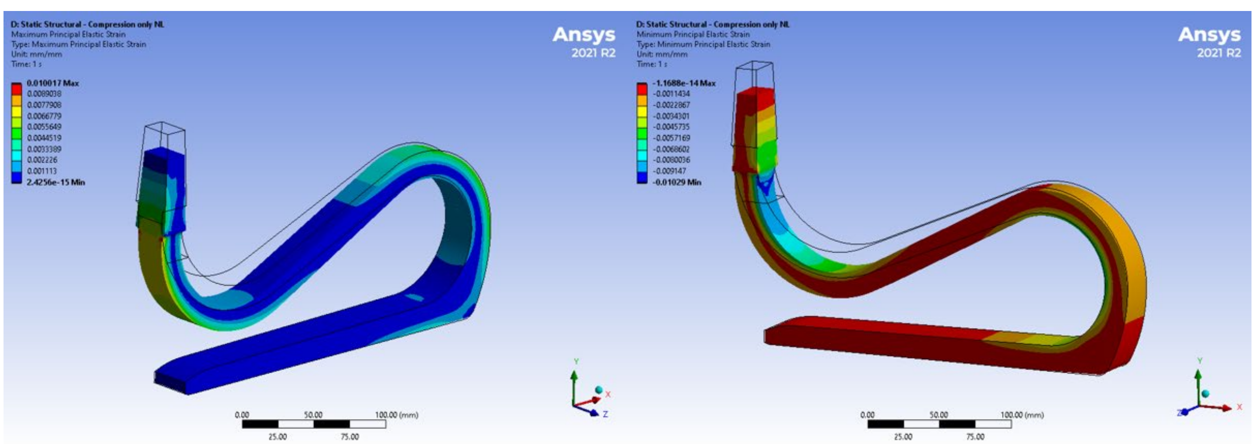


Figure 7: Results of calculation of stresses in a spoke made of CFRP exposed to the load of a fully loaded tyre of dimension 285/70R19.5. By LDAB [Fagerberg, 2022].

As a results of the discouraging results, the WP5 team decided to look for other materials than CFRP. One way to (potentially) obtain the required strength using CFRP, would be if the fibres could be directed in random (or at least varying) directions rather than just longitudinally. However, this would be much more complicated and require manufacturing resources which will not be available within the LEON-T budget. However, in a future airless tyre version produced by a big company with extensive resources, it is quite probable that CFRP improved with fibres in more than the longitudinal direction could be used for the spokes.

It soon became clear that using high-strength steel in the spokes instead of composite material would give a much more stress-resistant product. Contacts with an international steel-producing company Ovako AB, based in Sweden, was established. This company will produce steel fossil-free.

Using steel instead of CFRP comes at a cost in terms of the weight of the wheel. According to initial estimates for a simple steel spring design the extra weight per wheel/tyre unit may be around 25 %. However, optimization of steel springs may allow lighter variants [Fagerberg, 2022].

The work was then devoted to design optimum shape of steel spokes and to integrate them in an airless tyre design. An example of the proposed overall design from LDAB is shown in Figure 8 (note that there are four grooves in this example, but five grooves are used in the first physical prototype). The design of an individual steel spoke (before being bent) is shown in Figure 9. The steel is a version with extra high stiffness.

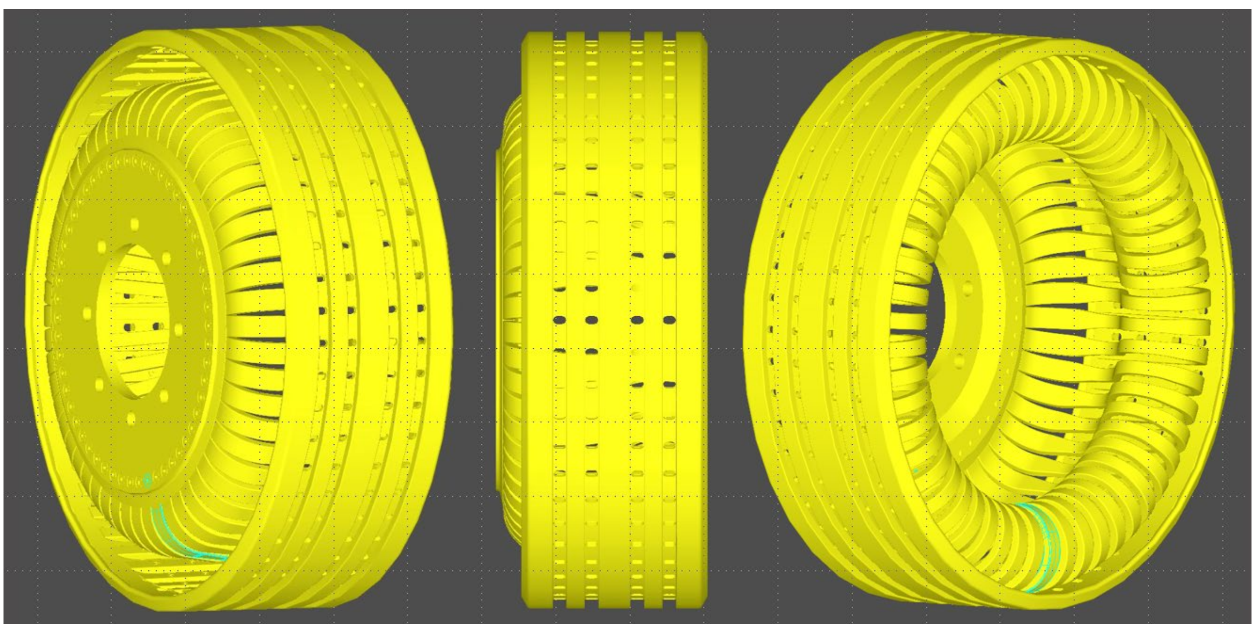


Figure 8: Example of overall design of the airless tyre, based on calculation of stresses for spokes made of high-strength steel. By Fagerberg at LDAB [internal memo].

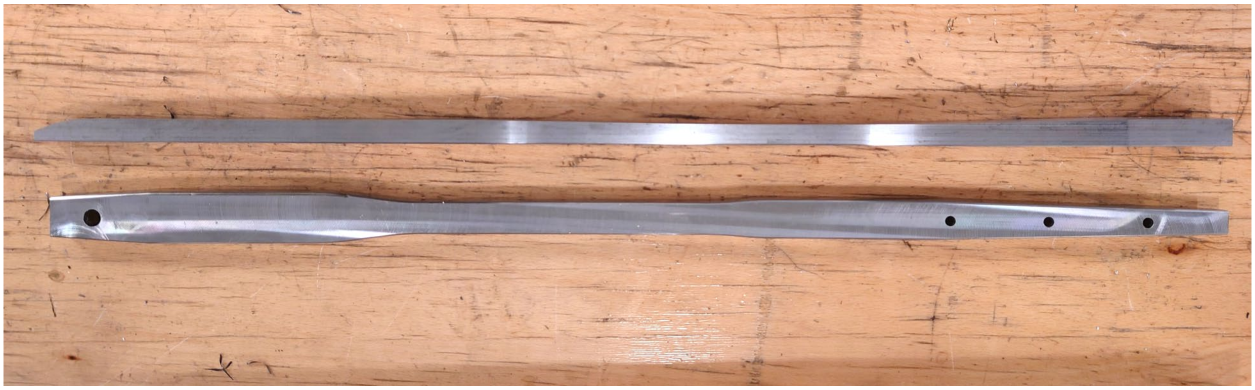


Figure 9: Optimal shape of a steel spoke, based on calculation of stresses for spokes made of high-strength steel. Two spokes shown; the lower one is seen from above, while the lower one is turned 90 degrees to show the profile of the lower one (but it is turned 180 degrees within the plane). By Fagerberg at LDAB [internal memo].

The bending was a challenge, as it required special tools and very high forces, and the initial trials had to be repeated with better equipment. It was also challenging to produce all the spokes within tight tolerances, since if spokes varied in dimension or strength, this may cause unwanted vibrations and noise of the tyre. The spokes were also annealed.

In the prototype, the number of spokes is 54, which means that the distance longitudinally between spokes (center-center) is approx. 50 mm. This distance is not randomized, which means that, potentially, there may be vibration-excited tonal noise from spokes at approx. 444 Hz at 80 km/h, due to belt stiffness variations and shear stresses over the spokes and between them.

In addition, Idiada has used its advanced resources to make models and calculations of the performance of the spokes, which have essentially confirmed the results by ETU and LDAB. Idiada also have made calculations on the old CW design for cars in an earlier project.

Idiada made calculations based on an FE model of the design shown in Figure 8. An example of results is shown in Figure 10. It shows the stresses in the contact patch as well as in the leading and trailing edges for a fully loaded tyre. The example is for radial stresses but results for lateral and longitudinal stresses have also been presented, with quite similar results. These results are satisfactory. Idiada has also calculated stiffnesses in different directions and found the results in Table 1. It appears that the radial stiffness of the airless design is a bit higher than for pneumatic tyres, but not much higher, while stiffness in longitudinal and lateral directions are much higher than normal. What this means in (for example) rubber wear is not yet known. Idiada’s comprehensive modelling work is published in [Anantharamaiah et al, 2023].

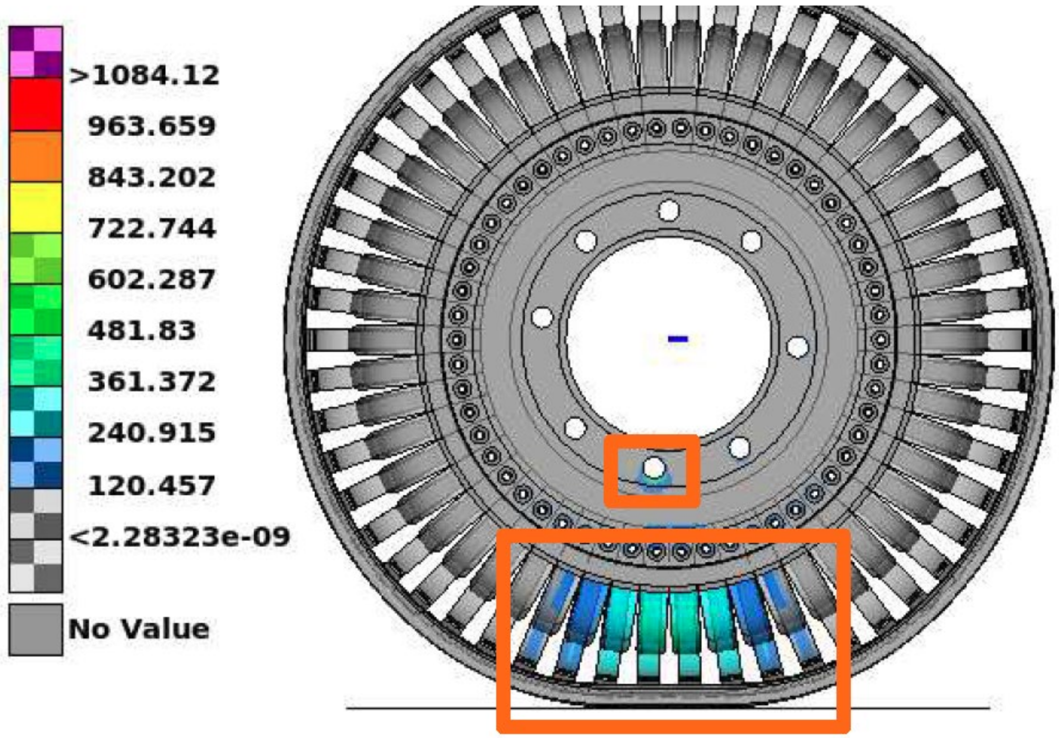


Figure 10: Example of stresses calculated for the airless tyre, based on the design of Figure 9. By Idiada [internal memo].

Table 1: Results of calculations of stiffnesses in the contact patch in 3 directions of the tyre design in Figure 8. "Simulated" are predicted stiffnesses for the airless tyre, while the other columns are typical (estimated) stiffnesses of pneumatic tyre designs of similar load capacity. By Idiada [internal memo].

Load case	Stiffness Values [N/mm]		
	Simulated	Theoretical	Reference
Radial	1500	1000	1000-1250
Longitudinal	1400	500	330-350
Lateral	1000	500	580-630

6.2.3 Belt, rubber tread and their connection to the spokes

A belt in the shape of a round tube, 270 mm wide and with a diameter of 870 mm, to provide the medium between the spokes and the rubber tread have been produced in CFRP material by ETU, with a nominal thickness of 4,5 mm (Prototype 2). This is intended to transfer the forces on the rubber tread to the spokes while as much as possible sharing the forces to the spokes in an even way due to an optimized stiffness. However, a belt of GFRP with a nominal thickness of 7.5 mm was also produced (Prototype 1).

A rather consistent feature of the presented airless tyre concepts, not the least in our version, is that the belt and treads will have a shape which is flat in the lateral direction, something which is opposite to the partly curved shapes of pneumatic tyres; especially in the shoulder regions, connecting the tread with the sidewalls. Extra thick rubber is not needed on the shoulders, in contrast to pneumatic tyres. This should be favourable to the stick-slip motions in the tyre/road contact patch and to the bending work in the shoulders at the edges of the contact patch.

For airless tyres, the rubber tread patterns can in principle be similar to those of pneumatic tyres, except that they can be of equal thickness all over the width. Of course, treads (especially the tread patterns) must be optimized for the use of the tyres they sit on; such as summer, winter or all-season car tyres, or steering axle, trailer axle or drive axle heavy vehicle tyres. In this case, the rubber tread has a pattern of so-called ribs between (five) longitudinal grooves. The very first prototype has no grooves or sipes across the ribs, but later versions have it. Figure 9 (especially the middle of the figure) shows such a pattern, although it has four grooves instead of five grooves. Such patterns were common in older tyres and are still common on steering and trailer axles, although they often have not straight but somewhat curved edges along the grooves. It is also very common that they have narrow grooves or sipes across the ribs. The actual tread of the first prototype version is shown in Figure 11.

The tread rubber was planned to be provided by the LEON-T partner Linglong Tires. One of the prototype versions used this rubber. However, we never received any information of the properties of this material. Therefore, in principle, it may be a rubber with compounds and proportions that are not state-of-the-art. The treads were supplied in bands fitting a tyre of width 285 mm, with a varying thickness across the width as is common for pneumatic tyres. We needed ribs of equal thickness, so they were cut longitudinally from the bands utilizing the middle part which was 15 mm thick. These (six) ribs were then vulcanized to the belt in an autoclave using a pressure of 4.2 bars, a temperature of 115 ^{o}C for a duration of 3.5 hours. The grooves became 15 mm deep.

Instead of the Linglong rubber, having delaminated against the CFRP belt after the first drum test, another rubber was chosen for the tread for most of the prototype versions. It was Remaclave 60 supplied by Swedish company VulcTech, as it was found to stick better to the belt after vulcanization.

The connection between the spokes and the belt was provided by M8 steel bolts fastened by special treaded nuts in the grooves; see Figure 11. There is also a washer (diameter 35 mm) which sits around the bolts and in-between of the spoke and the belt, with the assumed intention to distribute the stresses in a more favourable way. In a more industrial-ready version this would be better made by rivets optimized for the purpose, which would reduce the weight of the tyre. The same applies to the bolts and nuts connecting the spokes to the rim. In later versions of the prototype, different solutions were applied; see later in this deliverable.

Figure 11: The first physical prototype shown at an angle where the rubber tread can be seen. Note that two wider grooves include bolts to connect the belt to the spokes.

6.2.4 Perforation of the tread and belt

A special feature of the CW design and the imitated design to be used in LEON-T is the "perforation of the tread". By this is meant that the tread and belt are constructed with holes running through them radially. The holes are located in the bottom of the grooves, at certain intervals. The area of the holes is important as well as the distance between them; probably also the length (or width) has some influence.

The idea (originally launched by this author in 1989) is that the holes would eliminate the build-up of local air pressure in the grooves due to the compression of air that occurs in the leading edge of the tyre/road contact as well as decompression occurring at the trailing edge. Such phenomena are known to cause what is known among tyre noise researchers as "air pumping". An additional phenomenon is that there are acoustical "pipe resonances" in the grooves, and if the grooves are perforated, the resonances will disappear. A third phenomenon which is affected is the so-called "horn effect" which occurs at the same edges of the tyre/road contact and which – like a horn in musical instruments or public address systems – amplifies the sound/noise towards the front and rear of the tyre. The horn effect relies on dense surfaces and when one of them (the tyre tread) is perforated, the amplifying effect diminishes. A fourth effect is that the holes will reduce the “baffle effect” for low frequencies, the basis for loudspeaker cabinets. See further [Sandberg, 2023].

A study of the effect of the perforations was made in the Composite Wheel project described in Section 5, by researchers at Chalmers University of Technology (which was one of the partners in that project). They used an adapted FEM model to calculate the effect of varying the holes [Larsson & Schade, 2008].

In the physical prototype, the perforations include circular holes of around 16 mm diameter drilled through the belt in the five grooves. They are drilled at a longitudinal distance resulting from drilling the holes between each pair of bolts. There are 162 such holes, which means that approx. 0.06 % of the belt and rubber area are perforations. In comparison to the tread groove area, which is where the air entrapped will be, it will be approx. 1 % of the grove area. It is less than desirable. In a more optimized version, it is intended that the area of the holes shall be larger, according to the results suggested in [Larsson & Schade, 2008]. However, the holes cannot be much larger as it would compromise the durability of the belt.

6.3 Host vehicle

The airless tyre has been designed for use on especially future electric-driven HGV:s. Today, goods transports create noise exposures to particularly sensitive areas; exposing people in and outside homes and especially sensitive services as education or medical or other health care. Consequently, there is a general trend already started to replace today’s HGV:s, presently using internal combustion engines (ICE) with new vehicles with electric powertrains. It is expected that in the years up to 2030-35 most of such ICE vehicles operating in urban or semi-urban areas will be replaced by electric-driven vehicles. For the electric vehicles, it is essentially only tyre/road noise which is created and, therefore, reducing tyre/road noise is the only way to create quiet transports in urban areas in the future.

The project team believes that this niche is where the first applications of airless tyres for heavy vehicles have a chance to become successful and where LEON-T has a fair chance to provide the solution.

Three such electric HGV:s are the Volvo FM electric, Volvo FL electric and Volvo FE electric, with the former two having two axles and a mass up to 17 tonnes while the latter with three axles and a mass up to 27 tonnes with the tyre dimension 285/70R19.5 chosen for this project. According to a Press Release dated 11 May 2023 from Volvo, “Volvo Trucks leads the market for heavy electric trucks after the first quarter of 2023, both in Europe and in North America. In total, the Swedish truck manufacturer has sold almost

5,000 electric trucks in about 40 countries." Based on that, the authors think that tyres for this kind of HGV (but not necessarily Volvo) are a suitable first application of such tyres on a commercial market.

Volvo AB is not partner in LEON-T but is engaged in the Advisory Board and the mentioned HGV:s are already sold in great numbers worldwide; therefore one of the best hosts for our tyres. In the final demonstration test, it is planned to use an HGV from MAN.

Figure 12: The first physical prototype was tested on this host truck, which is a Volvo FL Electric.

For the noise tests, a special DAF truck driven by a diesel engine, owned by Idiada and used only for testing purposes, was used. For the noise test it was modified with the purpose to reduce the noise emission from other tyres than the single test tyre in the right position on the drive axle. As this truck was used only for the noise measurements, it is described further only in the deliverable reporting the noise measurement results.

7. Testing the functionality of the prototypes

7.1 Initial testing

Before full-scale measurements of noise and rolling resistance can be made it is necessary to make sure that the tyres endure such measurements without getting serious damages. If such damages occur, this may damage even the testing trucks upon which the tyre(s) is/are mounted, which may result in substantial costs.

Such testing has been conducted at a facility owned by Idiada in Spain which includes a 1.7 diameter steel drum which is also used for measurement of rolling resistance. On this laboratory facility one can vary the load and speed while it is possible to interrupt a test momentarily by separating the tyre from the drum in case some problems are observed. This chapter describes the tests that were made there. The intention with these tests was to check if the airless tyre would operate under a substantial load and time without being damaged. If no damaged would be observed, the intention was to continue the test by regular tests of rolling resistance and noise.

But first of all, there was a simple driving test made in Sweden on a truck where one of the regular drive-axle tyres in dual mounting was replaced by our first prototype version.

In the project, two airless tyre prototypes have been produced. On these, some modifications have been made in order to mitigate problems occurring in the tests. It means that of each prototype there are a few versions. Chapter 8 describes the prototype versions and Table 2 (in Chapter 8) gives a summary of all prototype versions tested.

7.2 Initial driving test

For an initial driving test, we were generously allowed by Rejmes AB in Linkoping to use a Volvo FL Electric HGV, having two axles and allowing a mass of up to 17 tonnes with the tyre dimension 285/70R19.5, which is the same as was chosen for this project. The prototype tyre was mounted on the left rear axle, as the outside tyre in the double-mounting. Thus, the tyre mounted inside of the prototype could carry the load in case the airless tyre would break down. After mounting, the vehicle was driven to a nearby test facility having scales for measuring the loads of individual tyres. VTI also had portable scales for doing such measurements in the garage.

Driving tests were made 1 November 2023 on the large, paved areas around the Rejmes AB commercial facility in eastern Linköping and also on an adjacent local road with almost no traffic. Figure 12 shows the truck used for this purpose and Figures 13-14 show a close-up of the prototype tyre, while Figure 15 shows the tyre from the other side.

The mass of the airless tyre was 150 kg during these tests. This includes the spokes and all its components.

Figure 13: The first physical prototype when tested on the host truck, a Volvo FL Electric.

Figure 14: A closer view of the deflection of the spokes in the contact patch for a static load of approx. 2000 kg.

Figure 15: The tyre seen from the other side, held by Mr H.E. Hansson.

The following observations were made.

Test truck: Volvo FL Electric.
Loads on the rear axle tyres: 6270 kg in total, of which 3140 kg on the left tyres.
Loads on the rear axle left side: 1945 kg on the outer airless tyre and 1195 kg on the inner conventional tyre (the reason for the equality is that the airless tyre was somewhat larger).
Diameter of the tyres on the left rear axle: The airless tyre had 15 mm larger radius.
Contact patch of the airless tyre (static): Length 170 mm.
Driving test: 9500 m at speeds 0 – 75 km/h.
Road surface: Where the driving tests were done, the surface had an essentially smooth texture, rather similar to that of an ISO 10844 test track surface.

Visual observations: No damages or other problems could be observed during or after the tests. It was not possible to detect any tyre unevenness visually during the runs.

Acoustical observations (from listening beside the truck during pass-bys): At speeds below 30 km/h it was not possible to perceive any noise from the airless tyre compared to other sources on the electric truck. No tonal components were heard, except from the powering electric system of the truck (which were essentially above 1000 Hz). During pass-by at 50 km/h it was possible to distinguish noise from the airless tyre (although no distinct tonal components). But at 70 km/h one could hear a mix of various tonal components, which could have included noise from the truck electric system.

7.3 First drum test (Prototype 2a)

The first drum test was made 21 December 2023 on the Idiada platform for laboratory drum testing, also used for rolling resistance testing. The main purpose was to visually check how the prototype behaves under prolonged running, first starting with a very low load (12 kN), continuing with a medium load (19 kN) and finally exposing the tyre to the condition required according to ISO 28580 (25.5 kN). Another (also important) purpose was to monitor the temperature of various parts of the tyre during running, with the aim to see where most of the energy is consumed.

The test was made at Idiada, but this author and Mr Hansson were able to follow it virtually in Sweden as the screen in the control room was continuously shown via link. Furthermore, MP4 videos were recorded over the entire test and even after the test had stopped for checking the tyre condition.

The tested tyre was the second prototype (2a), slightly different from the one tested on the electric truck. Mainly, the difference was in terms of belt and rubber tread materials. See Table 2.

Equipment: The Idiada platform for laboratory drum testing, also used for rolling resistance testing, with a 1.7 m drum diameter and a smooth steel surface on the drum. A video camera was used to monitor the test from a safe control room adjacent to the laboratory. No microphone was used this time. For measurement of temperature a FLIR thermal imaging camera was used (FLIR means Forward-Looking Infrared) pointing at the airless tyre's spokes and belt from the belt's underside.

Measurement method: Essentially, the method described in ISO 28580 was followed, but with two extra tests at lower loads and relaxed requirements for tyre run-in and tyre warm-up. The ISO 28580 is the method used in ECE R117 for tyre type approval and also for determining the energy label of tyres according to the EC Regulation (EU) 2020/740.

Test conditions: The tyre was loaded to the drum with load condition 11.8 kN. Run-up from 0 to 80 km/h. Ambient temperature at start was 22 ^{o}C. When 80 km/h was reached, after 10 minutes, the test continued at the constant speed of 80 km/h. At the time of 11 minutes, it was noticed that something on the tyre had separated, and the test was stopped. The highest temperature on the tyre was then varying between 45 and 50 ^{o}C.

After that, the tyre condition was inspected. It was found that on substantial parts of the tyre circumference, the belt and rubber tread had separated. See further, Chapter 8 about damages and actions to improve the prototype. Figures 16-17 show examples of screenprints before (Figure 16) and near the end of the test (Figure 17).

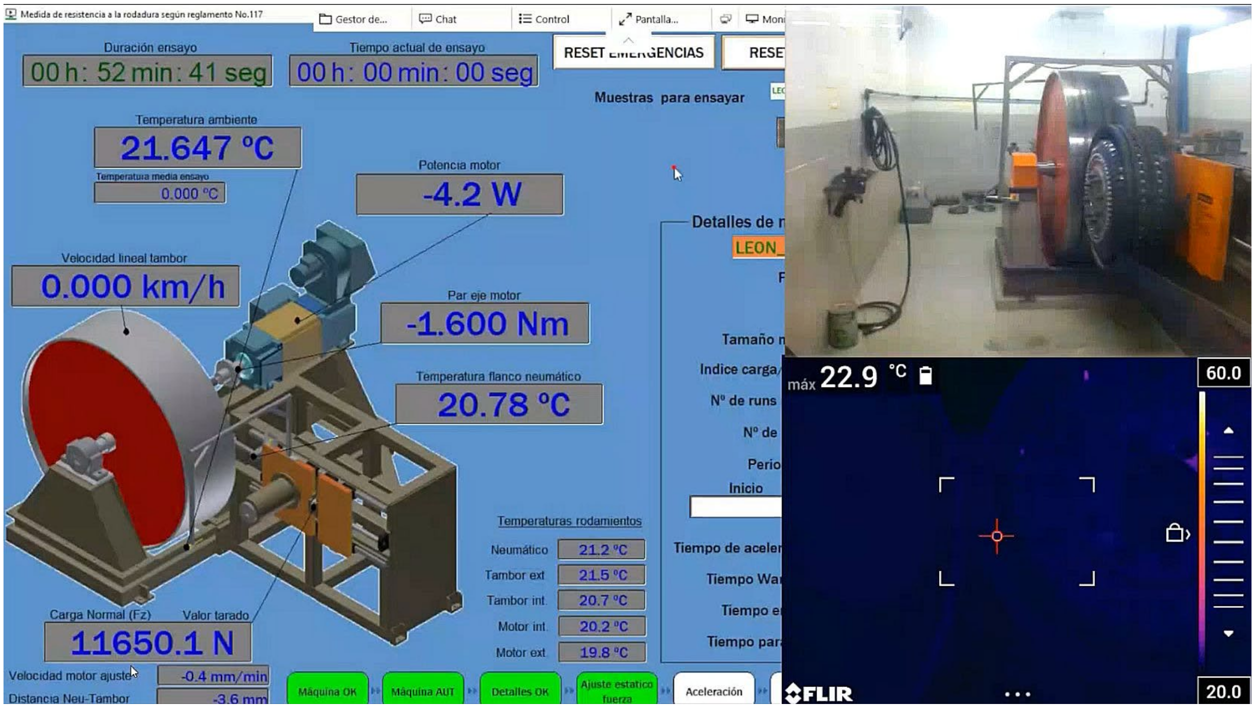


Figure 16: A screenprint made before the test begun.

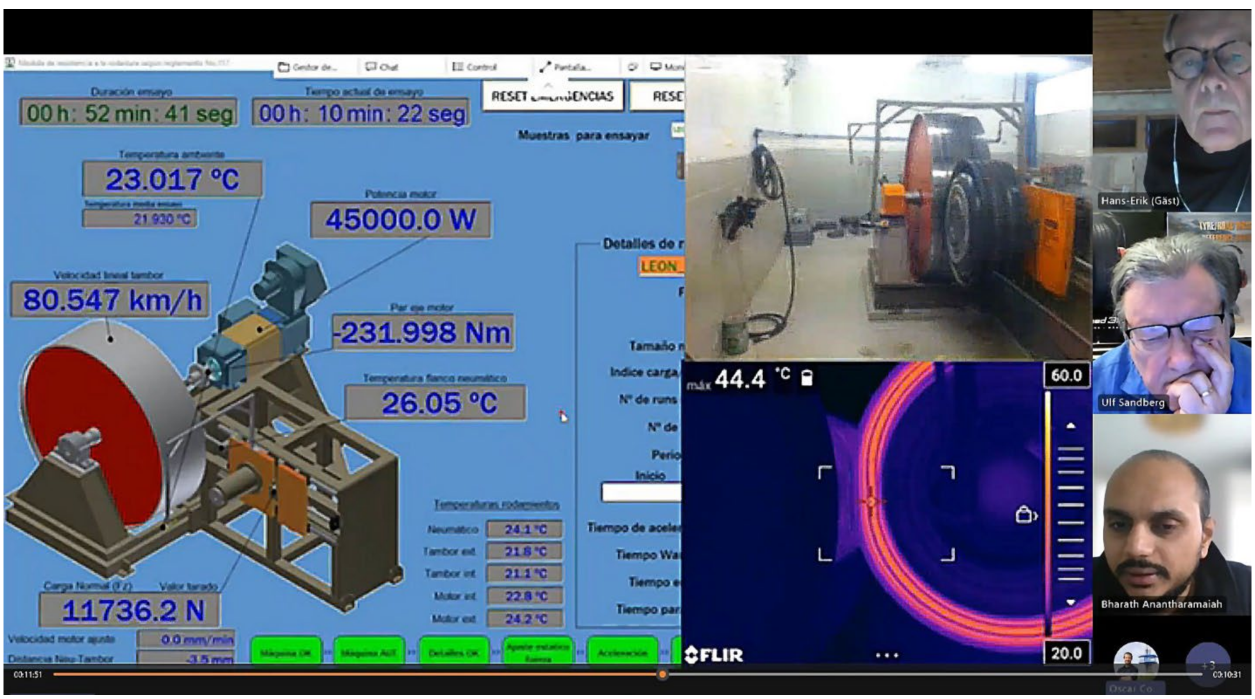


Figure 17: A screenprint made half a minute before the test was stopped. Note the thermal image in the lower right.

7.4 Second drum test (Prototype 2b)

The second drum test was made 9 July 2024 on the Idiada platform for laboratory drum testing. Very unfortunately, this test was delayed over and over again, until about half a year had passed. This was due to a failure in the Idiada drum facility (the main axle had to be replaced) which turned out to take a lot of time to replace. During this time no significant progress regarding the tyres could take place.

As for the first drum test, the main purpose was to visually check how the improved prototype behaved under prolonged running, first starting with a very low load (12 kN), continuing with a medium load (19 kN) and finally exposing the tyre to the condition required according to ISO 28580 (25.5 kN). Another (also important) purpose was to monitor the temperature of various parts of the tyre during running, with the aim to see where most of the energy is consumed.

Again, the test was made at Idiada, but this author and Mr Hansson were able to follow it virtually in Sweden as the screen in the control room was continuously shown via link. Furthermore, MP4 videos were recorded over the entire test.

Equipment: The same Idiada platform for laboratory drum testing, as in the first drum test. However, a microphone was added near the tyre.

Measurement method: The same as in the first drum test.

Test conditions: The tyre was loaded to the drum with load condition 11.8 kN. Run-up from 0 to 80 km/h. Ambient temperature at start was 23 ^{o}C. When 80 km/h was reached, after 10 minutes, the test continued at the constant speed of 80 km/h. The max tyre temperature seemed to stop increasing at around 40 ^{o}C at 20-40 minutes of driving. At the time of around 50 minutes, it was noticed that something on the tyre had separated, and the test was stopped.

After that, the tyre condition was inspected. It was found that on substantial parts of the tyre circumference, bolts and nuts had loosened and thrown away. See further Chapter 8 about damages and actions to improve the prototype. Figures 18-19 show examples of screenprints soon after start (Figure 18) and near the end of the test (Figure 19).

In conclusion, until the bolts started to be thrown away, the test worked fairly fine for about 50 minutes, and rolling resistance test had started but could not be completed.

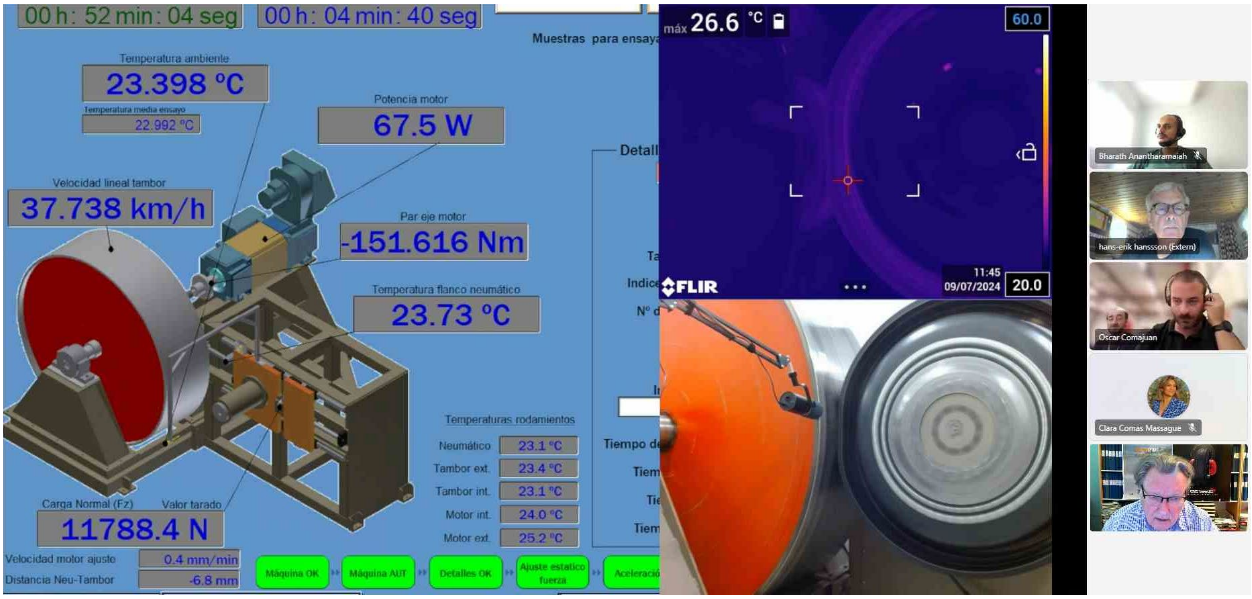


Figure 18: A screenprint made about 5 minutes after the test begun.

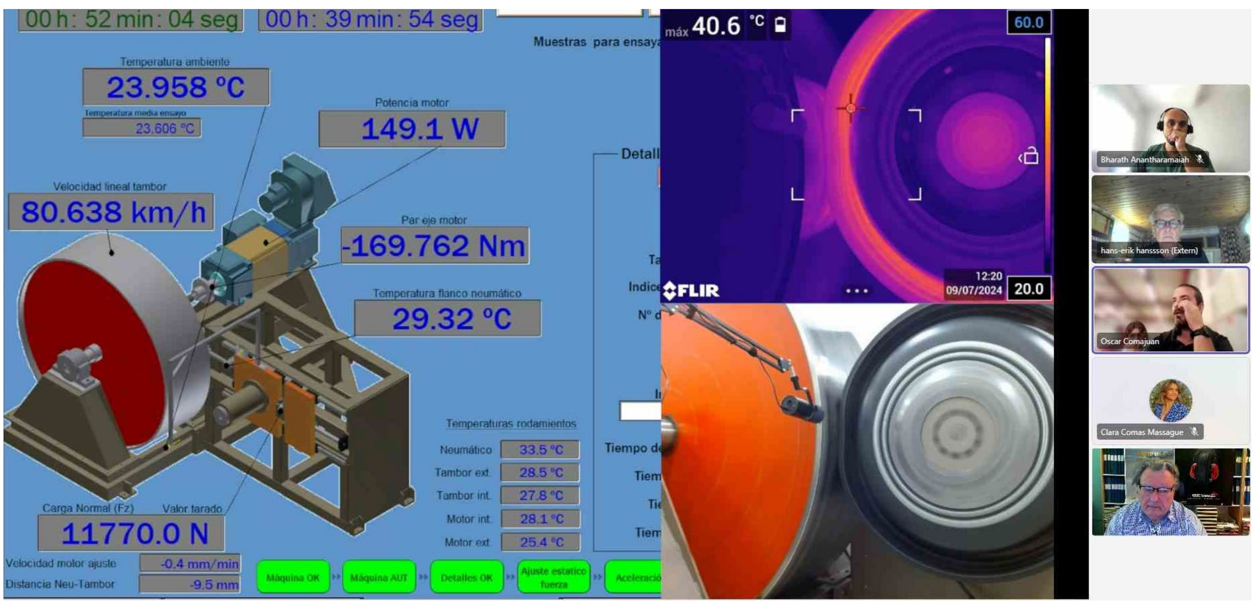


Figure 19: A screenprint made ten minutes before the test was stopped. Note the thermal image in the upper right.

7.5 Third drum test (Prototype 2c)

The third drum test was made 27 September 2024 on the Idiada platform for laboratory drum testing. The main purpose was, again, to visually check how the improved prototype behaved under prolonged running, first starting with a very low load (12 kN), continuing with a medium load (19 kN) and finally exposing the tyre to the condition required according to ISO 28580 (25.5 kN). Another (also important) purpose was to monitor the temperature of various parts of the tyre during running, with the aim to see where most of the energy is consumed.

As for the previous tests, the test was made at Idiada, but this author and Mr Hansson were able to follow it virtually in Sweden as the screen in the control room was continuously shown via link. Furthermore, MP4 videos were recorded over the entire test.

Equipment: The same Idiada platform for laboratory drum testing, as in the first drum test. However, a microphone was added near the tyre. This was carefully monitored.

Measurement method: The same as in the previous drum tests.

Test conditions: The tyre was loaded to the drum with load condition 12.0 kN. Run-up from 0 to 80 km/h. Ambient temperature at start was 25 ^{o}C. When 80 km/h was reached, after 10 minutes, the test continued at the constant speed of 80 km/h. At the time of around 15 minutes, it was noticed that something on the tyre had separated, and the test was stopped. The max tyre temperature first seemed to stop increasing at around 40 ^{o}C at 10 minutes of driving but was near 50 ^{o}C just before the test stopped.

After that, the tyre condition was inspected. It was found that on one part of the tyre circumference, tread rubber had moved partly over the bolt heads. See further, Chapter 8 about damages and actions to improve the prototype. Figures 20-21 show examples of screenprints at the start (Figure 20) and near the end of the test (Figure 21).

Acoustic observations: It was noticed already from the start of the tyre rotation that there was a repetitive noise – a complex noise like scraping. After frequency analysis revealed that it was repeated at approx. 8 Hz it became obvious that it was synchronized with the tyre rotation (not with the drum). The drum operator said that almost every (conventional) tyre tested created a similar type of noise.

In conclusion, until the bolts started to be covered by tread rubber, the test worked fairly fine (only) for 10-15 minutes.

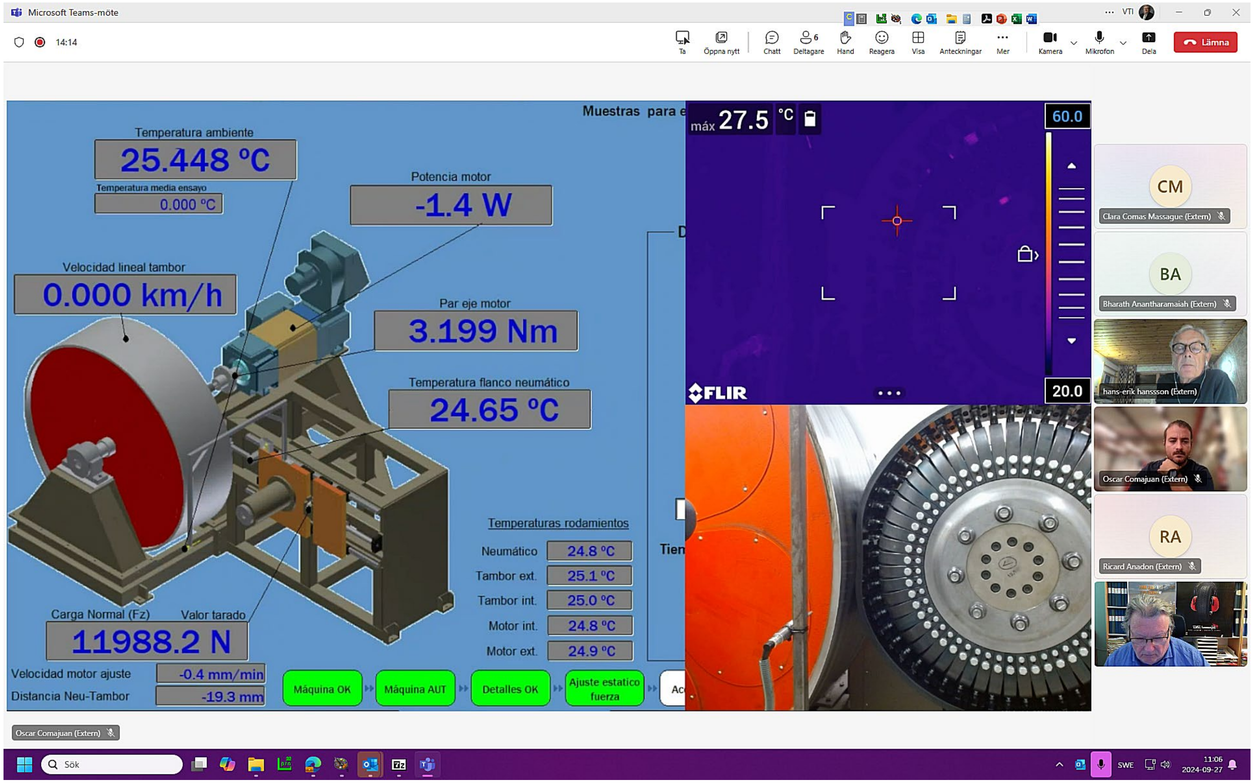


Figure 20: A screenprint made immediately before the test begun.

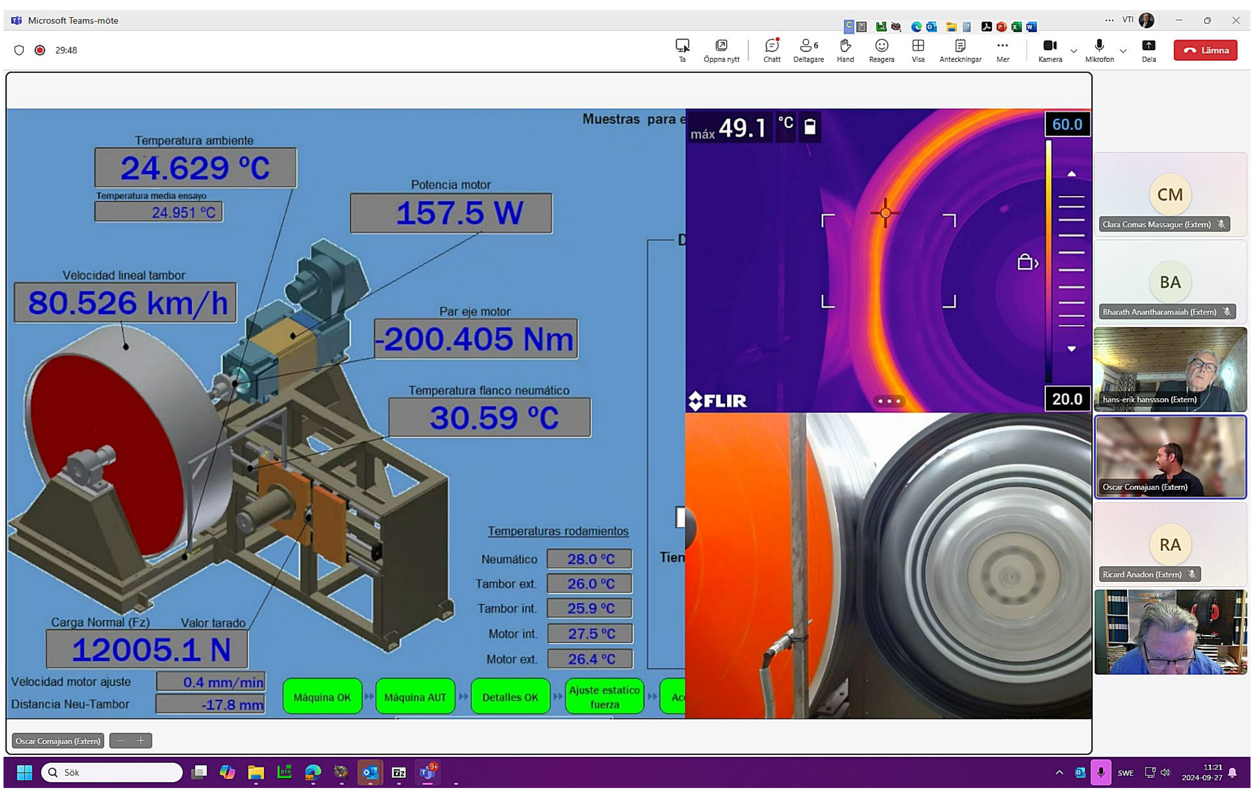


Figure 21: A screenprint made 15 minutes after the start and before the test was stopped. Note the thermal image in the upper right.

7.6 Noise test (Prototype 1b)

On 17 November 2024 a test of noise emission from the airless tyre was made on the Idiada test track, with the airless tyre mounted on the right rear (drive) axle on a truck. A microphone close to the tyre was used for the noise measurements. The results of those measurements are reported in another deliverable. The purpose was to measure the noise emission and tyre function or durability was just a secondary issue. Nevertheless, the experience in those terms is reported here.

The prototype variant was 1b, which had not so far been tested on a drum. The tyre was loaded by 1844 kg and run repeatedly on the regular asphalt pavement on the test track (thus, not the ISO test track normally used for noise tests). On a long straight section of the track the truck was accelerated slowly to a bit over 70 km/h, then the power unit was switched off and the truck coasted over this section, with a target speed of 70 km/h and then the speed gradually decreasing to under 50 km/h during the coasting. Such runs were made four times with an accumulated running distance of a few kilometres. After the test had been completed, the truck was stopped, the tyre dismounted, and the tyre condition carefully checked. Figure 22 shows the subject of the test when mounted on the test truck.

Figure 22: The airless tyre prototype 1b mounted on the test truck for noise measurements. Microphone holder is shown but the microphone itself was not mounted on this picture.

No severe problems were detected. One of the bolts had loosened and was lost somewhere along the track, which did not seem to result in any visual damage; just an empty hole in the tread and belt. Along the outer side of the tyre, at a few places along the circumference, it was noted that the connection between the belt and the rubber tread possibly might have loosened slightly. However, it was so little loosened that it might as well have existed before the runs were made. One could not with confidence say that it was the result of the runs on the test track.

7.7 Fourth drum test (Prototype 1b)

A fourth drum test was made 29 November 2024 on the Idiada platform for laboratory drum testing. The main purpose was, again, to visually check how the improved prototype behaved during exposure to the load, the speed and other conditions during the drum test. Before this test, the lost bolt from the noise test was replaced by a new similar one, also welded to make it firmly fixed.

The setup and initial conditions were as in the previous test (approx. 1200 kg of load). After about 8 minutes when the constant speed of 80 km/h was reached, a metallic transient noise was heard, and after another such noise was associated with a bolt hitting the window to the laboratory, it was obvious that bolts had loosened from the tyre and the test was stopped.

After exploring the tyre and the surroundings it was found that 5 bolts had loosened. Contrary to before, the mechanism was not that the nut had loosened from the bolt’s tread but that the bolt had broken in the tread between the head of the bolt and the welded nut. It was the same failure mechanism for all lost bolts. Neither the lost or the remaining bolts were very warm, as found when touching them just after the test was stopped.

It showed that the loss of a bolt on the test track was no unique occurrence. The bolts were of standard quality. Where they sit, they are exposed to forces in all directions, but probably mostly shear.

After this had happened, further tests were impossible as the project finished on the following day.

8. The various versions of the prototypes

8.1 The original prototype (1a) used for the first field test

All prototype versions are based on the similar construction of the hub, the rim and the 54 steel spokes, as described in Subchapter 6.2.2. Of this design, two samples were made: here named Prototype 1 and Prototype 2. The original idea was that the first sample (Prototype 1) would be used for steering and trailer axles, and thus have a tread pattern useful for such applications, with main features of longitudinal rather wide grooves and lateral-diagonal narrow grooves. The second sample (Prototype 2) would be used for driving axles and thus have a more “aggressive” tread pattern with larger lateral-diagonal grooves.

It must be reminded that due to the perforations in the grooves through the belt, there is not as much need for wide grooves in the tread pattern – water can escape partly through the belt. However, the problems with achieving sufficient durability made it necessary to focus on getting the steering and trailer tyre working, which made it necessary to skip the more complicated tread for drive axles. Also, the drilling of perforations was not fully applied, as it was intended to be made in the final prototypes, which were never produced.

The first prototype version (1a) was fitted with a belt made of GFRP (7.5 mm thick) and with a rubber tread (15 mm thick) made of a rubber, delivered by the Swedish company VulcTech, named Remaclave 60. It had only longitudinal grooves. Originally, a rubber from Linglong Tires was intended to be used, but at the occasion when the first prototype was made, enough Linglong rubber was not available, so Remaclave was fitted as a replacement.

The connection between spokes and belt was made by steel bolts and nuts with a washer between the nuts and the underside of the belt as well as between the bolt head and the upper side of the belt to distribute the stresses more favourably.

This version (Prototype 1a) was used only for the driving test (Subchapter 7.2). Figures 13-15 show how this prototype version looked like from various angles.

8.2 New prototype (2a) used for the first drum test

For the first drum test, a second prototype (2a) had been produced. It was similar to the first one (1a) except for the belt and rubber tread. The belt was made of CFRP (carbon fibres) and only 4.5 mm thick. ETU considered this belt is potentially better than the one made of GFRP (glass fibres). For this version, the Linglong rubber had been cut in strips long enough to be fitted around the belt and placed beside each other to create five longitudinal grooves in the tread.

This prototype version was shipped to Idiada in Spain and tested on their drum facility, as described in 7.3. As mentioned in 7.3, this tyre failed the test due to certain parts of the rubber tread separating from the belt after about 11 minutes operation at a load of 12 kN. See an illustration in Figure 22.

It was found that the reason was that the tensile strength (in radial direction) between the belt and the rubber tread was insufficient (1.4 N/mm). Why this happened was never clear, but it might have had something to do with the rubber and its vulcanization on the belt. ETU and VTI never got any detail specifications for the rubber from Linglong Tires.

Figure 22: An example of how the rubber tread had separated from the CFRP belt. This happened at several places along the tread.

8.3 New version (2b) with different rubber

The analyses of potential causes for the separations included measuring the tensile stresses between the rubber and the belt on a small sample of the belt and rubber. A very simple setup for this is shown in Figure 23.

The result showed that the strength of the bond between belt and rubber was only 1.4 N/mm.

Figure 23: Simple setup of a test to measure the available tensile stresses between belt and rubber before separation. The material samples in the picture are from another project.

This is too low; thus, to solve this problem, it was decided to modify the tread as follows:

- New type of rubber (Remaclave 60 supplied by VulcTech)
- Narrow grooves cut in the ribs between the longitudinal grooves (at about 30°)
- As for Prototype 1a, the rubber was vulcanized to the belt using a pressure of 4.2 bars, at a temperature of 115 °C for a duration of 3.5 hours.

A test of tensile strength for the new belt and rubber showed that it was increased by a factor 7.5 (from 1.4 to 10.6 N/mm). This was a remarkable improvement which was considered acceptable. The Remaclave rubber is not optimized for tyres but is used in very demanding conditions on conveyor belts in the mining industry. It is made of natural rubber having a hardness is 60 Shore A, so it is similar to what is common for tyres in new condition.

Consequently, a new prototype version was created (named 2b), based on Prototype 2a. It had a carbon fibre belt and a rubber tread (5 grooves and thus 6 parallell ribs) made from a natural rubber. This was different from Versions 1a and 2a also in its tread pattern, since narrow grooves were cut diagonally across the ribs. These grooves were about 2 mm wide, i.e. they were somewhat wider than common sipes in conventional tyre treads. The main reason for these was to reduce the longitudinal stresses in the rubber ribs. Additionally, holes ("perforations") for ventilations of air pressure were drilled through the belt in all grooves at the same distance as the distance between bolts (see Figure 24).

The connection between the steel spokes and the belt was the same as for Prototypes 1a and 2a. The appearance of the tread pattern is shown in Figure 24. This picture was taken after the second drum test, on an undamaged part of the tread.

At hindsight, it is important to remember that the tensile stress test was made on a separate small sample and not on the actual tyre; albeit the materials and vulcanizations were identical. However, there is no guarantee that such high tensile stresses were endured all around the belt and tread of the actual tyre.

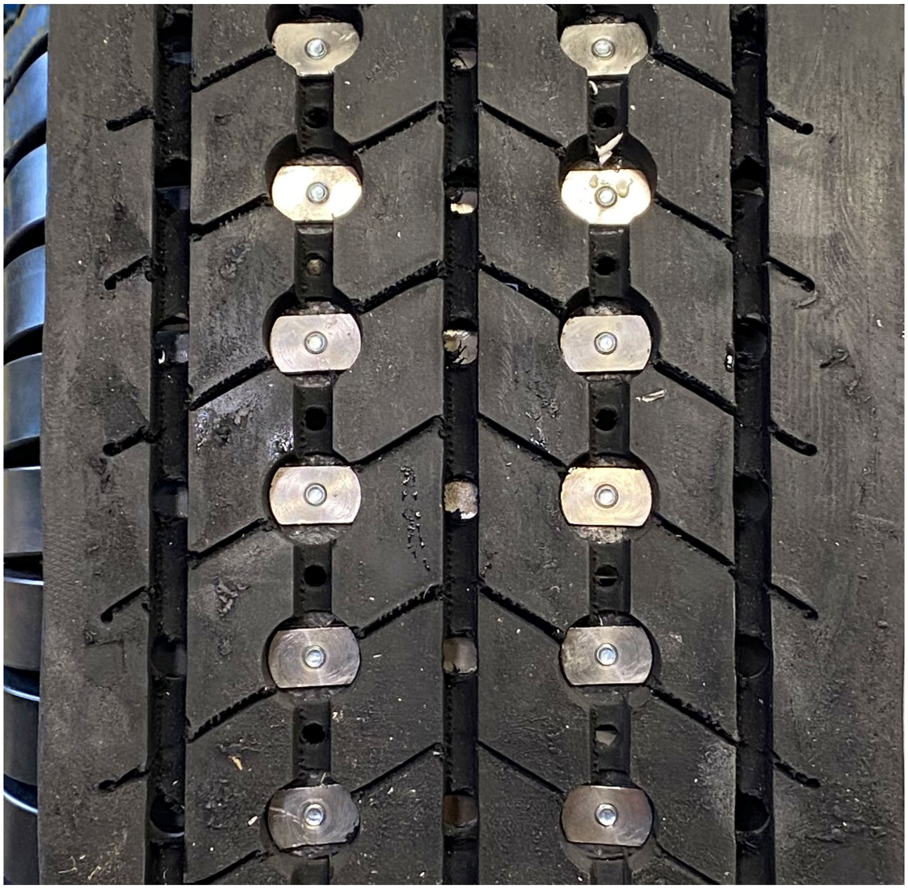


Figure 24: The tread of Prototype 2b. Note the holes in the bottom of all 5 longitudinal grooves. Note also the “semi-rectangular” steel nuts which hold the bolts from the spokes under the belt.

As reported in Subchapter 7.4, this tyre failed due to loosening of several bolts, which partly separated the spokes from the belt. About 15 % of them had loosened or had been thrown away.

8.4 New version (2c) with different spoke/belt connection

To repair the loosening of several bolts connecting the belt to the spokes, the immediate idea was to add special locking washers to the bolts in order to secure them from start rotating and loosening. ETU consulted the best available experts at the Swedish company Nord-Lock (https://www.nord-lock.com/). They supplied the best locking washers available; however, it turned out when testing the connection that the washers were unable to lock against the spokes, no matter the torque applied, since the spokes were made of exceptionally hard steel.

The next trial intended to weld the bolts to the spokes. Unfortunately, the first trials suggested that the heat was so excessive that the rubber and the belt may be compromised. As a last (?) option, ETU and Nord-Lock came up with the idea to add thin metal plates on both sides of each spoke, connecting the two bolts that held the spoke to the belt. See the photo in Figure 25. The locking washers worked well against those metal plates, which meant that the bolts could not move any more under normal circumstances. The metal plates were 2x54 (two rows for 54 spokes) and added a total of 4.3 kg to the weight of the tyre. This new version is named Prototype 2c.

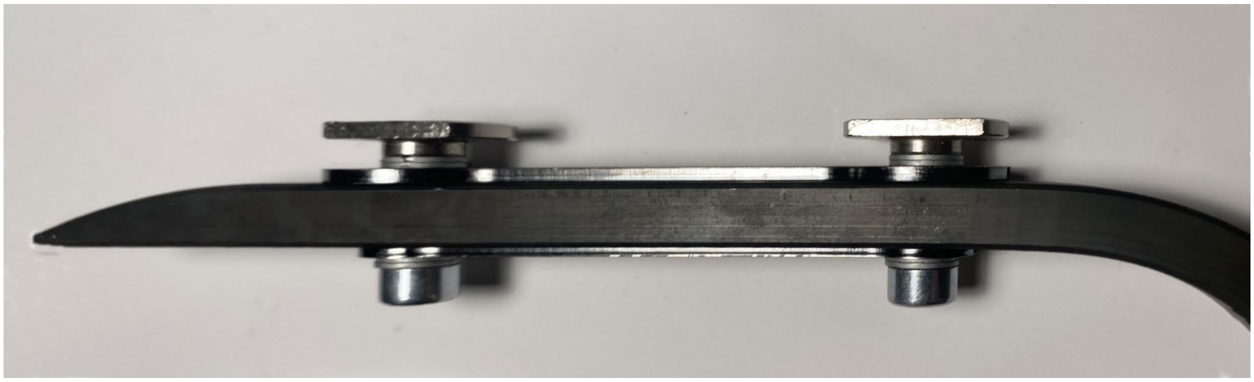
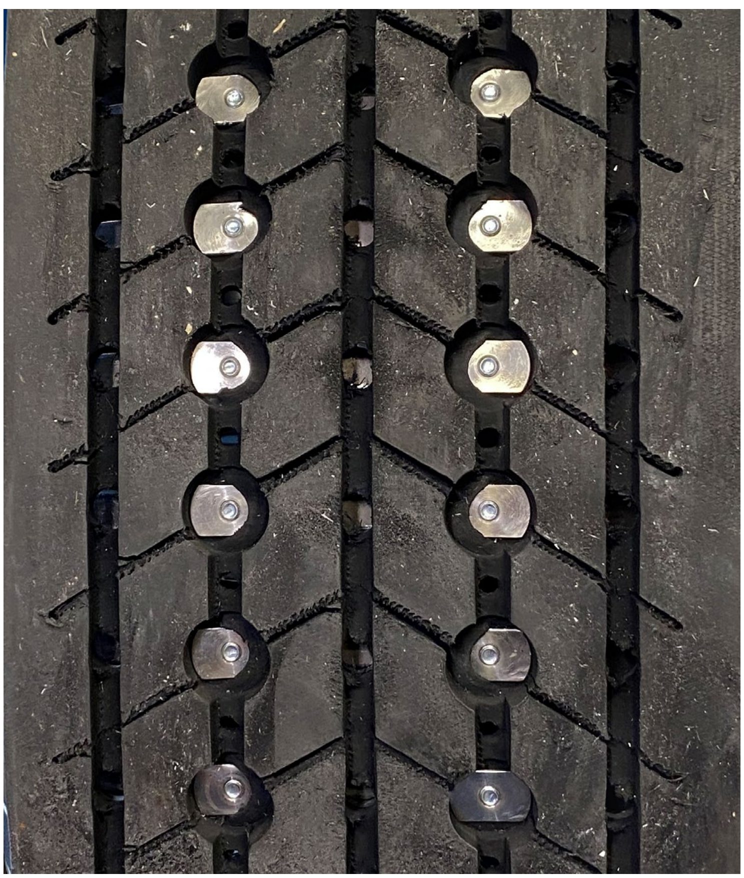


Figure 25: Showing the thin metal plates added on both sides of the spoke, with locking washers. Note that the belt and tread would be fitted on the top of the upper plate.

It is not an ideal solution but at the time and under time pressure it was the available solution. This main author was concerned about a possibility of some scratching noise between the metal plates and the spokes when the tyre was under serious dynamic loads. Note, however, that later trials with welding at VTI have suggested that it would be possible to weld the bolts to the spokes without the risk of overheating the belt and rubber.



In the third drum test described in Subchapter 7.5, this version (Prototype 2c) turned out to have insufficient tensile strength in the belt-rubber tread connection. Serious delamination was observed around the bolts in this area and rubber had moved up partly over the washers; see Figure 26. But no problems with loosening bolts were noticed, indicating that securing the bolts from loosening as shown in Figure 25 was successful in this trial.

Figure 26: The tread of Prototype 2c after the third drum test. Note that rubber had partly "crept-up" over the "semi-rectangular" steel nuts which hold the bolts from the spokes under the belt (compare with Figure 24). The reason was delamination near the bolts.

8.5 The last version (1b)

Fir the last tests, to be made at Idiada in the second half of November 2024, there was no other prototype in condition good enough for testing than the first one. Prototype 1a had been modified early in 2024 by adding diagonal narrow grooves in the tread. For the last tests, also the fixing of the bolts and nuts to avoid that they get loose needed attention. The modification chosen for this was to weld the nuts on the bolts. Figure 27 shows a picture of this. It was made in a way which did not damage the rubber or belt by the heat exposure.

This version (Prototype 1b) was used only for the noise measurement test (Subchapter 7.6) and also for the fourth drum test (Subchapter 7.7). In the latter case, however, the bolts and nuts were welded together, and diagonal grooves were cut in the tread.

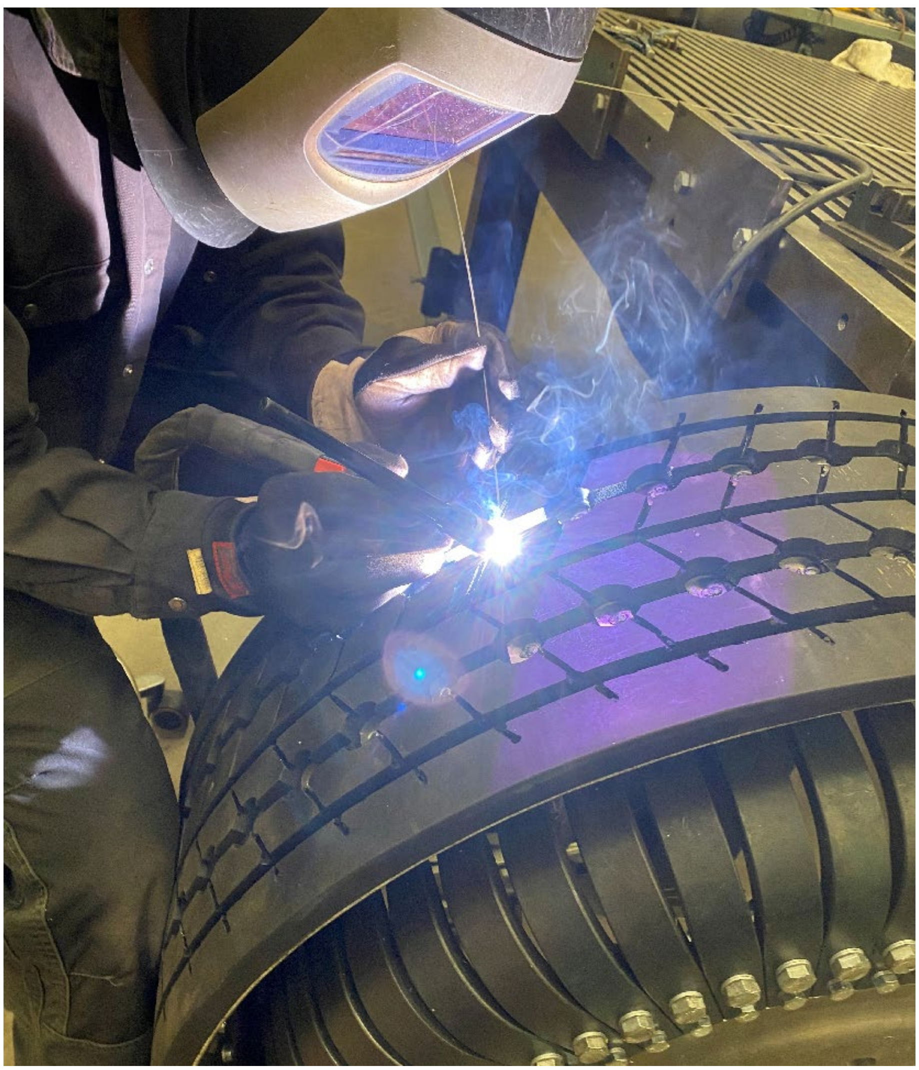


Figure 27: Welding of nuts on the bolts, made by the VTI welding specialist, to secure that they cannot separate during the tests.

8.6 Summary of the prototype versions

A summary of the prototype versions in table format is shown in Table 2.

Table 2: The different prototype versions and how their main features differ.

Proto-type	**Component**	**Description**	**Available**
1a	Spokes	High-strength steel	Nov 2023
	Belt	Glass fibre reinforced plastic GFRP, 7.5 mm	
	Connection spokes/belt	Bolt, nut and common washers	
	Tread rubber	Remaclave 60 (from VulcTech)	
	Tread pattern	4 wide + 1 narrow longit. grooves	
2a	Spokes	High-strength steel	Jan 2024
	Belt	Carbon fibre reinforced plastic CFRP, 4.5mm	
	Connection spokes/belt	Bolt, nut and common washers	
	Tread rubber	Linglong Tires	
	Tread pattern	5 wide longit. grooves + diag. narrow grooves	
2b	Spokes	High-strength steel	July 2024
	Belt	Carbon fibre reinforced plastic CFRP, 4.5mm	
	Connection spokes/belt	Bolt, nut and common washers	
	Tread rubber	Remaclave 60 (from VulcTech)	
	Tread pattern	5 wide longit. grooves + diag. narrow grooves	
2c	Spokes	High-strength steel	Sep 2024
	Belt	Carbon fibre reinforced plastic CFRP, 4.5mm	
	Connection spokes/belt	As before + Metal plates and locking washers	
	Tread rubber	Remaclav 60 (from VulcTech)	
	Tread pattern	5 wide long. grooves + diag. narrow grooves	
1b	Spokes	High-strength steel	Nov 2024
	Belt	Glass fibre reinforced plastic GFRP, 7.5 mm	
	Connection spokes/belt	Bolt, nut and common washers, welded	
	Tread rubber	Remaclave 60 (from VulcTech)	
	Tread pattern	4 wide + 1 narrow longit. grooves	

Note that the last one is being considered and worked on when this is written, and it is not entirely sure that it will be available before the end of LEON-T.

9. Future outlook for later prototypes

9.1 Potential improvements: spokes

The choice of steel for the spokes in this project is not optimal with respect to weight. There are more advanced composite materials that would be lighter, but not possible to use in the LEON-T project. It was recently reported that a new lightweight material which is stronger than steel has been developed. Using a novel polymerization process, MIT chemical engineers have created a new material that is stronger than steel and as light as plastic and can be easily manufactured in large quantities [MIT, 2022].

The new material is a two-dimensional polymer that self-assembles into sheets, unlike all other polymers, which form one-dimensional, spaghetti-like chains. Until now, scientists had believed it was impossible to induce polymers to form 2D sheets [MIT, 2022].

It was of course not possible to introduce this material already in the LEON-T project, but it may be something which can be a very favourable replacement of the steel in the future airless tyres, greatly reducing the weight of the tyre and also reducing rolling resistance.

The authors believe that an alternative to steel spokes would be CFRP, but instead of the unidirectional fibres, as was first tested in this project but failed, a multidirectional fibre reinforcement would potentially be sufficiently strong.

Another way to reduce the weight is to use lighter materials in the rim. Also, bolts, nuts and washers for fixing belt to spokes can potentially be replaced by using rivets or with completely different principle of connecting spokes to the belt.

With all these weight reducing measures, the total weight of the airless tyre will be lower than that of a conventional tyre for the same load capacity.

9.2 Potential improvements: belt

In this project a belt with thickness of only 4.5 mm was used. There was not enough time and capacity to calculate the optimum thickness. Stiffness measurements showed that the belt used gave a relatively high stiffness (Table 1) and even higher stiffness may not be desirable. Nevertheless, it is possible that a thicker belt would be needed for enduring longtime exposures to maximum loads, but then multidirectional fibres would be better than the unidirectional ones used here.

Autoclave conditions at vulcanization were rather similar to those used for a new tyre according to our information, but it could well be that in this special case and materials, one would find more optimal conditions. There was not time to experiment with this.

9.3 Potential improvements: rubber tread

The tread was far from optimal. For sure, there are rubber compounds that are better for noise and rolling resistance reduction, but this project relied on unknown rubber from Linglong Tires, and another rubber from VulcTech which is also unspecified. We did not attempt to produce a tread pattern of state-of-the-art type; simply because we did not consider it necessary since the basic construction of the airless tyre should reduce noise emission and provide good wet friction. Earlier truck tyres having longitudinal grooves (only), whether straight or zig-zag types, generally gave low noise emissions, except for the so-called pipe resonance in the grooves. But this resonance should not appear in our case if the perforations in the bottom of the grooves are well dimensioned.

Another potential improvement worth mentioning, among several other compound improvements, is improving the rubber with graphene, as proposed by the Levidian company in the UK. At the Tire Technology Expo in Hannover, the graphene-enhanced natural rubber and butadiene rubber tyre tread compound, typically to be used in commercial vehicle tyres, was suggested to deliver significant improvements in the mechanical and dynamic properties of the tyre [TTI Expo, 2024].

9.4 Potential improvements: tread/belt perforations

As shown in [Sandberg, 2009] perforations (holes) through the belt and tread are important for reducing some of the most dominating noise sources. In the Composite Wheel (the airless tyre made for cars) the area of holes in the tread/belt was about 2.8 % of the total tread area. It would have been even better with higher area, according to [Larsson & Schade, 2004].

In the airless tyre in this project, prototypes 1b and 2a, 2b and 2c had such perforations. This author calculated that the perforations of the grooves where bolts are placed account for approx. 5400 mm^2 and the ones in the outer grooves for approx. 10300 mm^2. The centre groove has perforations too, but they are mostly covered below by the spokes. This hole area corresponds to about 2.1 % of the tread area. However, the main part of the perforations is in the outer grooves where they would be less effective in reducing local air pressure gradients.

Consequently, it is expected that the perforations are not as effective for noise reduction as they could have been. The area of perforations should have been twice as large and be equally distributed in all grooves. It was the intention to drill more perforations in a later prototype version, before noise measurements were done, but project time did not allow this.

9.5 Potential improvements: spoke-to-belt connections

The tests suggested that the most critical part of the airless tyre prototype(s) is the connection between the spokes and the belt, and further between belt and rubber. When bolts, nuts and washers were only fixed by tightening of the nuts on the bolts (torque 21 Nm), some of the nuts loosened from the bolts and were thrown away. When the nuts were fixed by welding on the bolts, the bolts were broken. This demonstrates the excessive forces that are involved there.

The authors speculate that the system (belt/spokes) is too stiff and more flexibility should be introduced to reduce the dynamic forces. Probably, this would require a totally new connection system; possibly by producing a belt and tread system similar to conventional tyres but where the spokes are vulcanized into that system. The spokes should also be of a more flexible material than steel, such as GFRP. But first, the relevant dynamic forces should be modelled and simulated to give better background for the design.

9.6 Potential improvements: other means

A very interesting idea that may be especially useful for airless tyres is the “zipper” procedure for replacing treads put forward by Continental Tires. Essentially this enables the tread to be removed from a tyre, either leaving behind fresh tread or allowing a new tread to be attached – or zipped on, in other words [TTI, 2023]. Application of this would offer a rather fast change of rubber treads optimized for various climatic regions or seasons or simply for exchanging a worn tread by a new one.

9.7 Discussion about the future outlook for airless tyres

Obviously, airless tyres solve the potential problem of punctures. Depending on construction, there is also the possibility to use the same basic structure during the full lifetime of a road vehicle, and thus needing only replacement of rubber treads when they are worn-out. This would save substantial raw materials.

The authors believe that the airless tyres may be successfully implemented, especially, but not only, in the design of electric road vehicles. This is for three main reasons:

- Rolling resistance may potentially become substantially lower, increasing the operating range of such vehicles; while also reducing global energy production needs for the transportation sector and simultaneously the CO_2 emissions
- In at least the design proposed here and in earlier projects, there is space for integrating electric motors and brakes on the inside of the tyres (see Figures 5 and 13)
- Noise emission from airless tyres properly constructed will be reduced; thus, making electric vehicles quieter also at higher speeds

If WP5 of the LEON-T project would be a success, it might boost further development of airless tyres to a final market introduction. However, before that, the Uptis tyre may find a practical use on certain electric road vehicles. But other tyre manufacturers may not want to be left behind, given the expanding electric vehicle production in East Asia with China in the leading position. Therefore, the next 5-10 years will be very exciting for the tyre and vehicle industries and all other stakeholders, as well as engineers and researchers.

Additive manufacturing (also known as “3D-printing”) is becoming more common at an amazing rate. To produce road vehicle tyres by this process, utilizing maybe 100 different materials or compounds (as contained in modern conventional tyres), would be extremely complicated, and no such attempts have been reported publicly, so far. However, the airless tyre design, on which WP5 of LEON-T was based, promises much less complicated manufacturing, and future tyres of this type may well be manufactured in that way; something which probably would speed up the manufacturing a lot and also make it less expensive. Matters such as these are discussed in [Yurkovich, 2019].

Even if some airless tyres will give very favourable performance, one may expect that market introduction will be delayed, for the same (and amplified) reasons as the radial tyres introduction was delayed in North America due to restructuring of manufacturing plants, combined with vehicles needing some redesign. When airless tyres, apart from the treads, may last as long as the vehicle, the tyre replacement market will die in favour of a heavily expanded retreading market. The normal lifetime of tyre manufacturing plants lasts for decades, so everybody in the tyre and vehicle industries will not be happy with too rapid developments. Consequently, and unfortunately, an anticipated airless tyre revolution will likely take a long time.

10. Conclusions

The following present some conclusions from this Deliverable:

When this project was planned, the authors strongly suggested that the project time should be four years, as the initially proposed and decided three-year project duration is too short for development of airless tyre prototypes. However, the majority decision was a three-year project. Later, it was agreed to extend LEON-T to 3½ years. Time has shown that not even 3½ years was enough.

Initially, it was intended to scale up the CW concept for an airless tyre in an earlier project from car to truck size, using similar composite material (CFRP). An HGV tyre would require about 5-8 times higher load than the car version in the earlier project. Unfortunately, LEON-T's initial calculations and simulations indicated that using the CFRP did not result in a durable tyre. Instead, replacing the spokes made of CHRP with high-stress steel, showed promising results and has been the design which is worked on in LEON-T. Nothing has indicated that the spoke design with high-strength steel was a wrong decision, given the time frame and budget. Nevertheless, there are more advanced composite materials that might have been preferred, but project resources have not been enough to manufacture and use such advanced materials.

Developing an innovative new tyre for HGV tyres is of course a much more challenging task than to do so for car tyres. This is reflected in the fact that there are many concept tyres of airless type presented for cars but only one known so far for trucks, and that one is not for the heavy trucks. The call for the project which LEON-T answered to requested an HGV tyre, so consequently this was the challenge that WP5 had.

All of the tyre manufacturers' concepts for road vehicles feature an elaborated pattern of "spokes" or honeycomb structures in composite materials which seem to be rather complicated to manufacture. The LEON-T version developed by ETU is very different from those other concepts, with much simpler spokes which potentially are much easier to manufacture. Another unique feature of the LEON-T tyre is that it has holes drilled radially through the tread and belt, in order to ventilate air and thus reduce air pressure gradients in the contact area and around its edges. This also has the effect of draining water away from the tyre/road contact patch.

When the project is near its end, two physical prototypes have been produced, both of them having the same spoke construction and material. Of each one there have been different versions with differences in belt, rubber tread and the connection between belt and spokes. If an HGV tyre under test (with loads of up to 3000 kg) is substantially damaged, it may cause quite extensive damages to the vehicle it is mounted on, as well as to its environment, so initial durability tests were necessary. Therefore, the prototype versions were tested on a laboratory drum facility at Idiada to check that they could carry the intended loads long enough to go through advanced full-scale measurements. Unfortunately, all versions failed in providing sufficient durability.

All the versions look the same, except for some details in the tread and belt, and a representative illustration is seen in Figure 28.

Figure 28: The first prototype available, displayed at a meeting of LEON-T in Linköping in November 2023. Mr Hansson (ETU, inventor and tyre constructor) is the person in brown coat in the middle, the person in black coat is Dr Garcia (Idiada, Project Coordinator) and the person in blue shirt is Dr Sandberg (VTI, Leader of WP5).

The first version failed because the connection between belt and rubber tread was too weak, causing delamination between the belt and rubber at many locations along the tyre circumference. The reason was not definitely identified, but a change from the rubber obtained from Linglong Tires to a rubber proposed by the vulcanization company gave a dramatic increase in the radial tensile stresses that the connection could endure. The next version had this new rubber, also using a new belt material and implementing some minor changes in the tread pattern. The second version endured longer testing but it appeared that, by time the bolts, washers and nuts connecting the spokes with the belt started to loosen up, and finally some of them were thrown away by the centrifugal forces, requiring an immediate stop to the testing. The third version had special measures to secure that the bolts would not loosen. Unfortunately, instead, some delamination between the belt and rubber occurred near to the bolts on a part of the tyre circumference.

The final version had the bolts and nuts secured by welding but then radial and transverse forces were so strong that the bolts broke. This highlighted the major problem: the forces in connecting the belt to the spokes are so severe that the technique used for the passenger tyre version (the so-called CW tyre) and upgraded to the HGV case in project LEON-T, is not strong enough. For a durable construction it is first necessary to model the forces under dynamic conditions and then come up with an appropriate design.

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