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LEON-T

Low particle Emissions and lOw Noise Tyres

Airless tyres – History, previous trials and present concepts

LEON-T Report by
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Revision history

REVISION	DATE	DESCRIPTION	AUTHOR (ORGANIZATION)
--	2022-07-28	First complete version of the deliverable	Ulf Sandberg VTI
1	2022-08-04	Terminology, list of symbols and abbreviations added	Ulf Sandberg VTI

SUMMARY

This Deliverable is intended to provide a background and platform for WP5 in project LEON-T, in which two prototypes for airless heavy goods vehicles (HGV) tyres shall be be developed. It is intended to be a state-of-the-art report about the airless tyre concept, analysing both possibilities and challenges, while utilizing the experience of earlier projects dealing with innovative, especially airless tyres. The first experience of the work on an airless tyre prototype in LEON-T is also briefly reported to show how it relates to other concepts.

It is now exactly 40 years since Goodyear filed its patent for an airless tyre (called IWT), and a few years later published a scientific article about it; reporting very good performance in the tested respects. Given the intensive R&D work in the tyre industry sector, one may find it remarkable that after such a time there is still no such tyre on the market for road vehicles.

At the end of the 1980's, unaware of the Goodyear IWT, Hansson's Swedish invention of the "Composite Wheel (CW)" was tested, with a primary view of reducing exterior tyre/road noise and rolling resistance. This was probably the second airless concept. Later generations of the CW were tested about 15 years ago in a multi-national project led by the author, in which excellent noise reduction and rolling resistance was obtained along with good road handling. However, it did not endure the ultimate test: high-speed running on a pot-hole test track.

The construction of the CW (car) tyre was then accepted as a basis for airless tyre prototypes for HGV:s in LEON-T. The scaling-up of the CW concept from car to truck size, using similar composite material (CHRP), which would require about 5-8 times higher load than the car version, did not result in a durable tyre, according to initial calculations and simulations. However, replacing the spokes made of CHRP with high-stress steel, has showed promising results and is currently the design which is worked on in LEON-T.

The review made in this report of airless tyre concepts presented by tyre manufacturers has shown that most the major tyre manufacturers have been working on own concepts, more or less similar, which in a few cases have resulted in prototypes for testing. The first airless tyre reaching a market was the Tweel, although it is not used on road vehicles. The Uptis from Michelin is currently being tested on a GM electric car, and the Goodyear NPT has been tested on a Tesla car and is currently used on an in-service minibus in Florida.

All concepts have been designed for passenger cars, except that Bridgestone has a construction for a medium truck. Bridgestone also offers airless bicycle tyres, which also have been constructed by an Indian researcher at University of Rostock.

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. It is anticipated that they will be possible to produce by additive manufacturing (aka 3D printing). Nevertheless, those constructions are less complicated than pneumatic tyres.

Compared with the airless concept tyres by the tyre manufacturers, the design by Hansson, 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 CW and the LEON-T tyre will have a unique rubber tread, as it will have holes drilled radially through the tread and belt, in order to ventilate air and drain water away from the tyre/road contact patch.

Only a few scientific publications dealing with airless tyres could be found. Most of the information comes from press releases from the tyre manufacturers, or news articles based on marketing materials from them. With regard to quantitative information about noise or rolling resistance performance of airless tyre prototypes, only data from the earlier tests of CW tyres (by this author and his co-authors) are available. However, statements by representatives of tyre manufacturers rather consistently suggest that rolling resistance of airless tyres should be lower than for corresponding pneumatic tyres. Other performances seem to be more uncertain, except (of course) the puncture-proof operation of airless tyres.

It is anticipated in most publications and interviews with experts that airless tyres will win a significant part of the market in the future, especially for electric vehicles, albeit there is also much scepticism about it. Rolling resistance may be kept at a more optimal level as there will be no air that need to be filled to compensate for leakage. Maintenance-free operation is mentioned as something expected to be of special value to autonomous vehicle driving in the future.

It is likely that we will soon see some results of the ongoing tests of airless tyres on test vehicles. However, the outlook for marketing such tyres is uncertain, since airless tyres will require new factories and if they will take over a significant role of the pneumatic tyres, it will mean a revolution to the entire tyre industry with some of the existing facilities becoming obsolete. But at the end of the day the value of airless tyres in terms of lower rolling resistance and other environmental advantages should justify such a revolution.

Terminology issues

In this Deliverable the following terms are often used and below they are described or commented on. The descriptions are not necessarily internationally accepted definitions.

Term	**Description or comment**	**Note**
Tyre	British and other European English spelling	Same as tire in North America (and East Asia)
Tire	American English spelling	Same is tyre in the U.K. and other European countries
Airless tyre	Tyre which is not relying on inflation by air	Same as air-free tyre and non-pneumatic tyre
Sound	Air-pressure variations in the air, picked-up by human ears	In principle this is an objective parameter
Noise	Unwanted sound	In principle this is a subjective parameter, but represented by a technical parameter (noise level)
Noise level	Generally the same as sound level, but (unless otherwise noted) weighted by a filter of type A	The A-weighted noise level is intended to represent the general perception or disturbance of the noise (which is arguable)
Tyre/road noise	Noise emitted from the tyre when it is rolling on a road or test track	Same as tire-pavement noise in American English. In legislative documents in English in the UN ECE or in the EU “rolling noise” or “rolling sound” are often used
Power unit noise	Noise emitted from the power (or propulsion) unit of a vehicle (such as engine, exhaust, fan, transmission)	Sometimes referred to as propulsion noise or power-train noise

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	Partner
GM	General Motors Company	Not directly related to LEON-T
GUT or TUG	Gdansk University of Technology	Previously Technical Univ. of Gdansk, will be subcontractor for noise and rolling resistance measurements
Idiada	Idiada Automotive Technology S.A.	Partner
LDAB	Lightness by Design AB	Supplier to ETU
VTI	Swedish Road and Transport Research Institute (VTI)	Partner
Abbreviations		
C1 (tyres)	Tyres intended for passenger cars	
C3 (tyres)	Tyres intended for trucks and busses	
CFRP	Fibre reinforced plastic	
CPX	Close-Proximity	Measurement method used to measure tyre/road noise emission by means of microphones close to tyres. See ISO 11819-2, ISO/TS 11819-3.
CW	Composite wheel	Used for the airless tyre prototypes produced in Sweden previously
EV	Electric vehicle	
FE / FEM	Finite elements	Finite Elements Method
HGV	Heavy goods vehicles	
ICE	Internal combustion engine	
IWT	Integral Wheel-Tire	Used by Goodyear in early research
NPT	Non-pneumatic tyre	Often used by Goodyear
NVH	Noise, vibration and harshness	
TTI	Tire Technology International	Company publishing tyre information
WP5	Work Package 5	In LEON-T
Measures, symbols or units		
dB	decibel	Unit for sound or noise level
dBA or dB(A)	A-weighted decibels	Only dB preferred by ISO

List of content

1. The pneumatic tyre, an extremely sophisticated vehicle component

The pneumatic (or air-inflated) tyre as a concept was invented in the 19th century and was conquering the market for tyres in the first decades of the 20th century. Since then, this concept has completely dominated the tyre market and is currently stronger than ever. The basic idea is to use compressed air contained in a toroid or torus as a cushion between the vehicle and the road pavement and to let the solid materials in the outer part of this toroid or torus transfer the forces in both transverse and longitudinal directions between the axle and the pavement. To this end, a rubber tread is added around the torus. However, the most essential material in the tyres is air which, in case of punctures, will make the tyre non-useable. Trials have been made with inflation by other gases, primarily nitrogen, but air is used in almost all road vehicle tyres.

The product we call tyre and is used on all rolling vehicles, is thus pneumatic in its principle and relies on a proper inflation. From its invention until today, the main principle is the same, but today's product has been improved continually and in several relatively small steps over the more than 100 years since it entered the market. A layman looking at the tyres of his vehicle may get the impression that it is a quite simple component of the vehicle: a rubber ring pumped-up by air? Nothing can be more wrong; today's typical tyre is an incredibly sophisticated product; an average tyre for cars and trucks today contains well over 100 separate components of various materials. It is often claimed by experts that the tyres are the most important and sophisticated part of a road vehicle. Rubber is the main raw material used in manufacturing tyres, and both natural and synthetic rubber are used, where synthetic rubber constitutes 60-70 % of the total rubber amount. Other materials include carbon black, various oils, sulphur, silica, textile and steel reinforcements, to name a few.

Due to the combination of all the materials, it is clear that manufacturing pneumatic tyres is very complicated. This means that manufacturing plants and the materials chains get complicated too, which has led to very substantial investments by the manufacturers that must be paid off during decades of production. Thus, when the radial tyre was invented by Michelin in the 1940's, despite it soon was found to be technically much better than its predecessors (i.e., the diagonal or bias ply tyres), it took until the 1960's until the radial tyre became dominant on the European market. However, in USA, the tyre and vehicle manufacturers hesitated to accept the radial tyres. It was not until about 20 years after Europe when radial tyres started to dominate the market in USA. This was partly due to US cars with very soft suspension not being adapted to the new tyres, partly due to the refusal to rebuild their tyre plants, as radial tyres required very costly retooling.

This Deliverable will describe, explain and discuss a new tyre concept which by some experts is considered as a product that may be an alternative to or even replace the pneumatic tyre as the major tyre on future road vehicles: the airless tyre.

2. Purpose with this Deliverable

This Deliverable is intended to provide a background and platform for WP 5 in project LEON-T, in which two prototypes for airless HGV tyres are intended to be developed. It will be a state-of-the-art report about the airless tyre concept, analysing both possibilities and challenges, while utilizing the experience of earlier projects dealing with innovative, especially airless tyres.

3. Terminology – Pneumatic, airless and other tyres

There are many definitions of “tyre” (British English) or “tire” (American English). The Cambridge Dictionary defines it as “*a thick rubber ring, often filled with air, that is fitted around the outer edge of the wheel of a vehicle, allowing the vehicle to stick to the road surface and to travel over the ground more easily*”.

A more advanced and modern definition, as suggested in one of today’s major books about tyres, reads: *A tyre is a composite material which has rotational symmetry, is non-isotropic, and is comprised of several rubber components which are bound together, and whose strength characteristics are determined by textile or other steel reinforcement materials* [Leister, 2018].

As already indicated, the spelling of the word is different in British and American English: where tyre is used in British, and tire is used in American English. Since LEON-T is a European project, the British spelling is used in this Deliverable.

The types or concepts of various tyres which may potentially be used on road vehicles are the following:

Pneumatic tyres: tyres where air or another gas is contained in a torus inflated sufficiently to carry the load applied to the tyre. This is the almost totally dominating tyre type of today’s road vehicles.

Solid tyres: tyres similar to the pneumatic type, but in which the gas is replaced with some solid material(s) such as polyurethane. Such tyres are used mainly on military vehicles to avoid being punctured, but attempts have been made to try the concept also on road vehicles. Solid tyres are also available for bicycles.

Airless tyres: tyres where a solid, flexible material such as rubber, reinforced plastic or metal (separately or in combination), transfer the vehicle load from the hub to the circumferential tread. Other terms used are **air-free tyres** or **non-pneumatic tyres**.

Other concepts that have been tried recently include building air inflated tyres with essentially only a plastic torus fitted with a rubber tread.

4. Historical review

As early as in the May 1938 edition of Popular Science, it was reported that one J V Martin of Garden City, NY, had used spokes of ribbed rubber encased in rings of rubber-coated hickory hardwood to form a ‘safety tire’ [Heeps, 2020]. However, there seem to be no traces of further development of this design.

In 1982, Goodyear was granted a patent for an Integral Wheel-Tire (IWT) for passenger cars, based on a single-sided wheel rim with an asymmetrical deformation behaviour [US Patent, 1982]. The IWT was made of composite materials, having a circumferential part covered with a rubber tread. An extensive, scientific report dealing with this IWT was presented in 1989 [Su, 1989], showing a rather simple structure, intended for a passenger car tyre; see Figure 1. The Goodyear prototype had been tested quite extensively, indicating very good characteristics in many essential parameters (not including noise or rolling resistance). Yet, nothing more happened, at least not publicly reported.

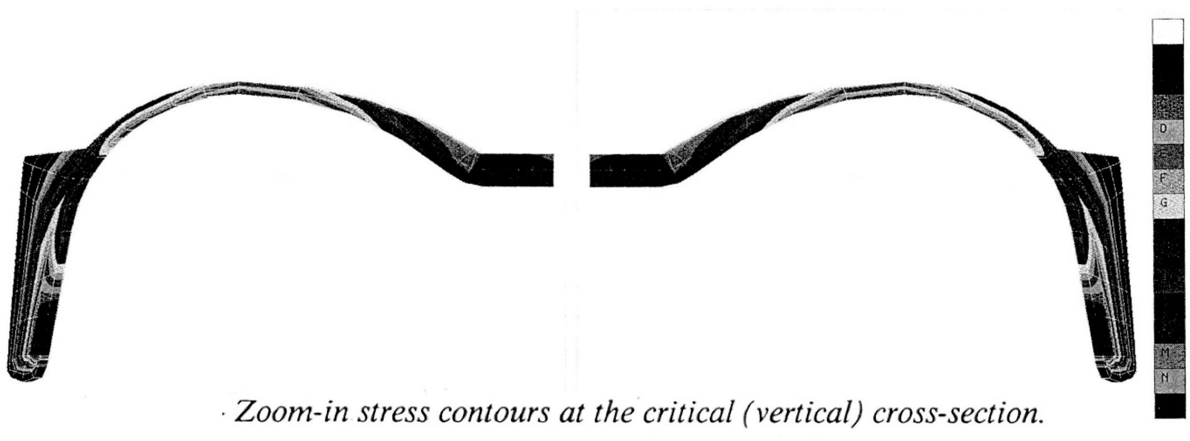


Figure 1: Cross-section of the Integral Wheel-Tire (IWT) by Goodyear [Su, 1989].

Without being aware of the Goodyear concept, another airless tyre (also 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, like the Goodyear IWT, was a non-pneumatic, highly flexible construction in composite materials giving unique characteristics. Relative to the Goodyear design it used a more sophisticated shape, potentially giving much more flexibility in the design. Hansson's first idea was to provide puncture-free and easy-rolling tyres for racing bicycles and trotting sulkies. When VTI was consulted, 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.

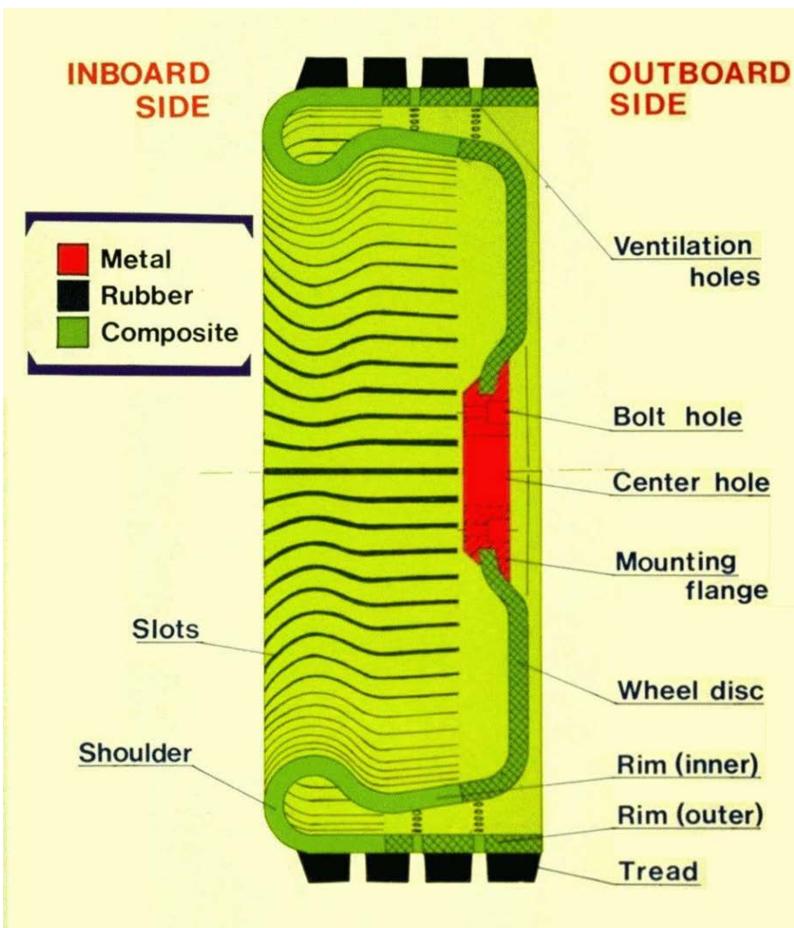


Figure 2: Cross-section of the Composite Wheel of 1989, as invented by Hansson and with ventilation holes by the author [Hansson, 1990].

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].

Only one prototype was available, making it necessary to do testing on a trailer. Therefore, a forerunner of the so-called CPX method for noise studies was used [ISO 11819-2], in which a single-wheel trailer covered with an acoustically screening enclosure, towed by a car, was used. A problem was that after some driving with normal loads at highway speeds in this trailer some cracks appeared in the “belt” area, making further tests meaningless. The design was apparently 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. Nevertheless, as intended, a substantial noise reduction potential had been demonstrated—much more than any other tyre had been able to. It should be noted that in today’s traffic, the noise emission of tyres constitutes the major part of traffic noise, so a 10 dB reduction would mean a revolution to traffic noise mitigation [Sandberg & Ejsmont, 2002].

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]. In the years after 1990, only very small funds were available to continue the work, allowing only some trial-and-error experiments, mainly in attempts to obtain sufficient durability. But no break-through was achieved. Instead, Hansson and Sandberg visited some major vehicle and tyre manufacturers in Europe and Asia demonstrating the wheel and suggesting to start-up some cooperation based on finances sufficient to make professional and systematic research.

No significant progress was made in the next ten years; except that a full-scale test on a Volvo 740 car was conducted in 1991; see Figure 3. Again, some cracks appeared after about 200 km of testing, but another problem was worse, namely that, although the tyres were almost “noiseless” at cruising and coasting, when the car was accelerating or braking hard, the spokes in the composite material made contacts to each other. This caused a very disturbing “maracas” noise. The spokes should have been more separated.

Figure 3: A Volvo car used for testing four samples of a composite wheel prototype, version 2, in 1991.

5. The Composite Wheel project

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 4.

The version of the wheel in Figure 4 was not considered technically useful by Hansson's co-researchers, but it was the inspiration for a new project sponsored by Vinnova, which is Sweden's Innovation Agency, running from 2002 to 2008. This project, "Tyre innovations for lower noise emission" led by VTI, was a cooperation between VTI, H E Hansson AB, 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 4: The inventor, Mr Hansson, with his wheel intended for a Volvo concept car.

Tyres are required to meet several very important requirements, of which noise would be one, but other performances should not be impaired when noise is reduced. Consequently, this project aimed at studying the CW concept from a holistic point of view, considering primarily noise, safety, wear, durability, vehicle handling, energy consumption and CO_2 emission (the latter two depending on rolling resistance). 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. With regard to safety, it was obvious that skid resistance or hydroplaning on wet roads would be improved by the CW design as long as the tread was “ventilated” by holes, so no measurements were needed to confirm it. In order to improve durability, some of the noise properties had to be sacrificed. Figure 5 shows the prototype samples 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. The latter result is extremely valuable, and it was our experience that the crucial issue for lowering rolling resistance was the way to connect the spokes with the belt. It appeared obvious that there is a potential to improve it further by optimized design and choice of material.

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 6). However, when the car was driven over a “pot-hole” test lane, the deflection of the CW tyre/road contact patch exceeded the available space between the belt and a part of the sidewall (see the left part of Figure 5). This resulted in mechanical contact between the two and highly non-linear behaviour, which created some minor cracks in a critical part 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 not have caused a problem. Attempts to get funds for a new project to correct the problem failed.

Figure 5: The airless tire (Composite Wheel) final prototypes produced in the author's project. The left tire shows the outside of the tire; the left tire 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 through the tread between the spokes. Photo by the author.

Figure 6: The Composite Wheels mounted on a Volvo car for various tests in 2008. Photo by the author.

6. The airless tyre concepts presented by the tyre industry

6.1 Introduction

The tyre manufacturers have of course not been sleeping since the Goodyear invention in 1982. Most of the attempts may not have been publicly presented, and those that have been presented have only been concepts or prototypes with no technical performance data released. Over the last 10-15 years it has been very popular to present such concepts at automotive shows or exhibitions, and a search on the web will show hundreds if not thousands of news reports of airless tyre concepts or visions. Those that seem to be somewhat more promising or interesting are mentioned in the following.

6.2 Michelin

6.2.1 Tweel

Tweel (acronym for Tire-WHEEL), by Michelin, was presented already in 2005 at a motor show [Michelin, 2005]; see Figure 7. Tweel consists of a composite reinforced tread band, connected to a flexible (deformable) wheel via rectangular, polyurethane spokes. The resulting mechanical structure provides weight-carrying ability, shock absorption, ride comfort, rolling resistance and mass similar to pneumatic tyres while adding suspension-like characteristics that greatly improve handling [Michelin, 2005]. However, this never made it to the road vehicle market, instead it is now used on industrial trucks, lawn mowers (“X Tweel Turf tire”) and some other off-road vehicles. The author believes that the main problem with the Tweel is that the spokes generate severe noise, which may be the reason why it is not implemented on road vehicles.

6.2.2 Uptis

Uptis (Unique Puncture-Proof Tire System) is a concept tyre by Michelin North America. In 2019 it was announced that GM will try this airless tyre on their Bolt electric car and that a market introduction may happen already in 2024; see Figure 8. This trial is ongoing at the time of writing, but no results have been revealed. However, Michelin claims (without data) that there will be advantages such as longer lifetime, less wear, while the rolling resistance target of Uptis is on par with a pneumatic ZP tyre. The material of the spokes is said in unconfirmed blogs to be “composite rubber and proprietary innovative high-strength resin embedded fiberglass” while it seems that the treads are essentially similar to conventional rubber treads. It is claimed that part of the tyre can be 3D-printed [Michelin, 2019].

Figure 7: The Tweel airless tyre. It is a terrain tyre, not for highway use. Photo by Michelin, used with permission.

Figure 8: The Uptis airless tyre mounted on a Bolt electric car by GM, presented by Michelin in 2019. Photo by Michelin, used with permission.

6.2.3 Vision

Vision is a concept tyre by Michelin North America, which was presented in 2017 as a visionary concept, claimed to be an "organic tyre". The materials used will be both bio-sourced and biodegradable to minimize the tyre's environmental footprint. Probably it will include artificial rubber made of dandelions. It will also rely greatly on 3D-printing [Michelin, 2019]. See Figure 9. More information is available at https://www.michelin.com/en/innovation/vision-concept/

Figure 9: The Michelin Vision concept tyre. From Michelin - The VISION Concept.

6.3 Goodyear

6.3.1 Integral Wheel-Tire (IWT)

This invention from 1982 is already reported about in Section 4.

6.3.2 Goodyear non-pneumatic tire (NPT)

The company has recently begun testing its airless tyre. This follows a goal that Goodyear set in 2020 to create a tyre made from entirely sustainable materials by 2030. The prototype is the first step toward that goal. The materials will also help Goodyear rely less upon petroleum-based products.

Goodyear's airless tyre seems to be made in different versions. The one that seems to be the simplest version to this author, is already implemented (whether it is a trial or permanent is unclear) by Starship Technologies, which builds and operates a fleet of over 1,000 autonomous robotic vehicles that deliver packages and food [Cleantechnica, 2022]. The tyre is made with 70 % sustainable materials. This tyre looks rather similar to a small version of the Tweel.

The Goodyear has an advanced goal with its airless tyres. In November 2021, InsideEVs reported that Goodyear's intention is to develop the tyres for EVs with a commercial launch by 2030. As part of that, an airless version is currently tested on Tesla 3 cars. These tyres are reported doing well as "*during testing, the tires performed admirable, hugging curves and navigating deftly around obstacles. The airless tires were able to do well while the Model 3 maintained impressive speeds. The idea is to pair Tesla vehicles and airless tires to support a larger and more sustainable vision*" [Cleantechnica, 2022] and [Insideevs, 2021]. The tyre tested is shown in Figure 10.

Figure 10: The Goodyear NPT used for testing on a Tesla 3 car. Picture from [Insideevs, 2021].

Goodyear has stated that: "*As part of its commitment to enable mobility now and in the future, Goodyear has extended testing of its non-pneumatic, airless tires to high-performance electric vehicles. After successfully executing durability testing of non-pneumatic tires at speeds up to 100 miles per hour, Goodyear recently tested the alternative tire architecture at the company's Akron Proving Grounds*" [Insideevs, 2021].

Goodyear then claimed that "*Testing has included maneuverability at speeds up to 55 miles per hour as well as acceleration and deceleration, with positive feedback from*

Goodyear and third-party trained test drivers" [Insideevs, 2021]. However, Insideevs' reporter noted that "*It's difficult to judge from the video, but it appears that the car handles a little bit differently - especially when it quickly changes direction*."

From a show for journalists at the Goodyear test track in Luxemburg, where a Tesla 3 was equipped with airless tyres, it was reported that "*The ride is smooth but the grip is not as good as on conventional tyres -- and they are noisier."*

The tyres were tested for 120,000 kilometres (75,000 miles) at speeds of up to 160 kph in both scorching temperatures as well as snow, said Michael Rachita, who heads up Goodyear's efforts to develop airless tyres". Mr Rachita also said that a second generation of airless tyres that are lighter, quieter and roll better are in the works [RFI, 2022].

Finally, it is interesting to note that the Goodyear NPT is being tested for urban autonomous vehicle transportation with the Jacksonville Transportation Authority in Florida, as being fitted on a local autonomous mini-bus; see Figure 11 [Ross, 2021] and Figure 12 [WJCT News].

"*The Jacksonville Transportation Authority is proud to integrate this innovative and sustainable technology into our Autonomous Vehicle Test & Learn program as we develop the future of mobility through the Ultimate Urban Circulator*," said JTA CEO Nathaniel P. Ford Sr [WJCT News, 2021].

6.3.3 Aero

Goodyear Aero is a futuristic concept airless tyre intended to be used on future "flying cars", as it can work both as an airless tyre and as a propeller [Goodyear, 2019]. The concept's spokes would provide support to carry the weight of the vehicle and also act as fan blades to provide lift when the tyre is tilted. It may sound as a joke to some, but it is serious. See Figure 13.

Figure 11: The Goodyear NPT tested on an autonomous mini-bus operated by the Jacksonville Transportation Authority [Ross, 2021].

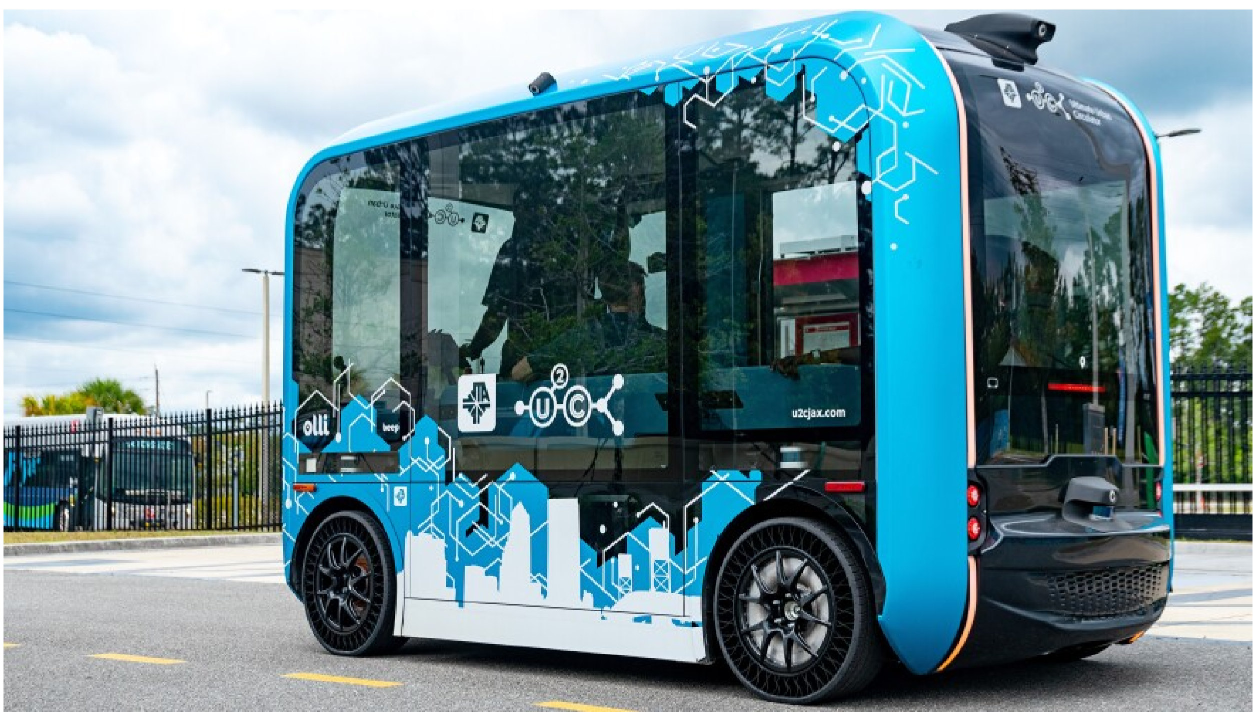


Figure 120: The Goodyear NPT tested on an autonomous mini-bus operated by the Jacksonville Transportation Authority [WCJT News, 2021].

Figure 13: The Goodyear Aero tyre, intended for autonomous, flying cars [Goodyear, 2019].

6.3.4 Goodyear Eagle 360 Spherical Tire

Another futuristic concept involving an airless tyre is the Goodyear Eagle 360 Spherical Tire, which is part of a concept vehicle by car manufacturer Citroën [Brook-Jones, 2021]; see Figure 14. One of the ideas behind it is to allow vehicle operation in all directions, for example parking by 100 % lateral movement, irrespective of how the vehicle body is directed.

Figure 14: The Goodyear Spherical Tire, used on a Citroën concept vehicle [Brook-Jones, 2021].

6.4 Bridgestone

6.4.1 Air-Free Tire concept (for cars)

Bridgestone corporation first announced that it had developed an "Air-Free (Non-Pneumatic) Tire" concept at the Tokyo Motor Show in 2011. The construction of their version mimicked the Tweel, with the exception of using inner and outer spokes that run in opposite directions, as opposed to the Tweel's V-shaped spokes. Their claim was that noise and vibration for their version was a non-issue (!). Bridgestone also argued that the materials are far easier to recycle than standard synthetic rubber [Gearpatrol, 2012]. See an illustration in Figure 15.

Later (at the Tokyo Motor Show 2013), they presented a second generation of the concept with higher load-bearing capacity used on a small two-seated car. It was claimed by Bridgestone that in the second generation of airless tyres, they had succeeded in making a significant reduction in energy loss by using proprietary materials technologies and simplifying the structure of the tyres. As a result, this "Air Free Concept tire" has achieved the same level of low rolling resistance as their pneumatic fuel-efficient tyres, making possible a contribution to reductions in CO2 emissions [Fareastgizmos, 2013).

Figure 15: The Air-Free Tire Concept by Bridgestone [Gearpatrol, 2012].

6.4.1 Air-Free Tire concept (for bicycles)

Bridgestone wants to become the first tyre maker to introduce airless tyres on the market by targeting commercial vehicles rather than passenger cars, according to a report from Automotive News. But first, it launched a smaller and lighter version of them on a fleet of airless-tyre bicycles at the 2020 Summer Olympic Games in Tokyo, where Bridgestone is an official sponsor [Autoblog, 2020]. A picture of this tyre is shown in Figure 16.

Figure 16: Air-free bicycle tyre by Bridgestone as presented at the Tokyo Olympics 2020. Picture from [Ideaconnection, 2020].

6.4.2 Air-Free Tire concept (for medium and heavy trucks)

For trucks, Bridgestone Americas, Inc. was showcasing its advanced air-free commercial truck tyre concept for the heavy-duty trucking market at the 2020 Technology & Maintenance Council (TMC) Annual Meeting and Transportation Technology Exhibition in Atlanta, Georgia, USA, according to a press release from Bridgestone [Bridgestone, 2020]. Figure 17 shows a picture from the Bridgestone exhibition.

According to the press release, Bridgestone writes that *the air-free commercial truck tire concept, designed to be used in high-speed, long-haul applications, leverages a proprietary design where tire tread is placed on a structure of high-strength, flexible spokes, eliminating the need for a tire to be filled and maintained with air. The initial design of the Bridgestone advanced air-free commercial truck tire concept is intended for the trailer position. Reported data from tire manufacturers shows trailer tires account for* *approximately 20 % of truck tire purchases; furthermore, research indicates 40 % of all tire failures occur in the trailer position*, Bridgestone writes.

The press release further claims "*The benefits of an air free commercial truck tire solution are many – this offering has the power to reduce downtime, maintenance and emergency roadside service calls,*" said Kimpel. "*Combine that with a high retread rate, and our advanced air free tire concept has potential to substantially lower the overall total cost of tire ownership for fleets*." While the commercial truck tyre concept is focused first on the trailer position, it is intended to be scalable to other commercial trucking wheel positions and applications.

The design replaces the pressurized air in normal tyres with a recycled thermoplastic 'web' that holds up to 2,270 kg (5,000 pounds) of tyre load [DailyMail, 2020]. Such loads correspond to tyre dimension 265/70R19.5.

Figure 17: The Air-Free Commercial Truck Tire Concept by Bridgestone, as exhibited at an event in 2020. Picture cropped from [Bridgestone, 2020].

6.5 Hankook

6.5.1 i-Flex

Hankook Tire in South Korea has worked with several generations of airless tyre concepts since 2010. The i-Flex, is the 5th generation of airless concepts (Figure 18). In 2015, an article based on a press release suggested that "*Hankook's airless car tires should hit the market very, very soon*" [Medlock, 2015]. However, this has not yet happened. Construction of the i-Flex is said to be centered on a new type of uni-material designed to maximize the tyre's eco-friendly potential. Several tests (durability, hardness, stability, slalom (zigzag), and speed) have been done and results are positive according to the manufacturer, but no data have been released.

Figure 18: Hankook's i-Flex airless tyre concept. Photo by Hankook, used with permission.

6.5.2 i-Flex for Hyundai Plug & Drive module

At the Consumer Electronics Show (CES) in Germany in January 2022, Hankook presented the latest version of the airless i-Flex concept tyre as part of a cooperation with the Hyundai Motor Company. At the same occasion, Hyundai Motor Company unveiled its Plug & Drive (PnD) Module for the first time. It is based on robotics technology that enables the Mobility of Things (MoT), an ecosystem in which all objects are mobile. Hankook's i-Flex is fitted to maximize the characteristics and functions of the PnD module. The format is 10-inch with a diameter of 400 mm and width of 105 mm. Source: press release from Hankook [Hankook, 2022]. They also presented an illustration (Figure 19). Note the honeycomb structure, which has many advantages [Ashofteh & Shahdadi, 2019].

The press release further reads: *The i-Flex was developed using rigorous biomimetic studies and testing. In order to absorb shocks from the road and for it to be able to carry heavy loads, the design of a multi-layer interlocking spoke inspired by the cellular structure of living organisms was adopted. The multi-layer interlocking spoke structures the cell in three dimensions for better shock absorption while allowing hexagonal and tetragonal cell structures of different rigidities to join together for more stable load support.*

In addition, a c-shaped concave tread profile ensures the maximum contact patch, contributing to safety on the road. The tread, designed for multidirectional vehicle movement, adopts the characteristic honeycomb design of the tyre body.

Hankook Tire is dedicated to building a more sustainable future in mobility, and therefore has been working on non-pneumatic tyre technology since 2010. This continuous effort led to the birth of the i-Flex, an airless tyre with high safety, low maintenance and high sustainability – which now serves as an ideal solution for future mobility. Hankook is continuing its research and development to make further improvements.

Figure 19: Hankook's i-Flex airless tyre concept as presented in cooperation with Hyundai [Hankook, 2022].

6.6 Barez

In a news article in 2019 it read [TiN News, 2019]: "*Iran's rubber industry is facing a problem to supply some raw materials due to sanctions, but has relied on the ability of domestic professionals to produce airless tires and become its fourth producer in the world."* An illustration to the article is reproduced in Figure 20. It is unclear what the figure really shows; whether the products are prototypes or parts of prototypes or if same of them really are for practical use and, if so, for what kind of vehicles.

Barez Tires, in Iran, has started to manufacture airless tyres due to the political sanctions imposed on Iran. Barez wrote in 2019 that 150 raw materials are needed to produce pneumatic tyres, of which 45 % are imported, and the latter has become a serious challenge due to the sanctions. A team was established in cooperation with the "Presidential Nano Headquarters". In 2019, three versions of airless tyres had been produced [Barez, 2020]. At an event it was stated "three samples from this product were produced in collaboration with the scientific and research centers". The latter appears to be the Polytechnic University and the Faculty of Engineering of the University of Tehran. A picture found on the web (Figure 20) shows hundreds of such tyres in a store, so this seems to be a serious approach for Iran under the circumstances, although there is no information indicating what the airless tyres should be used for. See also Section 7.4.

The author has information from a friend who has worked in the Iranian tyre industry, who asked some of his former colleagues about the situation. It appears that Barez produced some airless tyres around three years ago, but they were just concept tyres and now the project appears to be stopped [Habibnia, 2021].

Figure 20: Airless tyres as presented in [TiN News, 2019].

6.7 Kumho

Kumho Tires has worked extensively with airless concepts and have received design awards for this work with the so-called e-NIMF airless tyre (e-NIMF = eco-friendly, no-inflation and maintenance-free) [Butcher, 2020]. A picture of this concept appears in Section 11.3. Thanks to extensive testing and simulation of the shape, material and manufacturing methods of the tyre's spokes, Kumho claims that the tyre's durability, noise, vibration and rolling resistance are remarkably similar to that of today's pneumatic offerings [Butcher, 2020]. If this is not just invented by the marketing department, the statement Kumho has made (visually) about airless tyres may have some exciting justification; see Section 11.3.

6.8 Toyo Tires

Toyo Tires in Japan claim that they have been working with airless designs since 2006. Now they have a 6th generation tyre they call noair (from Neo-futuristic airless concept tyre). They claim that *in September 2017, Toyo became the first company in the industry to present the technology for new "noair", non-pneumatic tires that can actually be mounted on passenger cars and driven at high speeds* [Toyo, 2020].

The tyre is in fact rather different from the other industry concepts and not unlike the design of the earlier Swedish Composite Wheel and the one planned for LEON-T. Figure 21 shows the overall look, where (1) is X-shaped spoke configuration, (2) is a tread and (3) an external diameter ring.

About the spokes, Toyo writes "*An X-shaped spoke configuration that alternately crosses the width of the tire from the inside to the outside and vice-versa greatly improves durability*". The tread is described as "*Fuel efficient rubber developed using material design platform technology Nano Balance Technology is used for tire tread that comes in contact with the road*. *Additionally, the number of spokes has been increased to 100 pitches which reduces the load on each spoke and achieves a quieter ride*". The Ring is described as "*The external diameter resin ring is reinforced with Carbon Fiber Reinforced Plastic (CFRP), which serves to reduce the load imposed on the spokes*" [Toyo, 2020]. Figure 22 shows a crossection of the noair tyre.

Interestingly, Toyo claims that "noair" *has been developed with better rolling resistance as compared to conventional tires*, and that *fuel-efficient rubber developed using Nano Balance Technology is used for the tire tread that comes in contact with roads. We achieved all the core tire performance characteristics "driving, turning, stopping, supporting," without air inflation*.

Figure 21: "noair" airless tyre presented by Toyo Tires. Source: Toyo Tires at https://www.toyotires-global.com/rd/noair/

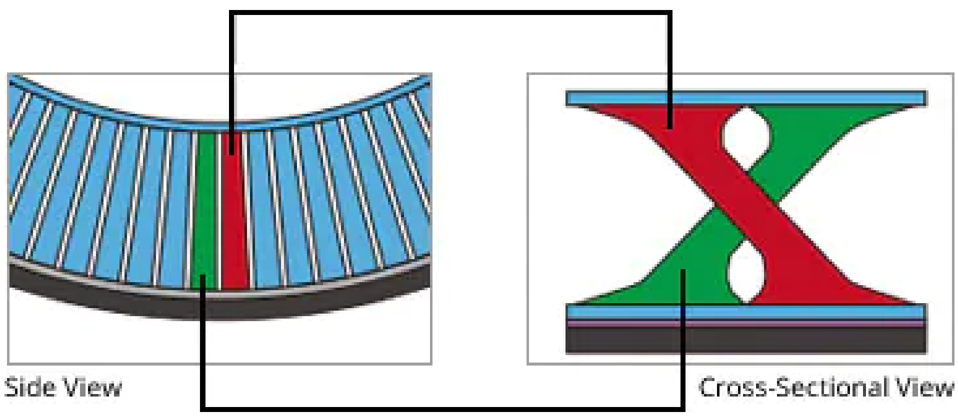


Figure 22: Side view and cross-section of the spokes of the "noair" airless tyre presented by Toyo Tires. Source: https://www.toyotires-global.com/rd/noair/

6.9 Other manufacturers

The tyres presented above, of which only some have reached the prototype stage which has allowed technical testing, are by no means the only ones. Similar concepts have been suggested by at least Sumitomo and Yokohama. Dunlop/Sumitomo has a concept tyre named Gyroblade. Yokohama already in 2011 presented its airless concept called Youmyaku, but since then the company has been relatively quiet about this concept or any other airless concept. Also Chinese Zhejiang/Hongyi has an airless tyre concept.

6.10 Discussion

Common to all airless tyre concepts seems to be that puncture-free operation is the most prominent feature, supplemented by the potential of using eco-friendly and renewable materials, as well as less complicated production. Implementation on EV:s, and with reduced rolling resistance so much needed for them, seems to be additional drivers for the development. The airless tires suggested most recently seem to be aimed mostly at electric car usage and 3D-printing is indicated as a real possibility.

As for the Uptis, nothing is presented yet from Goodyear about rolling resistance, wet friction or noise, but these parameters are undoubtedly of great concern and once they are found to be acceptable, we can expect to see General Motors EV:s with Uptis airless tyres and Tesla cars with airless tyres from Goodyear. On a small scale, this may happen rather soon, but on a larger scale, the industries will probably not soon be able to produce enough airless tyres needed for a large fleet.

This author expects that for electric cars, given that noise is almost only coming from the tyres, the (interior) noise parameter of both the Uptis and the Goodyear NPT will be a very critical parameter. The problem with the internal tube resonance is gone but may instead be replaced by the spoke impact frequency.

Information from tyre manufacturers about airless tyres for heavy vehicles is rare. The Bridgestone air-free tyre is the only exception found by the author. There are a couple of attempts to produce bicycle tyres. For such tyres the rolling resistance is of paramount importance, which would be appreciated especially in the bicycle sport.

Some of the illustrations (pictures) of concept tyres do not seem to be made by technical experts; rather, the illustrations seem to be made by marketing staff with little concern for technical realism. The author believes that in general the marketing departments have been strong influencers in presenting the airless tyre concepts to the mass-media and to the public.

Except for the Goodyear IWT in 1982, as far as this author has found, there is not yet any single scientific report about quantified technical performance of airless tyres from the tyre industry or its associates.

7. Published R&D work on airless tyres

7.1 Introduction

Most information and discussion regarding airless tyres have been in the form of press-releases or marketing publications, or reports from trade fairs or exhibitions. These have not revealed any technical performances or detailed development work. An exemption is the original description of the Goodyear IWT invention in 1982 [Su, 1989]; see Section 4.

This author and his co-researchers have published technical work at conferences in the past, e.g., references [Sandberg & Ejsmont, 1990], [Ejsmont, 1990], [Hansson, 1990], [Sandberg & Ejsmont, 2002], [Sandberg, 2009], and [Sandberg, 2020]. There have also been several presentations at Tire Technology International conferences. That work has been summarized in the earlier parts of this Deliverable and is the basis for much of it.

In [Ashofteh & Shahdadi, 2019] there are a number of important references of scientific relevance listed, which this author has not been able to retrieve so far.

Two examples of essential R&D work which has been presented in a scientific way will be mentioned in the two following sub-sections.

7.2 About the development of the Tweel

The basis for airless tyres is treated in an article that describes the background for development of the Tweel (by Michelin, see 6.2.1). The authors propose a non-pneumatic structure that exhibits four critical characteristics (low energy loss on rough surfaces, low vertical stiffness, low contact pressure, and low mass) while breaking some of the most restrictive design constraints imposed by pneumatic mechanics. The structure forming an integrated tyre/wheel is called a Tweel™ [Rhyne & Cron, 2006]. They claim that this construction offers low rolling resistance.

7.3 Dr Kundan Kumar about an airless bicycle tyre

In the time period 2006-2009, a PhD student, Mr Kundan Kumar, worked at the Institute of Lightweight Construction and Design at University of Rostock in Germany, with a project title "Inventing a ride-enhanced non-pneumatic wheel using fiber-reinforced composite material". This was a patented invention intended to become an airless bicycle tyre. An example of a presentation is [Kumar, 2009] from which Figure 23 is copied. It is the essential material taking up the load of the tyre with puncture-free and good ride comfort.

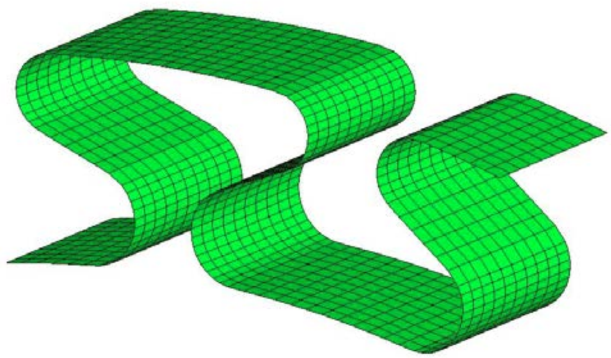


Figure 23: Spring in composite material shaped to provide “Large deformation but material does NOT undergo large strain”. From [Kumar, 2009].

Based on this spring, a bicycle wheel/tyre was produced, which is shown in Figure 24 (from the same presentation). Mr Kumar and this author planned to cooperate, but due to both our projects ending, it never happened.

Mr Kumar published his work at two conferences of the Tire Society [Kumar & Scharr, 2007], [Kumar & Scharr, 2008]. After his work in Rostock, Mr Kumar worked for a while at Goodyear technical centre in Luxemburg, but nowadays he is Head of Simulation and Thermal Measurement at FORVIA's (HELLA) Electronics Business Group in Lippstadt, Germany.

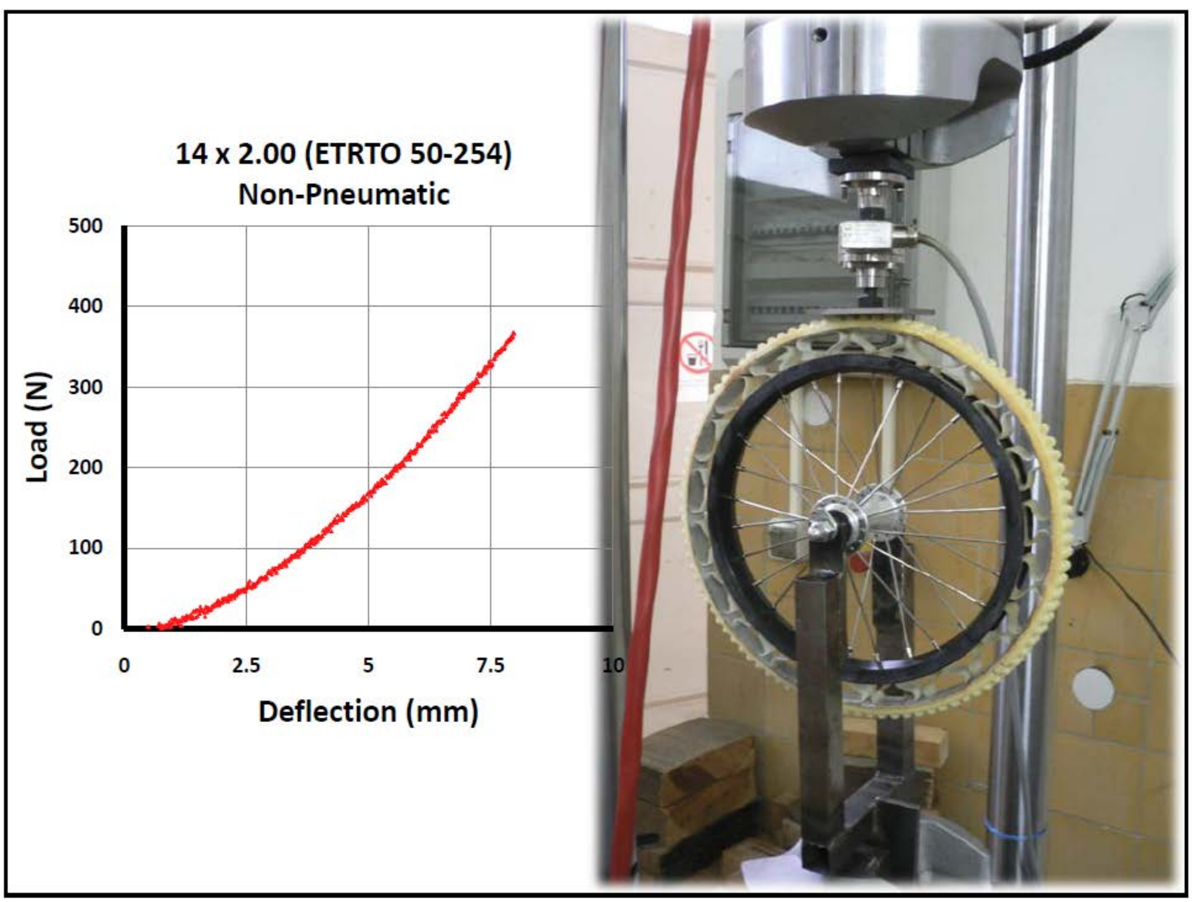


Figure 24: The airless bicycle tyre produced in Mr Kumar’s project. From [Kumar, 2009].

7.4 Barez researchers Ashofteh and Shahdadi

These Iranian researchers start with a valuable literature review of various structures useful for non-pneumatic tyres (NPT) (in this Deliverable called airless tyres) with a focus on honeycomb structures [Ashofteh & Shahdadi, 2019]. Then they model such structures in an NPT by means of a 2D finite-element model (FEM) and the parameters affecting the engineering design are discussed in detail. The honeycomb structure is made of polyurethane. They used inner and outer radii of 185 and 300 mm. A rigid hub was used inside the inner radius.

The model is used to predict the behaviour of the structure when rolling over seven different objects in the road surface. It was found that the performance was fine. The authors emphasized that dynamic deformation was much larger than static deformation of the "honeycomb spokes".

The final concept or prototype (?) is called HANA and is shown in Figure 25. The two authors reveal that in order to progress airless tyre technology, Barez Industrial Group had established a specialist innovation centre [Ashofteh & Shahdadi, 2019].

Please note that in Section 6.6 more about this concept tyre is shown.

Figure 25: The airless tyre concept named HANA, the development of which is presented in [Ashofteh & Shahdadi, 2019], featuring a typical honeycomb structure in polyurethane material.

8. Airless tyres in the LEON-T project

8.1 Introduction

The intention with this Section is not to describe how the LEON-T airless tyre prototypes will be designed and tested. Instead, the intention is to make it possible to see similarities and differences between the LEON-T planned prototypes and the other airless tyres or concepts described in this Deliverable.

8.2 Description according to the project plan

The work with airless tyres in LEON-T is done 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 and initial design work of 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 in a lab test 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 work will be assisted by the experience of one of the world's leading tyre manufacturers. The overall intention with this is to show the many environmental and safety advantages of the airless tyre concept for future road vehicles.

The first task is analysing and presenting 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 involves how the earlier Composite Wheel (CW) airless tyres for cars can 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 will be made. For example, this includes specifications for tyre dimensions, speed and load capacity, as well as performance parameters such as noise emission, rolling resistance, wet grip and tread wear. Other considerations and decisions include the wheel's basic shape and considering which composite materials and morphological features that can potentially achieve the specifications.

The second task will be focused on the production of the CW airless tyres. To produce the desired prototypes, ETU will first manufacture a prototype spoke and belt sample (main components of the CW structure) based on the design provided in the first task. Advanced calculations, especially about the strength of the spokes will be made by ETU and Idiada. Based on the results, ETU will manufacture a sufficient number of the spoke and belt components and integrate them into a prototype of Composite Wheel (CW) structure. Subsequently, rubber treads will be mounted on the belt on the CW structure. A critical process here will be how to give the tread a ventilation through itself and the underlying belt, which is one of the major methods to reduce noise and to increase wet grip. This will be done by producing holes at certain locations in grooves of the tread and through the belt, based on earlier experience and optimization.

In principle, the basic idea was to use essentially the design of the CW produced in the earlier project (Section 5) which was an airless tyre for a (Volvo) car, but to scale it up to the size needed for HGV:s (heavy goods vehicles).

8.3 Spoke design and material

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 “medium” size and subjected those to the loads expected for an HGV tyre (but scaled down to the used “medium” size). The material is uni-directional (UD) carbon fibre reinforced plastic (CFRP) composite. Figure 26 shows the physical setup used by ETU which also gives an impression about the planned spoke construction.

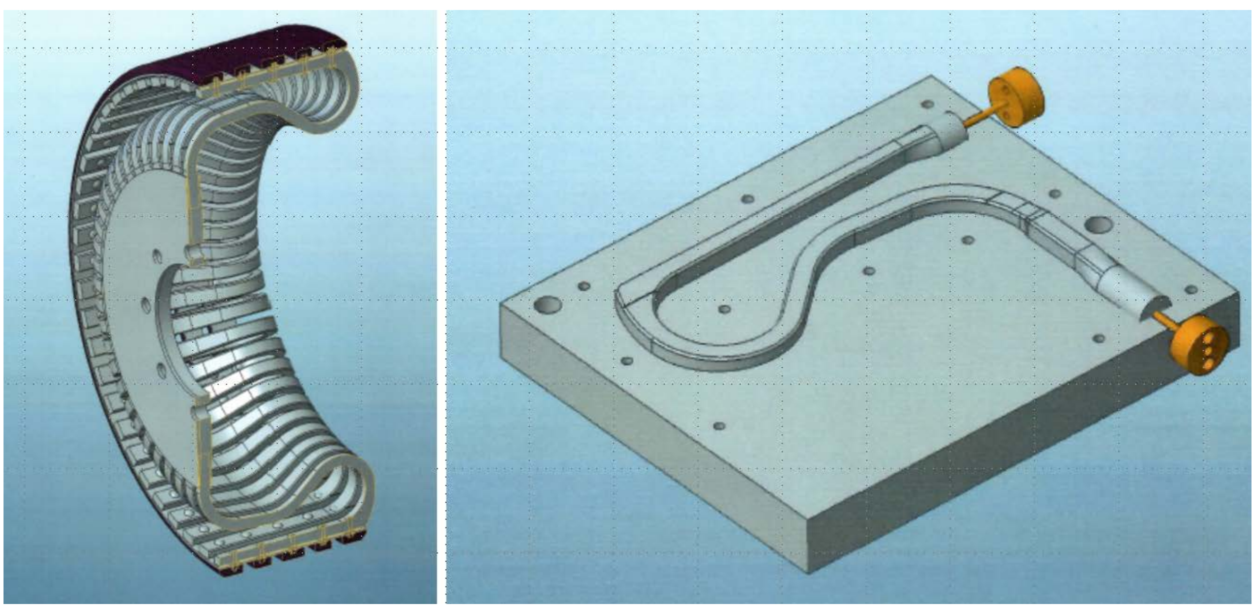


Figure 26: Initial setup to test the stresses of the spokes in the planned construction, as used by ETU. From a presentation at the first meeting of WP5.

The results were discouraging; it appeared that the spokes would have a problem to carry the load of a typical HGV tyre. Simultaneously, an expert (Dr Linus Fagerberg) at a company called Lightness by Design AB (here denoted as LDAB), specialized on calculating the stresses in light materials, was engaged to supplement the test with calculations. 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 27.

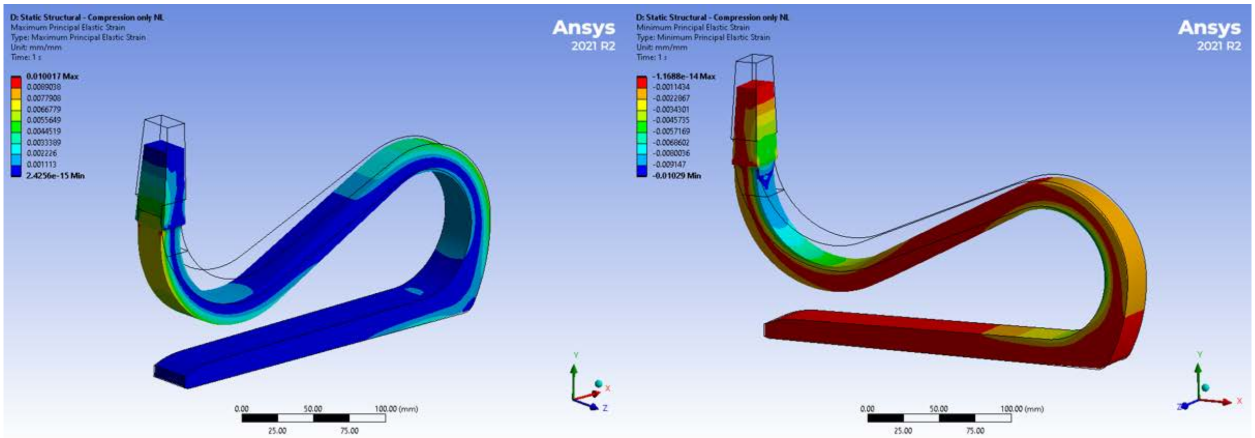


Figure 27: Results of calculation of stresses in a spoke made of CFRP exposed to the load of a fully-loaded tyre of dimension 285/70R19.5. By LDAB [Fagerberg, 2022].

As a results of the discouraging results, the 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 more) 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.

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 based in Sweden was established. This company now produces 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 increased weight per wheel/tyre unit may be around 25 %. However, optimization of steel springs may allow lighter variants [Fagerberg, 2022].

It shall be mentioned that also Idiada too 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. Results will be presented in another publication for LEON-T.

8.4 Tyre dimension

It was considered that producing a tyre of the common dimensions used for long-distance HGV:s (typically 315/70R22.5) would be too big a challenge, given the results of the first calculations.

It was then decided to design the CW to correspond to a truck tyre of dimension 285/70R19.5; i.e. it would be able to replace such a tyre on the HGV. This is a dimension typically used on 15-18 ton trucks 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.

Today such transports create noise exposures to particularly sensitive areas; exposing people in and outside homes and especially sensitive services in education or medical or other health care. Consequently, there is a general trend already started to replace such vehicles, 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 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.

8.5 The most recent design and material

The work has since been devoted to design optimum shape of steel spokes and to integrate them in an airless tyre design. An example of the present overall design from LDAB is shown in Figure 28 (note that there are four grooves in this example, but three grooves is an option too). The design of an individual steel spring (before being bent) is shown in Figure 29.

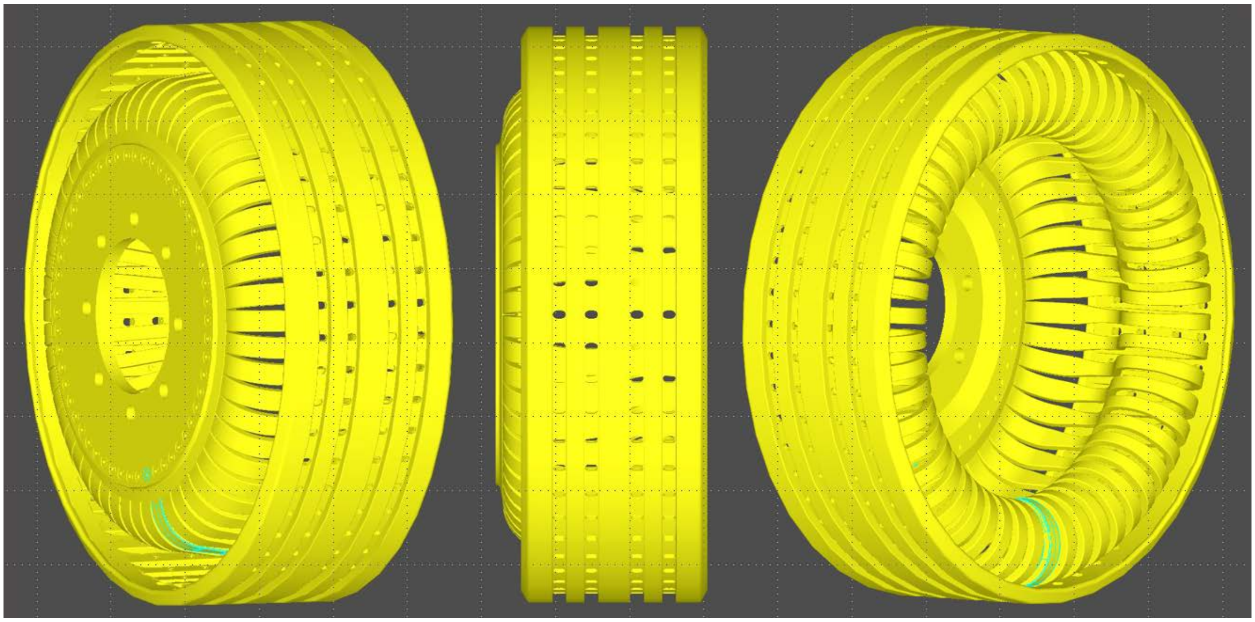


Figure 28: Example of overall design of the airless tyre, based on calculation of stresses for spokes made of high-strength steel. By Fagerberg at LDAB [internal memo].

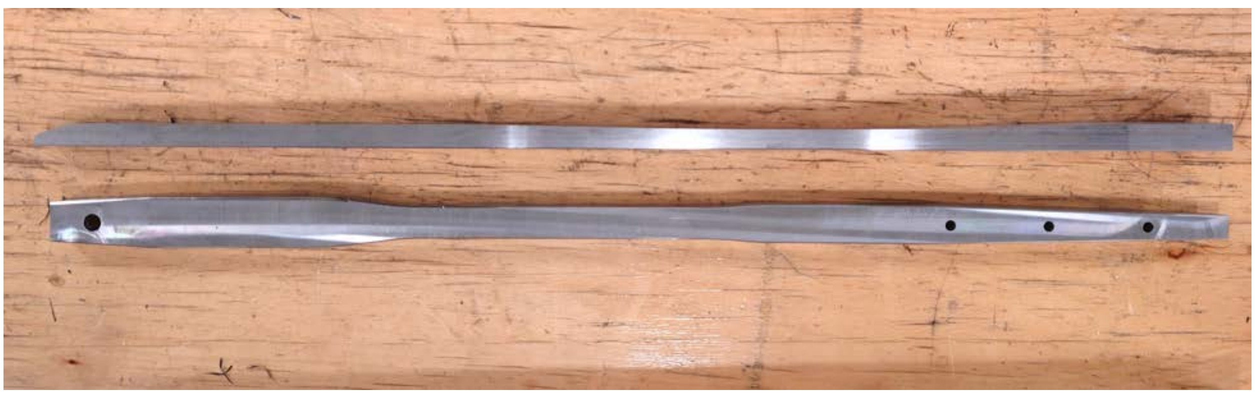


Figure 29: Optimal shape of a steel spoke, based on calculation of stresses for spokes made of high-strength steel. Two spokes shown; the lower one is seen from above, while the lower one is turned 90 degrees to show the profile of the lower one (but it is turned 180 degrees within the plane). By Fagerberg at LDAB [internal memo].

Also Idiada has made calculations based on an FE model of the design shown in Figure 28. An example is shown in Figure 30. 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.

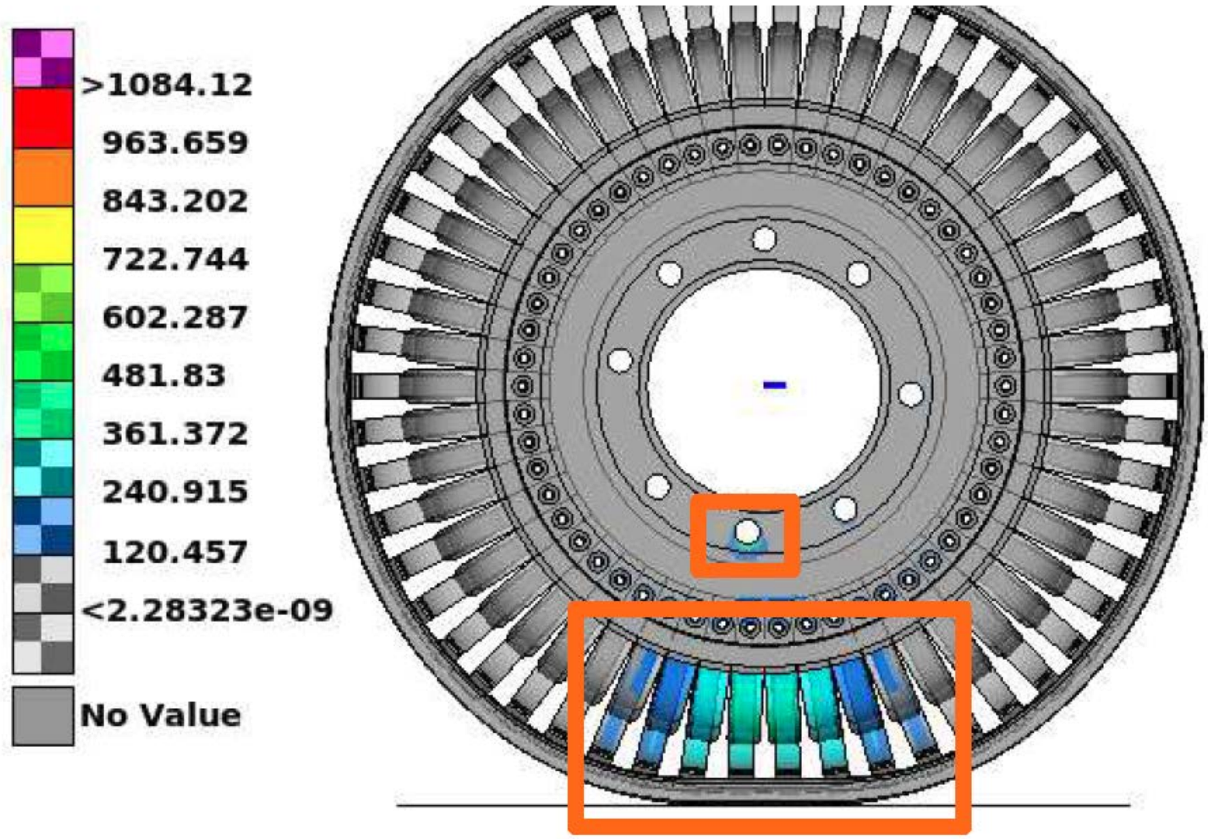


Figure 30: Example of stresses calculated for the airless tyre, based on the design of Figure 26. By Idiada [internal memo].

Table 1: Results of Idiada's calculations of stiffnesses in the contact patch in three directions of the tyre design in Figure 26. "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

Note that the work is ongoing, and things may change due to the progress of calculations and the further testing of physical components.

9. Tyre treads for airless tyres

9.1 Conventional and modified rubber treads

In the airless tyre concepts presented in Section 6, the treads are designed as similar to treads of any pneumatic tyre, generally using natural and/or synthetic rubber of traditional type. The tread patterns often look “futuristic”, what we are used to see at exhibitions and fairs, often designed by marketing departments to give a “sporty” or futuristic look. The rubber compound is a whole science in itself; requiring increasing attention as it is a key to produce lower rolling resistance without sacrificing wet friction or wear.

A rather consistent feature of the presented airless tyres is that the treads will have a shape which is rather flat in the lateral direction. This should be favourable to the stick-slip motions in the tyre/road contact patch. Usually, there are not what we call shoulders, connecting the tread with the sidewalls. This is favourable to reduce rolling resistance as the shoulders generally are where much of the energy losses appear.

For airless tyres presented in Section 6, the treads can in principle be similar to those of pneumatic tyres. 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.

9.2 Perforation of the treads

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) have 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 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.

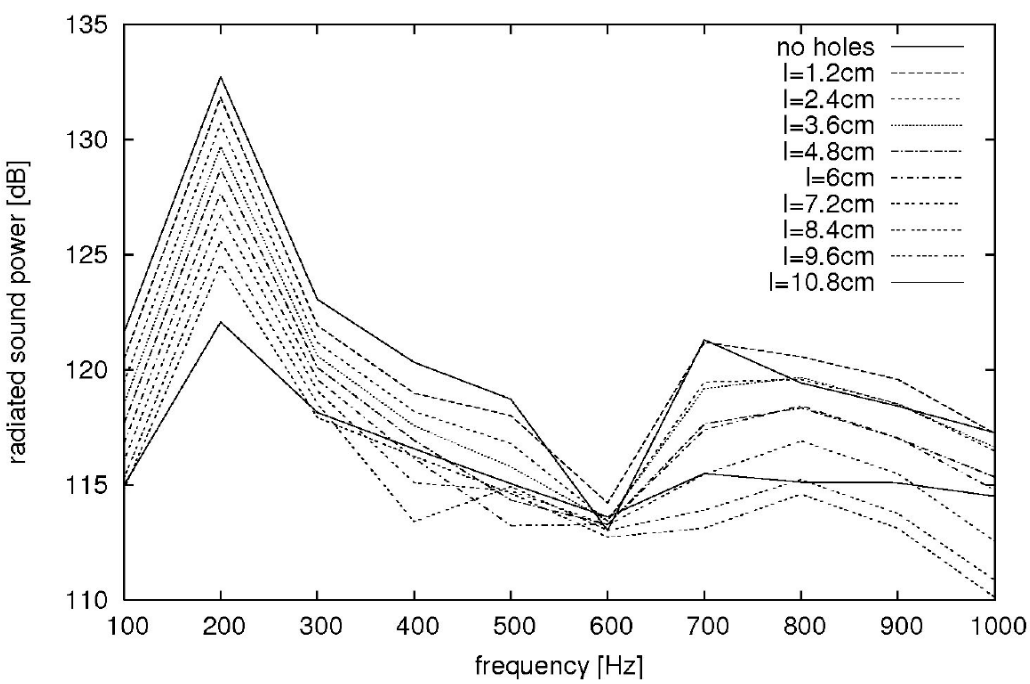
A study of the effect of the perforations was made in the Composite Wheel project described in Section 5, by researchers at Chalmers University of Technology (which was one of the partners in that project). They used an adapted FEM model to calculate the effect of varying the holes [Larsson & Schade,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

Figure 32 shows the effect on noise of the holes (perforations) in the grooves, which can be seen in the right part of Figure 31. When the holes are uncovered, the mid-frequencies are substantially reduced. This may be due to the holes eliminating much of the air pumping and pipe resonances in the grooves. The lack of effect at higher frequencies is probably due to too large spacing between the holes in the grooves, leaving pipe resonances at such high frequencies. Another interpretation is that the observation has to do with the baffle effect; which is "short-circuiting the baffle" for wavelengths longer than 2-4 times the spacing between the holes. At long wavelengths (corresponding to the 100-300 Hz range in the diagram) the effect of the holes is smaller since already the space between the spokes provides "baffle short-circuiting".

These effects will have to be considered in the LEON-T project.

Figure 31 (left): Illustration of the holes in the tyre tread/belt of the CW tyre variant used in the study by [Larsson & Schade, 2008].

Figure 32 (below): Radiated sound power for increasing hole size as function of frequency



9.3 Treads for the LEON-T prototypes

For airless tyres in project LEON-T, one prototype shall be designed for use on steering and trailer axles (these axles often use tyres with similar treads) and another for drive axles of a truck (HGV). This means that two very different tread patterns are needed:

For steering and trailer axles: a rubber tread with longitudinal grooves, featuring three or four grooves running longitudinally around the circumference, with tentatively a tread depth of the grooves of 16 mm. The location of the grooves will be fitted to the ventilation holes in the belt; in this way creating a ventilated or drained tread pattern to eliminate air and water pressure build-up in the grooves when rolling. For HGV:s, the tread depth of 16 mm would be common. In this case, we may aim at 15-16 mm. Since the grooves will have no rubber in the bottom; rather the ribs between the grooves can be mounted directly on the belt. This will mean that the tread rubber thickness would be only 15-16 mm which is expected to be extra favourable to rolling resistance. However, it is expected that in order to reduce rolling resistance further, as well as rubber wear, it will be necessary to cut some diagonally orientated sipes in the ribs. This is expected to reduce the stick-slip energy in the tyre/road contact area.

For drive axles: a rubber tread with longitudinal grooves, featuring three or four grooves running longitudinally around the circumference, should be combined with some tread blocks; i.e. the ribs mentioned in the previous design will have to be broken up into blocks in order to provide good traction on surfaces contaminated with dirt, snow or ice. Tentatively a tread depth of 16 mm is planned. In this case, perhaps we must find a suitable rubber tread from a retread factory. This will then require a higher thickness of the tread than for the steering axle prototype. A critical design procedure will be to fit the ventilation holes in the grooves to the tread pattern. The tread blocks must be randomized in longitudinal direction, both in length and in pitch (period).

9.4 Tyre treads made with dandelion “rubber”

Tyre rubber made of dandelions is already since more than 10 years subject to advanced development by Goodyear [Modernfarmer, 2022] and Continental, also by Michelin, and probably by most major tyre manufacturers. It is uncertain which company is most advanced so far, but it has been reported that Conti has shown a truck tyre made with dandelion “rubber” at some exhibit and have tried prototypes with successful results. Continental has already got a German reward for a bicycle tyre with dandelion rubber [Continental, 2022].

It seems that still a major problem is to get enough raw material to produce a market tyre in various sizes. Quite large areas are needed to grow the plants and most farmers are sceptical to the idea of growing what they consider as weeds.

9.5 Development in China of treads made with dandelion "rubber" (especially Linglong Tires)

The Chinese Linglong tyre company (partner in LEON-T) in 2017 hosted a Dandelion Rubber Technology Innovation Forum in partnership with the Dandelion Rubber Industry Technology Innovation Strategic Alliance in Beijing, China. The forum focused on innovations in the dandelion industry, "*aiming at accelerating the development of China's dandelion rubber industry*" [Bioplastics, 2017].

Linglong Tire planned *to invest $450 million to set up a company tentatively named Linglong Dandelion Science and Technology Development Company* [Bioplastics, 2017]. Dandelion rubber is seen by many in the tyre industry as a future possibility to replace natural and synthetic rubbers of today with an environmentally friendly material.

This information is important as it may make it possible to use more environmentally friendly rubber in the LEON-T prototypes. However, maybe the use of dandelions in our airless tyre first prototypes is premature. We want most of all to have a tread with the lowest possible rolling resistance; and the use of dandelions must not make that more difficult. Nevertheless, with the assistance of Linglong Tires, dandelion rubber may be an option later.

9.6 Additive manufacturing (aka 3D printing)

Advances in technology in the areas of additive manufacturing (also known as 3D printing), in connection with airless tyres are under exploration and/or development by many tyre companies, which means that they have a chance of making it to market. This may be especially practical for airless tyres.

In the opinion of [Yurkovich, 2019], *the 3D printing of complex 'tire mold features' to enhance performance aspects such as traction (snow, ice and wet) and treadwear, along with ease of manufacturing, is likely to see application prior to the other technologies. However, the 3D printing of a highly functional (*pneumatic*) tire in a commercial operation is not within reach for current technology. This will require a technological break-through in material/polymer science development to make it a competitive proposition for the future with respect to cost, performance, and durability*.

Additive manufacturing will not be possible in the LEON-T project, as we do not have resources for it, but in the future, it will be possible to produce both the tread and the belt in this way, and probably also the spokes.

10. Potential pros and cons of the airless tyre concept

10.1 Introduction

Airless tyres have a potential of extending the tyre life while decreasing maintenance for the fleet. As autonomous vehicles become more common, airless tyres could become a game-changer since they are supposed to be maintenance-free; except that the rubber treads will have to be changed when they have become worn-out.

The advantages and disadvantages with airless tyres versus pneumatic tyres for similar operation, of course depend on the construction, but in rather general terms the following is expected. Note that some issues may be considered as both an advantage and disadvantage and therefore is included in both lists.

10.2 Advantages

- Airless tyres cannot puncture; a spare tyre is not needed.
- The materials can be more eco-friendly and especially the need for rubber (both natural and synthetic) will be much less, as sidewalls of rubber will not exist.
- If steel is used in the spokes, it may be produced fossil-free.
- The production can be much less complicated than for pneumatic tyres; potentially by means of 3D-printing.
- Pneumatic tyres require grooves in the tread surface to transport water away from the contact patch to provide grip in wet conditions. Some airless tyre designs (so far only LEON-T) can transport this water through the tread and do not require such complicated groove patterns. Wet grip will be improved.
- Given that no air container is needed, some airless tyre designs allow more space on the inside of the tyre, which potentially gives more space for brakes or even for electric motors.
- The air cavity in a pneumatic tyre acts as a resonator, acoustically corresponding to a “loudspeaker cabinet”, which is a great concern for NVH and tyre engineers. In airless tyres this is not an issue.
- Exterior noise emission and rolling resistance can be substantially reduced compared to pneumatic tyres – at least for the LEON-T version.
- The lower rolling resistance, mainly because of the lack of tread rubber shoulders, leads to less energy consumption of road vehicles, thereby less consumption of fossil fuels, or of electricity. The latter can be utilized as increased operating range for EV:s.
- Rolling resistance of pneumatic tyres increase when the tyre is not enough inflated, but airless tyres do not depend on any reduced air pressure due to leaking air or to the varying temperature of pneumatic tyres.

- Drivers do not need to adjust air inflation. Tyre pressure systems are not needed.
- Flatter (rectangular) tyre/road contact patch may reduce rubber wear.
- Airless tyres may give vehicle designers new tools to optimize steering and other handling performance, but it may also mean new challenges.
- Vehicle designers would probably like airless tyres since they may give the vehicle a “sporty” and/or futuristic look.
- Depending on the material in the spokes, the weight may be decreased or increased which influences rolling resistance and the wear of the road structure.
- On today’s road vehicles, new tyres may be fitted 5-10 times during a vehicle’s lifetime, which obviously requires enormous volumes of raw material, even when implementing limited recycling. Airless tyres made of more recyclable material and constructed to serve as long as the vehicle they sit on (apart from the rubber treads), will mean substantial global savings for material resources and thus give a more sustainable future.

10.3 Disadvantages or challenges

In addition to the list below, it shall be realized that the whole tyre industry may be rocked if airless tyres will become popular, while the retread tyre industry will gain.

- There may be possible eigenfrequencies in the spokes.
- Interior noise in vehicles may be higher for airless tyres, since the filtering effect of tyre sidewalls and the “air cushion” in the pneumatic tyre is missing. It will be like an extremely-low-profile tyre.
- For trucks and their trailers running at very different loads, it will not be possible to adjust the tyre/road contact patch by adjusting the air inflation, which may be favourable for rolling resistance but may be a disadvantage in some other respects.
- On non-symmetrical airless tyre designs (such as the one planned in LEON-T) tyre irregular wear (sideways) may occur.
- Durability at high speeds of airless tyres is not yet proven to be sufficient. It may be necessary in the beginning to limit the maximum operating speed.
- Interior noise in road vehicles may become a challenge for airless tyres, since they would be stiffer than flexible sidewalls of pneumatic tyres; although the trend is that the sidewalls get lower and lower for modern high-performance tyres.
- Furthermore, it may be difficult to avoid the spokes generating audible noise.
- Airless tyres may give vehicle designers new tools to optimize steering and other handling performance, but it may also mean new challenges.
- Depending on the material in the spokes, the weight may be decreased or increased which influences rolling resistance and the wear of the road structure.

11. Future outlook

11.1 New material

The choice of steel for the spokes in this project is not optimal with respect to weight. However, 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 will not be 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.

11.2 Discussion by the author

The author believes that the airless tyres may be successfully implemented especially in the design of electric road vehicles. This is for three main reasons:

- Rolling resistance may 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 CW design, there is space for integrating electric motors and brakes on the inside of the tyres (see Figure 1)
- Noise emission from airless tyres will be reduced; thus, making electric vehicles quieter also at higher speeds

If WP5 of the LEON-T project will be a success, it may 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. As suggested above, Bridgestone and Hankook may not want to be left behind, given the expanding electric vehicle production in Japan and South Korea. 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.

Even if 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.

11.3 Statements by industry representatives

At a roundtable discussion at the conference of the 2020 Tire Technology Expo, including representatives of Michelin, Bridgestone and Continental plus three experts from the scientific community (Figure 33), the moderator asked the question whether airless tyres will be the tyres of the future. Despite all the concepts by the tyre industries described above, the answers from Bridgestone and Continental were sceptical while the other experts were more uncertain. It was only the Michelin expert who seemed to believe in this concept. He also held a presentation at the conference but did not reveal any technical data [Sandberg, 2020].

Figure 33: Panelists at the 2020 Tire Technology Expo, addressing a.o. airless tyres. Source: The program of the conference at the Expo.

Some other statements from industry representatives, as reported in [RFI, 2022]:
Michelin's CEO Florent Menegaux doesn't expect airless tyres to squeeze out regular tyres anytime soon. "We're going continue to have air tyres for several decades," he said.

Goodyear …. aims to have a maintenance-free and long-lasting airless tyre for cars by the end of the decade. It already has an early version for shuttle buses and automated delivery vehicles on university campuses.

Goodyear's vice president for product development in Europe, Xavier Fraipont, acknowledged that airless tyres requires a "rethinking our business model, of rethinking our manufacturing".

Bridgestone also hopes to have an airless tyre ready within a decade, having already tested early versions on utility vehicles.

Other manufacturers are more sceptical that airless tyres will ever offer comparable shock absorption as traditional tyres and the noise can be reduced sufficiently. "They aren't a viable solution and I don't expect they will become one," a Continental researcher, Gerrit Bolz, said at a tyre convention in 2017.

In a recent article in Tire Technology International, Chuck Yurkovich, senior VP of global research and development at Cooper Tire & Rubber Company, expressed the following [Yurkovich, 2019]:

On the other hand, the airless tire has already been applied in niche fitments for small tires like bikes, mowers, golf carts, ATVs, and slow moving tires needed in heavy equipment applications. These milestones may help catapult its use into passenger and light truck tires once 'new' designs and materials make the technology competitive with pneumatic tires and inherent airless tire issues – including durability, ride/comfort, tire weight, manufacturability and cost – are solved.

An interesting statement by South Korean manufacturer Kumho Tire (Europe GmbH) was issued recently, as an input to a tradefair exhibition Autopromotec 2022 in Bologna. See Figure 34, in which it is suggested that the "future of tires" is airless tyres as illustrated by a concept tyre from Kumho.

Figure 34: The "future of tires" according to a poster by Kumho at an Italian trade-fair in 2022. Picture is from @KumhoTyreUK, on Twitter.com. The tyre seems to be the so-called e-NIMF.

11.4 View of readers of TTI

Tire Technology International (TTI) is the most wide-spread publication for people working in the tyre industry and its suppliers, including also the scientific community. In 2018, in an email to its readers, the magazine presented the results of a poll it issued to the readers at the end of 2017. The results of the poll are shown as horizontal bars in Figure 35. The airless tyre technology for mass-market production appeared to collect many more selections than 3D printing, morphing treads and spherical tyres. This is an indication of the trust tyre experts have in the future development of the airless technology.

Figure 35: Result of a poll among the several thousands of readers of the Tire Technology International magazine. From part of an email 2018 to the readers, in this case the author.

12. Conclusions

It is now exactly 40 years since Goodyear filed its patent for an airless tyre (called IWT), and a few years later published a scientific article about it; reporting very good performance in the tested respects. Given the intensive R&D work in the tyre industry sector, one may find it remarkable that after such a time there is still no such tyre on the market for road vehicles.

The following present some conclusions from this Deliverable:

At the end of the 1980's, unaware of the Goodyear IWT, Hansson's Swedish invention of the "Composite Wheel (CW)" was tested, with a primary view of reducing exterior tyre/road noise and rolling resistance. Later generations of the CW were tested about 15 years ago in a multi-national project, in which excellent noise reduction and rolling resistance was obtained along with good road handling. However, it did not endure the ultimate test: high-speed running on a pot-hole test track.

The scaling-up of the CW concept from car to truck size, using similar composite material (CHRP), which would require about 5-8 times higher load than the car version, did not result in a durable tyre, according to LEON-T's initial calculations and simulations. However, replacing the spokes made of CHRP with high-stress steel, has showed promising results and is currently the design which is worked on in LEON-T.

Most the major tyre manufacturers have been working on own airless tyre concepts, which in a few cases have resulted in prototypes for testing. The Uptis from Michelin is currently being tested on a GM electric car, and the Goodyear NPT has been tested on a Tesla car and is currently used on an in-service minibus in Florida.

All concepts have been designed for passenger cars, except that Bridgestone has a construction for a medium truck.

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.

Compared with the airless concept tyres by the tyre manufacturers, the design by Hansson, 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 CW and the LEON-T tyre will have a unique rubber tread, as it will have holes drilled radially through the tread and belt, in order to ventilate air and drain water away from the tyre/road contact patch.

Only a few scientific publications dealing with airless tyres could be found. Most of the information comes from press releases from the tyre manufacturers, or news articles based on marketing materials from them. However, statements by representatives of tyre manufacturers rather consistently suggest that rolling resistance of airless tyres should be lower than for corresponding pneumatic tyres. Other performances seem to be more uncertain, except (of course) the puncture-proof operation of airless tyres.

It is anticipated in most publications and interviews with experts that airless tyres will win a significant part of the market in the future, especially for electric vehicles, albeit there is also much scepticism about it. Maintenance-free operation is mentioned as something expected to be of special value to autonomous vehicle driving in the future.

The outlook for marketing airless tyres is uncertain, since they will require new infrastructure in terms of new factories and if they will take over a significant role of the pneumatic tyres, it will mean a revolution to the entire tyre industry with some of the existing facilities representing huge values becoming obsolete. The tyre retread industries will be one of the foremost winners. Probably, the environment will be the winner too.

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