Systematic Review of Tyre Technology

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Yasuhiro Ishikawa

■ Abstract

The history of the tyre starts with the use of the wheel, using a log or its x-section. Tyres then came into common use on the wheels of carts or horse carts. The pneumatic tyre was originally invented by R.W. Thomson in the middle of 19th century. Then at the end of 19th century, a pneumatic tyre for automobiles was invented. The history of the Japanese rubber industry also starts around this time: the latter half of 19th century, out of which the tyre industry then developed. The history of the Japanese tyre industry is divided into the three following stages:

Stage 1: Dawn of the Industry

The Japanese tyre industry began in the Meiji era (1868-1912) with the initial development of the Japanese rubber industry. The foundation of Tsuchiya Rubber Factory in 1886 (Meiji 19) is generally taken to herald the start of the Japanese rubber industry, approximately fifty years after the invention of vulcanization by C. Goodyear in 1839.

Stage 2: Age of Growth

This period from the beginning of the Taisho era (1912-1926) to the end of World War II saw the introduction to Japan of rubber technology from foreign countries, when domestic industry as a whole was developing with the importation of various technologies. The founding of domestic tyre manufacture dates from this period. Domestically-developed tyre technology showed dramatic growth during the War and played an important role in military supplies.

Stage 3: Maturity

This stage covers the time from the end of the War II to the present. Although tyre manufacturing suffered significant damaged during the War, recovery was rapid, and tyre technology saw further dramatic development with the growth of motorisation. This period of growing post-War motorisation is divided into three parts.

The first period was when new materials such as nylon and synthetic rubber were developed. In this period, processing technology that could deal with these new raw materials was developed for the tyre.

The second period saw tyre construction completely change from bias to radial tyres. This significant development in tyre construction saw not only major changes in materials, such as the use of steel cord, but also in the modification of production equipment.

In the third period, the various elemental technologies were integrated, resulting in the further refinement of the steel radial tyre and the achievement of its durability in terms of adhesion between

the rubber and steel cords, and preventing rubber fatigue throughout the tyre's working life.
Following this period, better motion performance was required of tyres. However, it was well known that a tyre with lower rolling resistance had the problem of lower skid resistance. This performance trade-off is still major issue with tyres today. In addition, the improvement of ride quality, such as the reduction of noise and vibration, came to be increasingly important in tyre performance. Therefore, more exacting demands have been made of tyre performance since the 1980s.
Many epoch-making technologies have been developed since the War in the areas of raw materials and construction, and which have then been incorporated into tyre technology. How much Japan has contributed to these developments in tyre technology is debatable; however, Japanese tyre technology has recently been earning itself recognition in the tyre industry by further consolidating these technologies. The next decade will see rising demand for environmentally friendly solutions, spurring the need for new technology that addresses this major issue.

■Profile

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March 1969	Completed Master's degree at Tokyo Institute of Technology Graduate School of Engineering
April 1969	Employed in the laboratory at Yokohama Rubber Company
October 1993	Head of the Tire Materials Development Department, Yokohama Rubber Company
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July 2003	Chief Engineer, Yokohama Rubber Company
July 2005	Consultant, Yokohama Rubber Company
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■Contents

1. Introduction

1.1. Outline of Tyre Technology

Tyres are an essential component to the establishment of the automobile mechanism.
Tyres can be viewed as having the following four functions [1)].
- Bearing a load (support)
- Acting as a spring (absorption)
- Conveying driving and braking forces (transmission)
- Facilitating steering of the vehicle (turning)

These are vital functions in which the tyres as part of the vehicle serve as an intermediary in establishing a mutual relationship between the vehicle and the surface of the road.
The history of tyre technology is the history of developments carried out to achieve these functions. This technology is expansive in extent, combining many materials to form the mechanics of the tyre, which in turn plays a complex role being incorporated as a component into the automobile mechanism. Thus, tyre technology is expansive and has come to hold an important place in the industry.
Tyres are a rubber product. Rubber technology had a long history before the invention of the tyre in the 19th century. The technology followed the same path in Japan, albeit later.

1.2. Progress of Japanese Tyre

Technology (Systematisation) (See Fig. 1.1)
The history of the tyre industry in Japan can be divided into three stages.
Stage 1: Dawn of the Industry – Meiji Period. The dawn of the Japanese rubber industry saw some rudimentary developments.
Stage 2: Stage of Growth – Early Taisho Period to the Second World War. From the Taisho Period to the early Showa Period, Japan either introduced overseas technology or started developing its own independent technology. This technology later played a role as military goods during wartime.
Stage 3: Stage of Maturity – Post-War to the present. While various companies suffered during the war, they bounced back from the ravages of war and, accompanied by the later spread of motorisation, grew rapidly to the present day [2)].
The Stage 3 post-war age of motorisation can be divided into three further stages.
The first stage was the age of incorporating new materials into the existing bias tyres. Instead of cotton or rayon for reinforcing, synthetic nylon appeared; synthetic rubbers such as SBR (styrene-butadiene rubber) and BR (butadiene rubber) also appeared as a replacement for natural rubber. This stage is remembered as an age in which new materials appeared and much effort was spent on processing techniques in order to fully utilise them (post-war – 1960s)

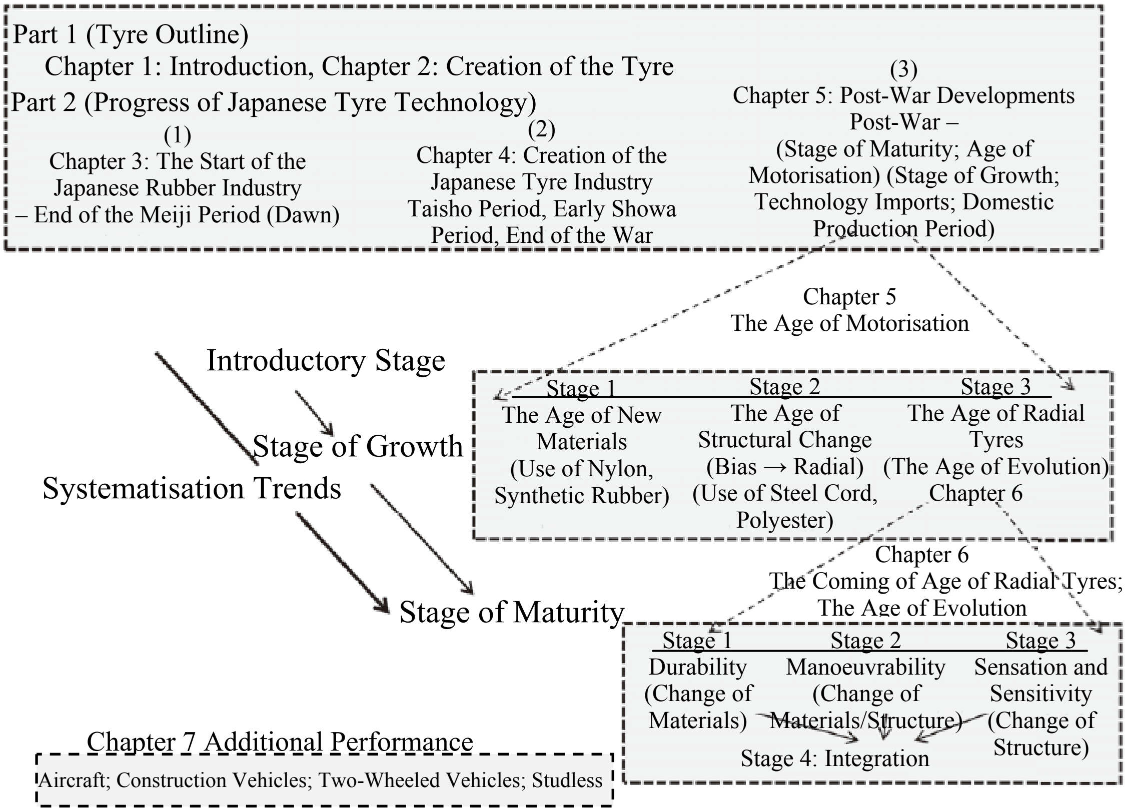


Fig. 1.1. Progress of Japanese Tyre Technology (Systematisation)

The second stage was the age in which tyre structure changed from bias to radial. This major change in tyre structure was accompanied by major changes in manufacturing facilities. The appearance of steel cord reinforcing meant major changes in tyre structure and manufacturing facilities, accompanied by major progress in tyre performance.

The third stage is the age of integrating various elements of existing technology and improving radial tyre performance. This stage can be divided into a further four stages.

The first was the age of perfecting radial tyre durability. This was an age of ensuring durability, fraught with issues such as how to fasten steel cord and rubber together and dealing with separation due to breakdown in the rubber. 1970s-1980s.

The second was the age of ensuring high manoeuvrability as a required performance over and above durability. This was affected by the 1979 oil crisis, with a rapidly-increasing demand for improved fuel economy. This presented some issues with safety, since tyres with good fuel economy moved easily but were difficult to stop. Competition soared around the world to resolve this paradox. 1980s onwards.

The third was the age of increased sensation and sensitivity, such as noise and vibration. 1980s onwards.

The fourth was the coming of age of tyre performance. There was a demand for a high degree of all-round perfection, with high levels of durability and manoeuvrability as well as sensation and sensitivity factors such as noise and vibration taken care of. In other words, it was an age of demand for perfection in all component technologies in all areas of performance and of theories developed to that end.

Other tyres (such as aircraft tyres, tyres for construction vehicles, tyres for two-wheeled vehicles and studless tyres) require additional performance capabilities than normal. These have played a role in presenting tyre technology with the challenges of additional performance (such as heat resistance and friction on ice).

Broadly, the progress of post-war technology development has alternated between material (nylon and synthetic rubber), structural (radial tyres), material (rolling resistance due to radial material durability and variety of SBR) and structural (sensation, sensitivity, noise, vibration, ride comfort). At each stage, the most suitable techniques have been eagerly sought out and surpassed.

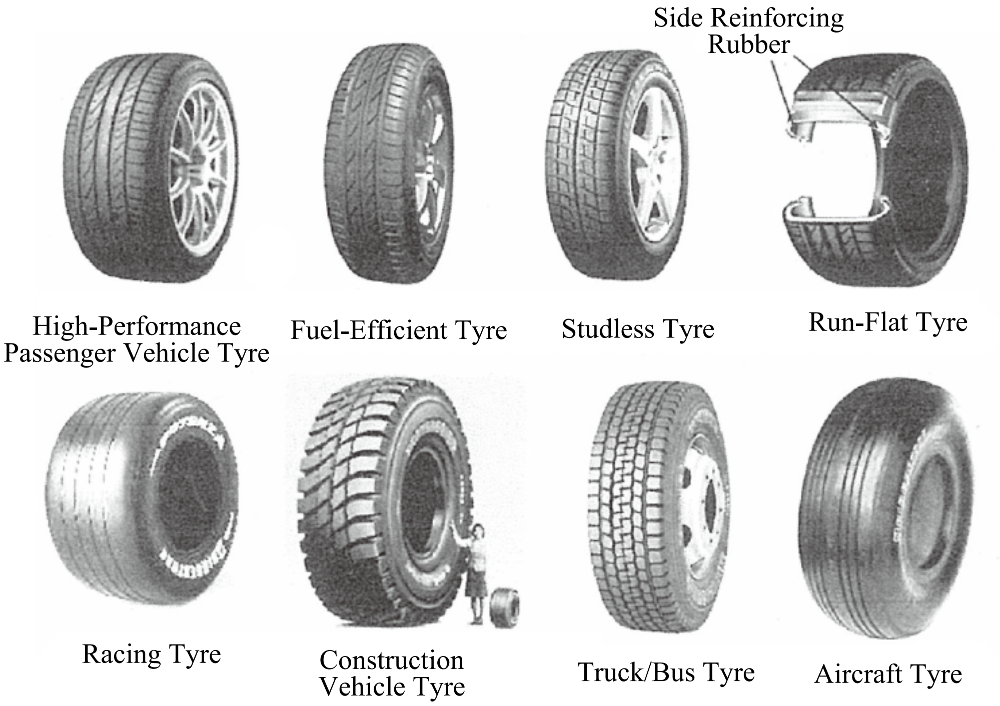


Fig 1.2. Current Types of Tyres [3)]Gomu / Erasutomā to Mirai no Kōtsū [Rubbers / Elastomers and Future Transportation] Rubber Technology Forum, ed., Gomutimes, March 2010, p

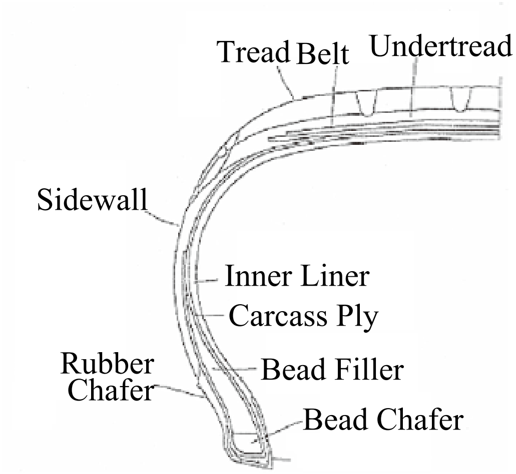


Fig. 1.3. Tyre Structure (Radial Tyre)
(Cross-Section)

Looking back through this history of development, there are very few major breakthroughs in which Japan actively contributed to epoch-making technology, such as the change from bias tyres to radial tyres, or the appearance of synthetic rubber or steel cords. However, Japan's later presence in the tyre industry has been unwavering; ultimately, its strength in the industry – its operational strength combined with its technological strength (optimisation strength) – is significant. This is probably due to the significant presence of its technological strength based on manufacturing. It is also probably a combination of the Japanese-style technology prioritisation (diligent manufacturing for optimisation rather than major innovation) and the emphasis on companies (enterprises).

Tyre Size Designations

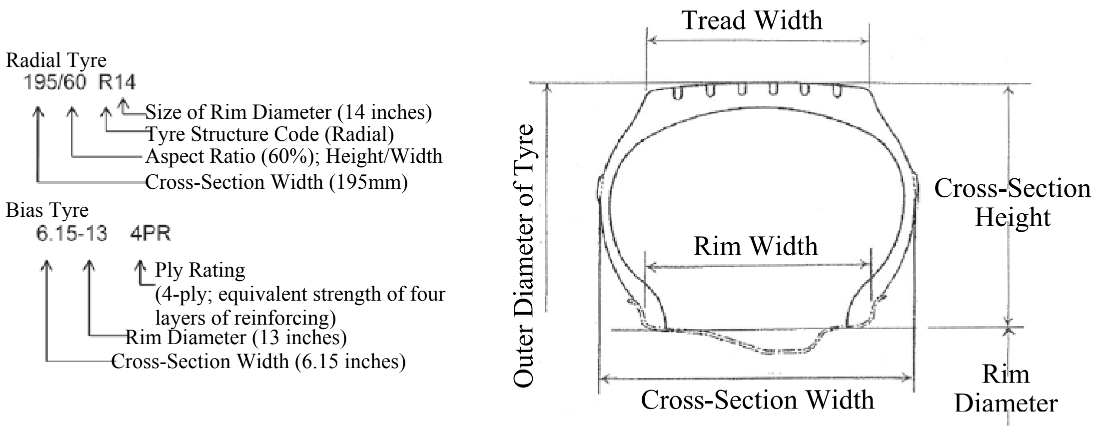
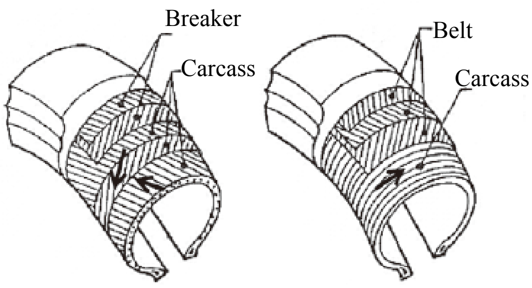


Fig. 1.4. Tyre Dimensions. Aspect Ratio = Cross-Section Width / Cross-Section Height

However, stricter environmental measures will mean further hurdles will need to be crossed in future. Mere optimisation will not be enough; major breakthrough will be necessary.



a) Bias Tyre b) Radial Tyre

a) Bias Tyre : Carcass is oriented in a biased direction

b) Radial Tyre : Carcass is oriented in a radial direction

Fig. 1.5. Comparison of Tyre Structures (Bias / Radial)

Notes on Writing:

1. There are many types of tyres; it was not possible to describe them all. This report does not touch on racing tyres, agricultural tyres or bicycle tyres.
2. Regarding company names. Company names have been dealt with as follows for the writing of this report. The former name of the company has been used where doing so has served to better convey the content.

(Name used):	(Former name(s); current official name)
Sumitomo Rubber:	Dunlop Rubber Company (Far East); Dunlop Rubber Company (Japan); Chuo Rubber Industries(*Chuō Gomu Kōgyo Kabushikigaisya*); Sumitomo Rubber Industries
Yokohama Rubber:	Yokohama Rubber Manufacturing Company(*Yokohama Gomu Seizou Kabushikigaisya*); Yokohama Rubber Company
Bridgestone:	Bridgestone Tire Company; Nippon Tire Company(*Nippon Taiya Kabushikigaisya*); Bridgestone Tire Company; Bridgestone Corporation
Toyo Rubber:	Toyo Tire Industrial Company(*Tōyō Taiya Kabushikigaisya*); Toyo Rubber Manufacturing Company(*Tōyō Gomu Kakou Kabushikigaisya*) ; Toyo Rubber Industrial Company

(in order of founding)

3. Handling of Numbers in the Japanese Text, years, months and days cited from sources originally written vertically, such as company histories and *The History of the Japanese Rubber Industry*, are written in Sino-Japanese characters in the Japanese texts. Since the Japanese text of this report is written horizontally, it uses Arabic numerals.

Cited references:

1) Hattori, Rokuro: *Taiya no Hanashi [The Story of the Tyre]*, Taiseisha, June 1992, p. 34.
Jidōsha-yō Taiya no g [Studies on Automobile Tyres], Yokohama Rubber Company ed., Sankaido, 15 April 1995, p. 7, etc.

2) “Gomu Kōgyō ni okeru Gijutsu Yosoku — Jidōsha taiya wo Chūshin ni shite [Technology Forecasting in the Rubber Industry: Focus on Automobile Tyres]”, Rubber Technology Forum, ed., (1990) December, p. 35 – p. 43. Latter division of time periods considered with reference to “Kongo no Taiya Gijutsu Yosoku [Future Tyre Technology Forecasting]”.

3) *Gomu / Erasutomā to Mirai no Kōtsū [Rubbers / Elastomers and Future Transportation]*, Rubber Technology Forum, ed., Gomutimes, March 2010, p. 69.

2. Creation of the Tyre

2.1. Beginnings as a Wheel

Tyres originally began as wheels. The origin of the wheel is unclear, although it is thought to have been at least 4,000 years ago. The use of the wheel shows that it was at least known that rolling results in less friction than sliding.

Logs or round slices of logs were first used (Fig. 2.1). Gradually, these were replaced by discs made of several planks joined together (Fig. 2.2), followed by spoked wheels (Fig. 2.3). Wagons were the main means of transportation until automobiles became popular. These wagons had hubs of evergreen oak or elm, as shown in Fig. 2.3; these were supported by spokes encircled by a rim or felloe, while an iron band around the outside to prevent wear from contact with the ground could truly be called a tyre.

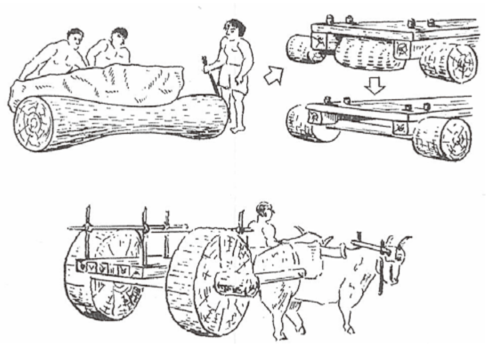


Fig. 2.1. Early Wooden Wagons [1)]

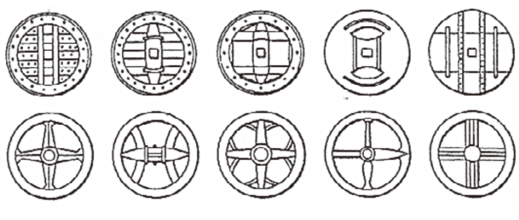


Fig. 2.2. Various Improved Wheels [1)]

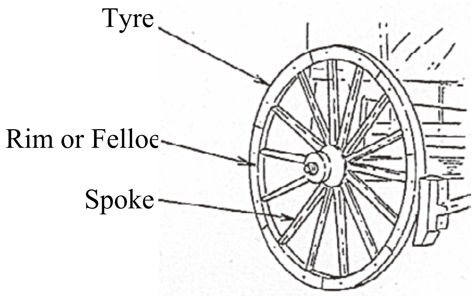


Fig. 2.3. Cart or Wagon Wheel [2)]

The steel rim that surrounds a railcar wheel and comes in contact with the rail is called a tyre (Fig. 2.4).

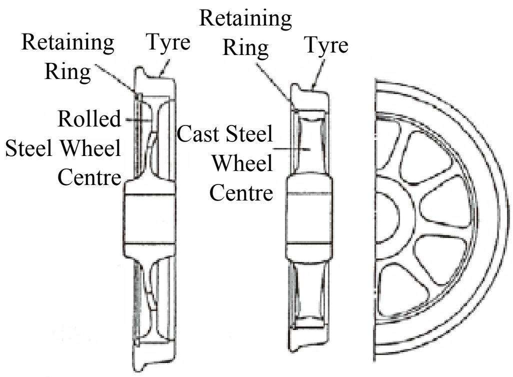
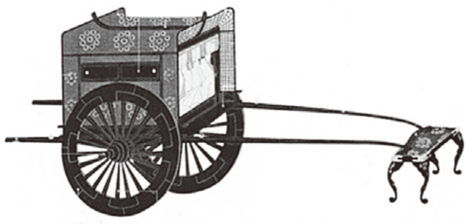


Fig. 2.4. Railcar Wheel with Tyre [1)]

Wheels have been used on vehicles (even the Heian Period ox carriages) in completely different time periods and completely different countries. The vehicles from this time were made of wood and probably did not offer much in the way of riding comfort (Fig. 2.5) [3)].



Ox Carriage

Fig. 2.5. Heian Period Vehicle (Ox Carriage) [3)]

2.1.1. The Beginning of the Tyre

The discussion below draws heavily from *Taiya no Hanashi [The Story of the Tyre]* [1]. Vehicles with iron or wooden wheels were difficult to pull on rough road surfaces. Accordingly, early tyres were the result of various inventors competing to somehow make vehicles travel more comfortably. Attempts were made to give tyres greater elasticity; what is now known as the solid tyre (a tyre made wholly from rubber with no air inside) was invented in 1835 (see figures below).

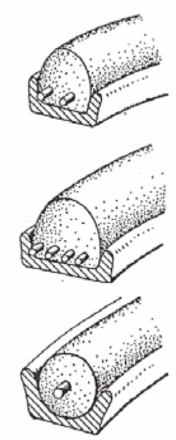


Fig. 2.6. Various Early Solid Tyres [1]

The first automobile with a gasoline engine was built in 1886 by German company Daimler-Benz. Production of this vehicle started in France in 1890. Although this vehicle had solid rubber tyres, later automobile manufacturers still used metal rings. In 1895, the first pneumatic tyre was developed for such vehicles.

A replica of the first Benz vehicle with solid tyres is on display at the Toyota Automobile Museum (see Fig. 2.7).

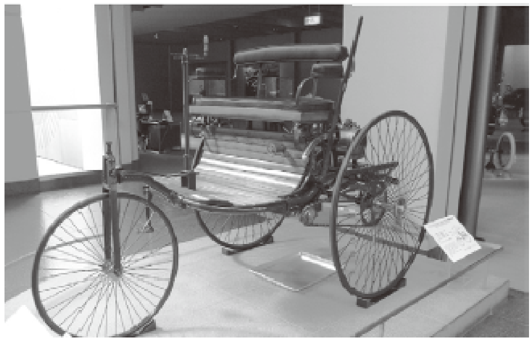


Fig. 2.7. Benz Automobile Built in 1886 (Replica)

Fitted with Solid Tyres (Toyota Automobile Museum Collection) [4]

2.2. History of the Tyre

The epoch-making invention of the time was the pneumatic tyre. R. W. Thomson was the first to invent and patent the pneumatic tyre in 1845 (see Fig. 2.8).

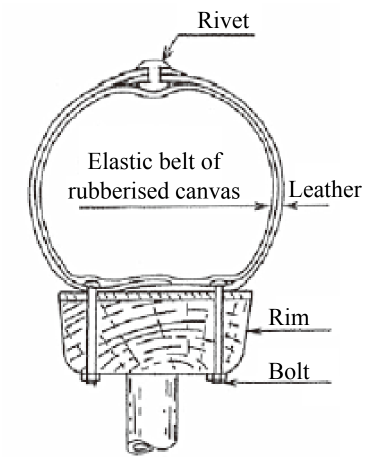


Fig. 2.8. Thomson's Pneumatic Carriage Tyre Patented 1845 (UK) [5]

This was granted a UK patent [5] relating to an improvement in carriage wheels. The distinguishing feature of this invention was the elastic body around the wheel, which reduced the running resistance and noise of the wheel and improved the riding comfort, resulting in a wheel that was also suitable for high-speed applications such as steam vehicles. The elastic body comprised a hollow belt made of a high molecular substance such as rubber or gutta percha (a type of natural rubber) and filled with air.

Structurally, it was a pneumatic elastic belt of rubberised canvas. Functionally, it worked on the same principle as the tyres of today. It is surprising to think that the same idea for the modern-day tyre existed over 160 years ago.

This tyre was made for horse-drawn carriages. Rubberised fabric was pasted together to form a tube, which was riveted to a leather outer layer and also riveted to a wooden rim.

However, it was not very effective on actual vehicles and it was eventually forgotten. The actual tyre was invented by Dunlop in 1888, around 40 years after Thomson's tyre. The idea was taken up by J. B. Dunlop and patented again. Dunlop's patent was for a hollow tyre or tube made of India rubber, fabric or other suitable material filled with pressurised air and fitted to a wheel by appropriate methods. As shown in Fig. 2.9, Dunlop's tyre comprised a rubber tube encircling a thick wooden disc about 40cm in diameter, covered in rubberised canvas with the ends nailed into the disc. Not only did it improve the riding comfort, it also significantly reduced the rolling resistance compared to solid rubber tyres, making it run more comfortably [9].

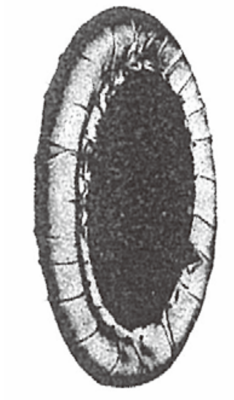


Fig. 2.9. The First Dunlop Tyre Pneumatic Tyre [9] (Replica)

According to *100: The First Hundred Years of Pneumatic Tyres 1888-1988*, J. B. Dunlop finally came up with this invention after repeated experiments because his ten-year-old son, Johnny, had asked him to "make my tricycle go easier and faster".

In his first experiment, Dunlop removed the solid rubber tyre from a tricycle wheel and tried to roll it along, but it fell over mid-flight. When Dunlop rolled his pneumatic tyre along with the same force, it rolled across the garden, hit a door and rebounded. Having ridden a bicycle with pneumatic tyres fitted, Johnny rated it very highly (see Fig. 2.10).

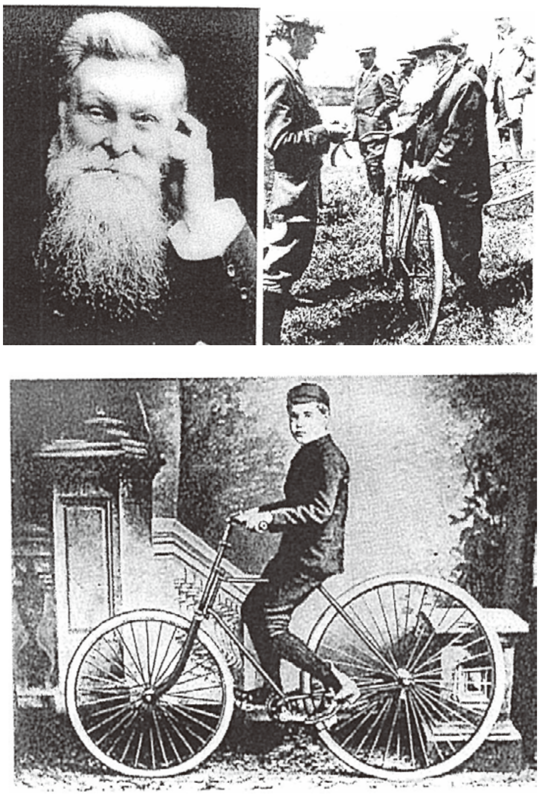


Fig. 2.10. J. B. Dunlop with a Bicycle Fitted with Pneumatic Tyres [6][7] His Son Johnny

2.2.1. Commercialisation of the Pneumatic Tyre

Around this time, cycling was becoming a popular sport. J. B. Dunlop's pneumatic tyre appeared just as cycling was beginning to grow in popularity and its performance was epoch-making. Sports-loving entrepreneurs, publishers of cycling magazines, newspaper journalists and bicycle dealers alike joined forces with Dunlop to commercialise the pneumatic tyre. In November 1889, The Pneumatic Tyre and Booth's Cycle Agency, Ltd. was established in Dublin, Ireland, with capital stock of £25,000. J. B. Dunlop transferred his patent rights to the company and became a company director. Today, there is a bronze plaque at the site, which reads, "The first pneumatic tyre factory in the world was started here in 1889, to make tyres under John Boyd Dunlop's patent of the 7th December, 1888" [10]. (Fig. 2.11)

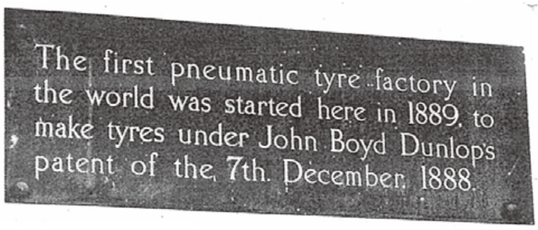
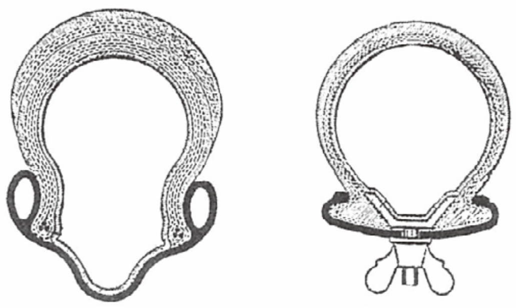


Fig. 2.11. Bronze Plaque [10]

Following the emergence of pneumatic tyres, various efforts were put into making them easier to use. One such initiative was to make it easier to assemble and disassemble the tyre and rim; two methods were devised for this purpose. The first was the wired-on (wire-type) method devised by C. K. Welch; the second was the clincher (pull-on, Fig. 2.12) method devised by W. E. Bartlett. Both were granted patents in 1890. A valve was invented that allowed air to be let out as well as pumped in; the patent for this was granted to C. H. Woods in 1891. Not long after its establishment, The Pneumatic Tyre and Booth's Cycle Agency, Ltd. spent a lot of money for the patent rights to these three inventions, all of which contributed to the expansion of the company [10]. The wired-on method (Fig. 2.12), which used a ring of steel wire to affix the base of the carcass into the rim, was the prototype for the modern-day method of affixing automobile tyres to their rims [1].



Wired-On Tyre Clincher Tyre

Fig. 2.12. Early Tyre Structures and Methods for Attaching Them to Rims [1)]

The Michelin brothers in France were the first to use pneumatic tyres on an automobile. The story is well-known how the brothers entered and somehow completed the 1,000km Paris-Bordeaux-Paris automobile race in 1895, replacing their pneumatic tyres one after another. From then on, pneumatic tyres steadily advanced into the field of automobiles. However, the roads at the time were very smooth and the tyres had no tread pattern; with a little speed built up, a vehicle could not be easily stopped. Tyres also often suffered punctures [10)].

The Dunlop Company in the United Kingdom put the first tread on a tyre in 1905, a simple horizontal groove pattern. This was produced by placing short iron rods on the unvulcanized rubber; the vulcanizing temperature would imprint the pattern into the rubber [6)]. This is shown in Fig. 2.13.

Fig. 2.13. The First Horizontal Groove Pattern Tyre, Made by Dunlop in 1905 [6)]

2.3. Rubber, an Essential Material for Tyres

Without rubber, the modern-day pneumatic tyre would not exist. Rubber is an essential material for tyres. Natural rubber was the first type of rubber to be used in tyres; looking back, the discovery of natural rubber was the first step in tyre history.

2.3.1. The History of Natural Rubber

Natural rubber has long served humankind; of all the types of rubber, it is still the best source material. The history of natural rubber is outlined below.

In the mid-1490s, Christopher Columbus saw the indigenous people of Hispaniola (Haiti) in the West Indies playing with a rubber ball. Following the discovery of the New World, the properties of natural rubber, such as its elasticity and water resistance, were noted and studies began on its uses. However, until C. Goodyear discovered the use of sulphur to vulcanise rubber in 1839, rubber was simply a rare commodity and served no purpose as an industrial raw material. The discovery of vulcanisation enabled the development of the rubber industry. Coupled with the emergence of the automotive industry in the 19th and 20th centuries, this formed the basis for the modern-day industry. Research on natural rubber continued in the 19th century, with M. Faraday confirming the chemical composition of natural rubber as C_5H_8 in 1826. In 1860, G. Williams dry-distilled rubber and isolated the isoprene monomer [8)].

Rubber later dramatically increased in consumption with the growth of the automotive industry. Since the United Kingdom had the monopoly on 80% of the world's cultivated rubber, other countries struggled to secure raw rubber.

Later, rubber became an essential military commodity in the World Wars. Full-scale research on synthetic rubber as a strategic resource was carried out around the time of the First World War (1914). Until the Second World War (1939-45) prompted mass production of synthetic rubber, other countries around the world were unable to break the United Kingdom's monopoly.

During the First and Second World Wars, the industrialisation of butadiene synthetic rubber was fast-tracked because it was necessary to ensure vast amounts of rubber for military manoeuvres. After the wars, synthetic rubber proved to be a worthy competitor to natural rubber, with improvement to the quality and reduction in the cost of SBR as well as the development of the petrochemical industry; in 1963, worldwide synthetic rubber consumption finally overtook that of natural rubber.

In light of such circumstances, improvements were made to natural rubber. Efforts began in Malaysia – the world's largest producer of natural rubber at the time – and other countries to systematically replant with higher-yield species to increase yields, improve tapping methods (extracting rubber latex by cutting the tree trunk), use latex secretion promoters, prune trees while young, fertilise, carry out soil management and prevent disease. Rationalisation and centralisation of raw rubber production processes meant improved quality and reduced costs, all of which combined to provide competition against synthetic rubber. Some attempts were made to catch up to synthetic rubber through chemical modification of natural rubber and development of new forms of natural rubber [8)]. Currently, natural rubber is very highly priced, with a strong demand for it in emerging nations.

The natural rubber tree used industrially is the Pará rubber tree *Hevea brasiliensis*, which has very low non-rubber content and a very high yield of rubber hydrocarbons, namely cis-1.4-polyisoprene. The latex extracted when the bark is cut has a 30% rubber content. This rubber content contains proteins and small amounts of lipids,

sugars and ash. Although the latex remains stable while inside the rubber tree, once harvested it is prone to spontaneous coagulation due to enzyme action, so a protectant like ammonia is added to prevent coagulation. The latex is a milky juice in the ductal tissue that develops near the cambium layer within the *Hevea* tree, extracted by cutting the bark (tapping) of trees that are at least 5-7 years old. The latex coagulates when acid is added to it. The dried form of this is known as raw or crude rubber.

Hevea rubber is polyisoprene with a 1.4-cis structure and has very high tensile strength. It crystallises when stretched and usually has high mechanical strength, low heat resistance and high abrasion resistance. Accordingly, it has a high use ratio in high-load tyres.

Natural rubber, discovered and improved by humans, is a high-quality rubber with superior physical properties that has led to the formation of a wide range of industrial fields. The properties of natural rubber, such as its high strength and low heat build-up, make it perfect for tyres and it has been a key component in the development of the modern tyre industry.

2.4. The Importance of the Physical Properties of Rubber

2.4.1. Why Does Rubber Stretch?

If it were not for a unique elastic material such as rubber that can bounce, stretch and spring back, there would be no tyres.

Let us consider the structure of rubber.

Unlike other materials, rubber stretches when pulled and instantly springs back when released. It is also elastic and bounces. Why does rubber have such properties? After much research, the following are currently thought to hold true.

1) Rubber molecules themselves are shaped like springs. When subjected to some deformation, such as pulling, they are subjected to stress from changes in shape, such as when a spring is pulled (this called entropic elasticity). Even where there is no direct force on the molecules, they are subjected to force from the change in shape.
2) Such behaviour means that rubber molecules have gas-like properties and the so-called gas-like molecules form a polymer structure. Fig. 2.14 shows model

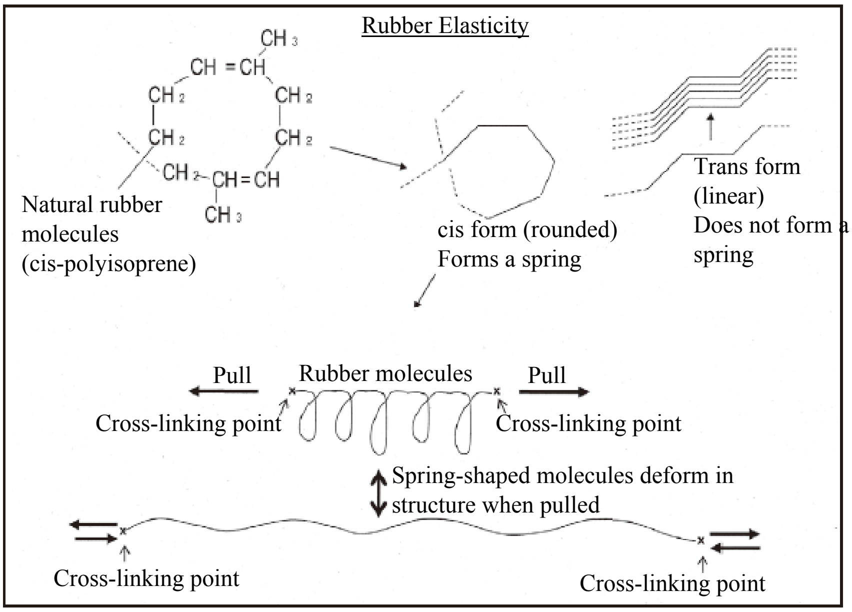


Fig. 2.14. Structural Model of Natural Rubber

2.4.2. The Discovery of Vulcanisation

The elasticity of rubber cannot be achieved by rubber molecules alone; it requires vulcanisation. This discovery by Goodyear in 1939 was the most important discovery in the history of rubber. Vulcanisation is the process of causing rubber molecules to bond together (in many cases the cross-linking is achieved by sulphur). The vulcanisation reaction causes adjoining molecules to bond together and form a network; any stress to any part of the network is transmitted to the entire network, which demonstrates rubber elasticity; in other words, it has turned into rubber. Fig. 2.15 clarifies this phenomenon. A standard test in the rubber industry is to apply torsional deformation to sulphur-added unvulcanised rubber over heat and to measure the corresponding force (torque) and the increased rigidity over time. When this reaches a certain level (plateau), vulcanisation is complete. Vulcanisation accelerators significantly reduce the vulcanisation time. Quicker vulcanisation has been a major issue in the rubber industry, particularly for tyres. Since natural rubber in particular deteriorates when exposed to heat, a major question has been how to complete the vulcanisation in a shorter amount of time.

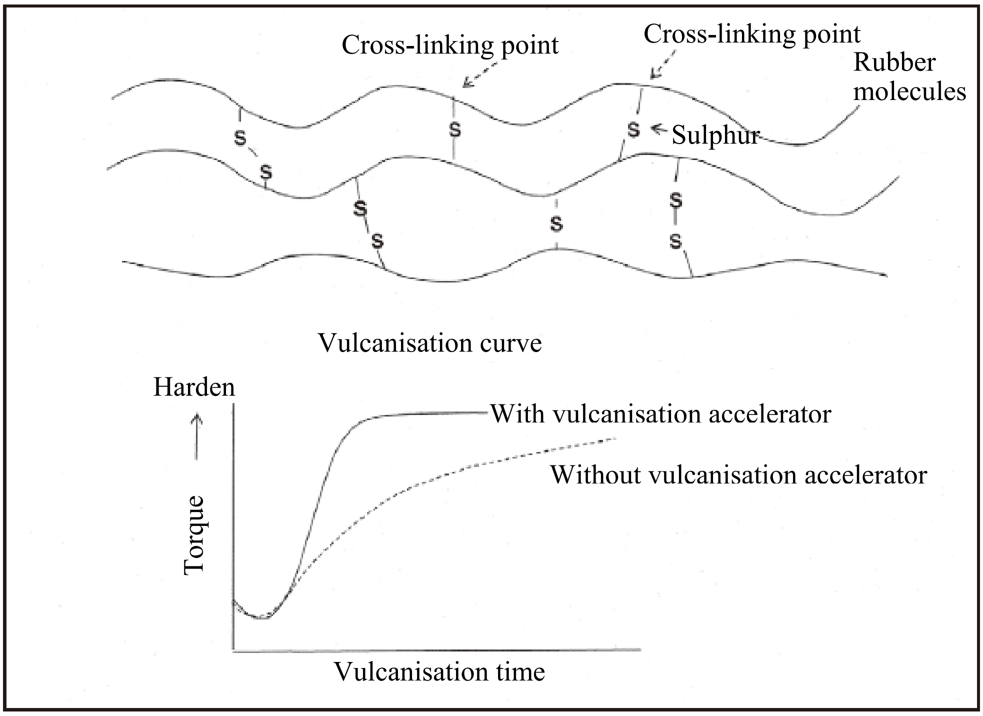


Fig. 2.15. Vulcanisation and Vulcanisation Curve

2.5. Natural Rubber and Environmental Issues

As environmental issues have intensified in the 21st century, natural rubber has been seen as carbon neutral and there has been an increase in its use.

In the 2010s, it is thought that the strong demand for natural rubber by emerging nations such as China and India will continue for the time being. With other emerging nations coming onto the scene, the price of natural rubber will probably continue to soar for some time yet. Conversely, there may be a shortage of natural rubber as a raw material.

The properties of natural rubber can change significantly when epoxy-modified. Recent research has examined new scopes of usage for it; accordingly, it is expected to continue to expand in use [10) 11)]

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3) *Shin Sōgō Zusetsu Kokugo [New Comprehensive Illustrated Language]*, Tokyo Shoseki, 2004, p. 21.

4) “Toyota Automobile Museum” Collection, 41-100 Yokomichi, Nagakute, Aichi.

5) UK Patent No. 10990.

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7) Best Car, ed., *Taiya no Subete ga Wakaru Hon [The Book that Tells You Everything You Need to Know About Tyres]*, Sansuisha, Kodansha, 2008, p. 95.

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10) *Sumitomo Gomu Hyakunen-shi [Hundred-year History of Sumitomo Rubber]*, Sumitomo Rubber Industries, Ltd., December 2009, pp. 33-35.

11) *Tokushu Erasutomā no Mirai Tenkai o Saguru Part I [Exploring Future Development of Special Elastomers Part I]*, Rubber Technology Forum, ed., Gomutimes, pp. 21-22, 1992, and Laid-Open Patent No. 2000-169504: Sumitomo Rubber Industries, Ltd., Kao Co., Ltd., Fuji Latex Co., Ltd., and Higashi Kagaku, Co., Ltd.

3. Dawn of the Japanese Rubber Industry (The Age of Early Compounding Techniques)

3.1. Meiji Period – Early Taisho Period

As mentioned in the previous chapters, Japanese tyre production started at the end of the Meiji Period (initially bicycle and rickshaw tyres; the first automobile tyres were produced in the second year of the Taisho Period, 1913). The core technologies at the time were rubber compounding and vulcanisation. Let us now address the rubber technology of the day.

The rubber industry was just dawning at the time; rubber compounding and vulcanisation were being developed independently through trial and error.

3.1.1. Late Meiji Rubber Technology

The Japan Rubber Ball Factory(*Nihon Gomudama Seizōzyo*) (or more correctly, the Japan Rubber Factory(*Nihon Gomu Seizōzyo*), according to *Hyōgo Gomu Kōgyō-shi [History of the Hyogo Rubber Industry]*; author note) is said to have been established in Kobe in 1885, manufacturing balls and pillows (*Kōbe Kaikō Sanjū-nen-shi [Thirty-Year History of the Opening of Kobe Port]*, published 1898) [3].

However, it is generally said that the Japanese rubber industry began in 1886. Namely, the Tsuchiya Rubber Factory (later the Mitatsuchi Rubber Manufacturing Partnership(*Mitatsuchi Gomu Seizō Gōmēgaisya*)) was established at the end of that year, moving on from repairing personal diving costumes to successfully vulcanising rubber. Accordingly, this formed the foundation of the modern rubber industry in Japan, at least technically speaking. This was around 50 years after Goodyear's discovery of vulcanisation [3) 2)].

In this era of compound-focused development, experimentation was carried out on rubber compounds and many compounding specialists emerged, having mastered the art of compounding. The compounds were kept secret, technical knowledge was monopolised and they received higher salaries than factory managers. This continued until around the end of the Taisho Period. The technology changed drastically with the invention of organic vulcanisation accelerators. Before there were organic vulcanisation accelerators, the most important issue was how to combine inorganic vulcanisation agents with inorganic vulcanisation accelerators.

Let us now examine compounding techniques. This discussion draws heavily from Yamada, Hitoshi: "Haigō-Shi [Compounding Specialists]", *Haigō no Tatekata [Compounding Techniques]*, Compounding Techniques Research Subcommittee, The Society of Rubber Science and Technology, Japan, ed.) [1]. (Hitoshi Yamada is a chief examiner for the Compounding Techniques Research Subcommittee, The Society of Rubber Science and Technology, Japan and has researched these compounding specialists in depth; the author is also a member of the Subcommittee.)

As mentioned previously, the Japanese rubber industry is generally said to have started in 1886 with the establishment of the Tsuchiya Rubber Factory. The Tsuchiya Rubber Factory changed its name to Mitatsuchi Rubber Manufacturing Partnership in 1892. Mitatsuchi merged with Showa Rubber Co., Ltd. in 1945.

(1) Early Technology (Mitatsuchi Technology)

Despite reference to original documentation, early attempts at vulcanisation by Mitatsuchi resulted in a series of failures with no specific method of vulcanisation attained [15].

Following much trial and error, researchers settled on a type of heated-stone method used for roasting sweet potatoes. The final method adopted was a unique vulcanisation method in which unvulcanised rubber was buried in a container of small stones and sand and gradually heated to produce even vulcanisation [4) 5) 9) 15)]. This was also adopted by other companies in 1904-1905 [4) 11) 16)]. Various compounds were used, such as adding lime or litharge (lead oxide; PbO) [15]. During mixing, the natural rubber was cut with scissors, soaked in volatile oil until swollen, then transferred to a roller or mortar [4) 5) 17)]. It then had to be pounded continuously with a pestle for several hours and workers are said to have become intoxicated from the volatile oil [15].

3.1.2. The Rubber Industry at the End of the 19th Century and Start of the 20th Century

A few years after Mitatsuchi was established (from 1888 onwards), several rubber seal businesses started operating [4) 11)]. The industry started growing in Japan in the 1890s; in 1894, the Yoshida brothers, who had cold vulcanisation technology, established a rubber firm in Kobe [4-7) 11) 12)]. In 1896, the Tokyo Rubber Factory(*Tokyo Gomu Seisakuzyo*) was launched, as was the Yoshida Rubber Factory(*Yoshida Gomu Seizō*), founded by former Mitatsuchi employees [4) 9)]. Hirano Works(*Hirano Seizōzyo*) [18] and Fujikura Rubber(*Fujikura Gomu*) [19] also started around the same time.

Although rubber factories were opening across the country, these were home-based businesses [8) 9)]. In 1900, there were only two rubber factories nationwide that employed ten or more regular staff members. Even by around 1909, there were no more than 19 factories that employed five or more staff members [4) 5) 8) 13)]. At the end of 1907, the three major companies in Tokyo Prefecture were Mitatsuchi with 229 employees, Meiji Rubber with 140 and Japan Rubber with 100 [4) 12)]. Mitatsuchi had held a near monopoly in the rubber industry for ten years until Meiji Rubber was founded [4) 9) 10) 14)]. All rubber shops sought out Mitatsuchi's compound [14]. This suggests a relationship between the compounding specialists and Mitatsuchi.

3.2. The Rubber Industry in the Late Meiji Period (Start of the Tyre Industry; author note)

The British-funded Japan Ingram Rubber

Company (hereinafter abbreviated as 'Ingram') was founded in 1908, while the Dunlop Rubber Company (Far East) (now Sumitomo Rubber Industries; hereinafter abbreviated as 'Dunlop') was founded in 1909 [4-7) 9) 11-13)]. Both had the same capital system; Ingram merged into Dunlop in 1911 [4-7) 9) 11) 12)].

Bicycles grew in popularity from around 1907, precipitating a sudden rise in demand for tyres [4) 5) 9-12)]. There was an increased demand for rickshaw tyres as well; companies leapt into production. Mitatsuchi and Meiji Rubber made prototypes in the early 1900s, launching into full-scale production around 1908 [4) 5) 9)].

The Japanese rubber industry followed contemporary trends and gradually built up its capabilities by imitating the technology of Dunlop and Ingram.

3.2.1. Dunlop

Dunlop had the best technologies and facilities with large amounts of capital provided by Dunlop in the United Kingdom. According to *Nihon Gomu Kōgyō-shi [The History of the Japanese Rubber Industry]*, "the Dunlop factory was also called the rubber school", with many engineers passing through its doors and playing active roles in other rubber companies [4) 5) 7) 12)]. The rapid spread of technology such as Dunlop Rubber's "compounding" techniques is said to be one reason why so many rubber factories were established in Kobe [4) 5) 9)].

3.2.2. Changes to Tyre Compounds

Dunlop/Mitatsuchi Compounds

Dunlop compounds are shown in Table 3.1, based on *Gomu Haigō Kokinshū [Collection of Rubber Compounds Old and New]*, published in 1940, although it is not clear if they were used in the late Meiji Period. A fixed natural rubber content is characteristic of Dunlop [2)].

A significant amount of Mitatsuchi compounds were versions of Dunlop compounds, giving an Oriental take on the British rubber compounds. Mitatsuchi quietly built up its compounding techniques and slipped in to take the reins of the Japanese rubber compounding domain alongside Dunlop. The two of them dominated from 1897 to the early Taisho Period and were still making a number of noteworthy achievements in the early Showa Period [14)].

3.3. The Rubber Industry from the Late Meiji Period to the Early Taisho Period

In the late Meiji Period, the Japanese rubber industry acquired some technology, but remained in an embryonic stage. Rather than an academic discipline, it involved "using chemicals and persisting with sulphur, the mixing of which was a closely guarded secret at each factory" (discussion with Masanosuke Sasabe of Bando Chemical Industries). There were no testing facilities; compounding relied on experience and intuition. However, each company kept their compounds a secret while each trying to work out

3.3.1. The Rise of Compounding Specialists

The Rubber Industry in the Late Taisho Period

The idea of compound secrecy continued after the Meiji Period [20], with rubber product manufacturers keeping their compound recipes locked away in vaults like valuables. It was not easy for new materials to gain acceptance.

In the early Taisho Period, Sōichirō Tanaka (trans.) published *Kōgyō Gomu Kagaku [The Chemistry of Industrial Rubber]*. This work outlined manufacturing methods in detail, as well as vulcanisation theory and testing and analysis methods [21] and was majorly utilised by rubber engineers [4]. However, although this was the partial beginning of academic investigation, many factories still relied on the secrets held by compounding specialists.

3.3.2. The World of the Compounding Specialists

Compounding specialists had an apprenticeship system. Novices would work for a specialist for around five years for almost no pay, memorising formulations [5]. Nonetheless, there were many studious compounding specialists. The compounding formulations were of course kept secret by the specialists and were never to be taught to workers within the factory [5].

These flourishing compounding specialists were later put out of business by the introduction of vulcanisation accelerators. Let us examine the changes to compounds from the Meiji Period on.

Table 3.1. Dunlop Automobile Tyre Compounds

Ribbed smoked (natural rubber)	72
Reclaimed (recycled rubber)	56
Zinc oxide (ZnO)	26
Calcium carbonate (heavy)	26
Flower of sulphur	21
Rubber powder	15
Litharge (PbO)	5
Mineral rubber (pitch, asphalt)	8
Pale machine oil	15
Quicklime	5
Pine resin	5
Vulcanizing time	40min

Ribbed smoked (natural rubber)	79
Reclaimed (recycled rubber)	42
Calcium carbonate (heavy)	47
Carbon black	5
Deacidified sulphur	11
Litharge (PbO)	11
Mineral rubber (pitch, asphalt)	8
Caustic magnesia	3
Pale machine oil	16
Vulcanizing time	60min

(Dunlop compound specialist compound presumed to be from the Taisho Period. Unclear whether or not it is Dunlop; Yamada comment. Compound features multiple inorganic vulcanisation accelerators; author note)

3.4. Compounding Agents from the End of the Meiji Period to the Taisho Period

Matsutarō Hanaki states the following [9) 23)].

"At that time, Meiji Rubber and Toyo Rubber had mostly the same rubber compounding agents, with the most important being sulphur or slaked lime as an accelerant. Other agents used included zinc oxide (ZnO), sedimentary calcium carbonate, magnesium carbonate, with browning achieved by a mix of burnt-pine ink or lamp soot for black and red iron oxide for red, and golden antimony sulphide."

Several compounding agents are described below.

(i) Zinc Oxide (ZnO)

Zinc oxide was the most commonly used reinforcing agent in the Meiji Period. It was replaced by calcium carbonate and carbon in the late Taisho to early Showa Period. As organic accelerators grew in popularity from the end of the Taisho Period, more modern accelerators began to be more widely used [4)].

(ii) Basic Magnesium Carbonate

Various chemical formulations of compounding agents, such as $3MgCO_3{\cdot}Mg(OH)_2{\cdot}3H_2O$, $4MgCO_3{\cdot}Mg(OH)_2{\cdot}5H_2O$, and $5MgCO_3{\cdot}2Mg(OH)_2{\cdot}5H_2O$, were called magnesium carbonate or light magnesium carbonate [1) 4) 8) 24)]. These were first used in rubber in 1918 and were used in most rubber products by the end of the late Taisho to early Showa Period [4)].

(iii) Calcium Carbonate

Initially, heavy calcium carbonate was often used, under names such as whitening, calcium carbonate or coal stone. While light calcium carbonate was first mass produced in 1919 by Shiraishi Kogyo, its value was not appreciated for quite some time afterwards. However, this was gradually recognised through research at the National Osaka Laboratory(*Kokuritsu Ōsaka Shikenzyo*) ; by the early Showa Period, it had become a major rubber chemical alongside zinc oxide and magnesium carbonate [4) 20)].

Fatty-acid-soap surface-treated calcium carbonate was also developed in the early Showa Period. While this, too, was underappreciated to begin with, it made a significant contribution to the field of rubber compounding once research at the University of Akron demonstrated its superiority as a reinforcing filler for rubber [20)].

(iv) Carbon Black

Imported since 1901, it was first used as a colourant. It grew in popularity as a reinforcing agent for tyres from the end of the Taisho Period and was being produced domestically in 1931 [4)].

(v) Accelerators

Initially, "the three most important accelerators in compounds were slaked lime, litharge and magnesia; it took experience to use these properly" (discussion with Tetsunosuke Mori, formerly of Kakuichi Rubber) [4)]. This was the reason that rubber compounding was thought to be difficult and kept secret [25)]. "Following a visit by a British compounding specialist to Meiji Rubber, other compounds were known about, but only quicklime was used" (discussion with Hanaki) [23]. Inorganic chemicals such as sodium silicate were also used as kinds of accelerators, but were not called accelerators [4) 23)].

The spread of organic accelerators in Japan can be pinpointed to this time period, with some factories starting to use them from this time on.

3.5. The Rubber Industry in the Late Taisho Period

The use of magnesium carbonate made it possible to produce clear rubber, as well as improvements in the physical properties of the rubber. By the late Taisho Period, there had been significant development in the production of rubber boots from these rubber compounds; these were even being exported overseas [4) 5)].

From the manufacturing perspective, there was a division of labour between vulcanisation and production, with mixing factories carrying out compounding and simple vulcanisation, while production factories carried out production [4) 5)].

The preface to *Gomu Haigō-hō [Rubber Compounding Methods]*, published in 1922, provides an insight into the state of the rubber industry at the time. "Manufacturing methods, particularly compounding methods, are kept completely secret; there are many people who have worked in production for many years and do not even know the components of their products." This suggests the presence of compounding specialists.

For comparative reference between two typical compounds of the time, the sample compound cited in the literature (*Gomu Haigō-hō: Fukuoka, Harutarō 1922 [Rubber Compounding Methods: Harutaro Fukuoka 1922]*) in *Gomu Haigō-hō [Rubber Compounding Methods]* [26], published in 1922, and a 'Mitatsuchi-style' compound are shown in Tables 3.2 and 3.3.

Table 3.2. Sample Automobile Tyre Compounds [26) 14)]

	Fukuoka	Mitatsuchi
Ribbed smoked (natural rubber)	100	100
Magnesium carbonate	21	23
Brown factice (softening agent, processing agent)	9	9
Carbon black	4	5
Deacidified sulphur	4	4
Paraffin	3	3
Caustic magnesia	4	3
Vulcanizing time	50 min	50 min

Table 3.3. Sample Automobile Tyre Compounds [26) 14)]

	Fukuoka	Mitatsuchi
Ribbed smoked (natural rubber)	100	100
Zinc oxide (ZnO)	29	29
Magnesium carbonate	18	18
Deacidified sulphur	5	5
Litharge (PbO)	7	7
Carbon black	4	4
Mineral rubber	5	5
Vulcanizing time	60 min	120 min

Fukuoka: *Gomu Haigō-hō [Rubber Compounding Methods]*,

	Fukuoka, Harutaro (1922)
Mitatsuchi:	*Gomu Haigō Kokinshū [Collection of Rubber Compounds Old and New]* [14], Moriyama, Tokichirō (1940)

(Compounds presumed to be from the early to mid-Taisho Period; Yamada comment)

The two tables show that the compound recorded in *Gomu Haigō-hō [Rubber Compounding Methods]* published in 1922 is almost identical to the 'Mitatsuchi-style' compound cited in the literature [14] (both sources show the compounding amounts in terms of weight used, given in the tables as parts per hundred rubber). Since early rubber compounds were more complex, these sample compounds were probably a simplified version used for a public lecture. Literature published in 1943 states that "complex formulations were effective for keeping compounds a secret, but nothing more," while another source conjectured that compounding specialists added in unnecessary raw materials to make it needlessly complicated so that the compounds could not be easily learned [27]. The parts per hundred rubber (phr) representation indicates the weight of other compounding agents in proportion to 100 parts (weight) of natural rubber.

It seems that progress had been made on the research/education front by the late Taisho Period, with *Gomu Seizō Kagaku [The Chemistry of Rubber Manufacturing]* [28] published in 1924 and *Gomu no Kenkyū [Studies in Rubber]* [29] published in 1926. *Gomu Seizō Kagaku [The Chemistry of Rubber Manufacturing]* was a publication by Waseda University; *Gomu no Kenkyū [Studies in Rubber]* was a book based on lectures at Tohoku Imperial University. A sample compound from *Gomu Seizō Kagaku [The Chemistry of Rubber Manufacturing]* is shown in Table 3.4.

Table 3.4. Sample Automobile Tyre Compounds [28]

Pará (wild rubber)	40
Caucho (wild rubber)	27
Upper Congo	27
Reclaimed	13
Zinc oxide (ZnO)	17
Lime	1
Sulphur	9

(Compounds presumed to be from the late Meiji to early Taisho Periods; Yamada comment)

Upper Congo; unclear but probably wild rubber [8]

Gomu Seizō Kagaku [The Chemistry of Rubber Manufacturing] has a detailed record on vulcanisation accelerators; Table 3.5 shows the changes in sample compounds [28].

Table 3.5. Changes in Tyre Tread Compounds [1) 4) 8)]

1912 (Meiji~Taisho)	Reinforcing agent : zinc flower Colourant : lamp black Accelerators : slaked lime, magnesia, aniline
1918	Carbon black and accelerators appear
1933	Carbon black and accelerators become popular Vulcanisation time reduces due to accelerator combination Effectiveness of anti-ageing agents becomes clear

Generally speaking, the amount of rubber increased while the amount of sulphur decreased.

Automobile tyre compounds had reached the highest level of technology available at the time.

3.5.1. Popularisation of Vulcanisation Accelerators

(1) Inorganic Accelerators

While metal oxides such as slaked lime and magnesia had been used as vulcanisation accelerators in the Meiji Period, the new inorganic accelerator developed by Matsutarō Hanaki in the early Taisho Period was a fired basic lead carbonate and was promoted in 1918-19. It is said to have been developed following repeated research and analysis on compounds imported from the United States. Since Goodyear used basic lead carbonate as an accelerator, this is said to be related technology [30].

This had the effect of reducing the vulcanising time from 1-3 hours to 15 minutes.

(2) Organic Accelerators

Compound-focused rubber technology progressed with compounding specialists at the core.

The central technology was vulcanization speed; the vulcanization accelerators of the day were inorganic vulcanization accelerators. Vulcanization time could be adjusted through proficient use of vulcanization accelerators; accordingly, these accelerators were the most important technology the compounding specialists had. The discovery of organic vulcanization accelerators reduced the vulcanization time even further and it was theorised that the vulcanization phenomenon was an organic reaction. Thus, there was a transition from a secret technology formulated by compounding specialists using complex inorganic accelerators to a theoretical technology; the world of rubber compounds gradually transitioned from the domain of compound specialists to the domain of organic chemistry, making the compound specialists obsolete.

Compounds from this time on became fundamentally simplified, closer to the compounds of today.

3.5.2. Popularisation of Organic Accelerators

While the timing of the popularisation of organic accelerators in Japan cannot be precisely defined due to differing accounts between factories, it was after 1920, at the end of the Taisho Period or start of the Showa Period [1) 4) 14) 23) 31)]. It is very likely to have been from around 1920, as George Oenschlager (who discovered organic accelerators) is said to have visited Yokohama Rubber in 1919 and passed on some cutting-edge compounding techniques [4) 23)].

New compounds based on organic accelerators were adopted by industrial laboratory employees and researchers as “compounds that apply scientific principles”, but were generally not used in practice [14)]. This is because the Japanese rubber industry at the time was largely dominated by the Mitatsuchi and Dunlop schools and researchers could not become active enough under that influence. Many engineers in the Mitatsuchi and Dunlop schools in the late Taisho Period did not know about changes in formulation, believing the idea that rubber would become brittle if accelerators were used [4) 14)].

Many would say that the expensive organic accelerators are useless, and that lime was enough [23)]. Many rubber companies at the time had no testing equipment and no confidence in using new compounding agents. However, once Japan Rubber, which had good testing facilities, placed a substantial order, it immediately began to be used [4)].

Meanwhile, Mitatsuchi – arguably the mother of the compounding specialists, Meiji Rubber, Furukawa, Fujikura and other companies started importing or producing their own accelerators from the end of the Taisho Period [14)]. By some accounts, some had been using these since the end of the Meiji Period or start of the Taisho Period; several other companies were secretly using organic accelerators [4) 8) 14) 23)].

The Great Kanto Earthquake of 1923 had a huge impact. Since all-purpose inorganic accelerator compounds had a long vulcanization time, a large number of metal moulds had to be set up for mass production. Despite organic accelerators having a shorter vulcanisation time, they would mean that the substantial investment that went into these metal moulds would have gone to waste. This factor, combined with apprehension about the effectiveness of the new accelerators, resulted in many factories putting off introducing the new accelerators. However, due to the earthquake, the metal moulds had to be rebuilt; this resulted in a growing trend towards using organic accelerators [22) 23)].

Despite some twists and turns along the way, organic accelerators grew in popularity, resulting in a dramatic reduction in vulcanization time and improved product quality [4)].

3.5.3. Disclosure of Compounds

In the early Showa Period, information on compounds was beginning to be made available to the public. When Heisen Yoko established its affiliated rubber laboratory in 1928, it was completely open to the industry [4) 22) 23) 32)]. The monthly magazine *Gomu [Rubber]* was published and distributed to factories from 1933 onwards, explaining how to use chemicals and providing data on accelerators [4) 5) 32)]. Dunlop also began inviting British engineers to provide open lectures on basic compounds in the early Showa Period [4)]. Prior to this, the Ministry of Communications and Transportation had published the results of tests on accelerators in 1924 [4].

3.5.4. The Fate of the Compounding Specialists

Thus, as organic accelerators grew in popularity, the rubber industry underwent an epoch-making transition from an alchemical stage with secret mixtures made compounding specialists to a modern industry based on science and technology.

There was also an increase in so-called educated engineers.

Consequently, the revolution in compounding due to organic accelerators and the emergence of orthodox-educated engineers spelled the end for the compounding specialists.

3.5.5. Comparison of the Mechanisms of Inorganic and Organic Vulcanisation Accelerators

(1) Inorganic Vulcanization Accelerators

As mentioned previously, during the age of inorganic vulcanization accelerators, metal oxides such as litharge (lead oxide; PbO) or zinc oxide (ZnO) were used in addition to various other kinds of compounding agents. The use of metal oxides also required the use of organic acids, such as oleic acid or stearic acid. The reaction formula below (Fig. 3.1) shows the cross-linking reaction mechanism between organic acid and PbO. The Pb forms a metallic soap, which makes a polysulphide, releasing active sulphur and accelerates vulcanization [34].

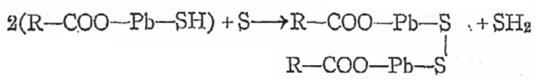


Fig. 3.1. Vulcanisation Mechanism by means of an Inorganic Vulcanization Accelerator

(2) Organic Vulcanization Accelerators

Let us now describe the mechanism of action of organic vulcanization accelerator MBT (2-Mercaptobenzothiazole), still in use today. Vulcanization accelerators act as a catalyst for a sulphur cross-linking reaction. At this point, the reaction between the vulcanization accelerator and zinc oxide is essential. Both are necessary; without either of them, vulcanization would not work. The reaction formula is given in Fig. 3.2.

Sulphur chains are trapped between MBT (reactions 1-2). The sulphur breaks down within the sulphur chains and reacts with the rubber molecules (reactions 3-4). A reaction takes places between the sulphur and the molecules and cross-linking is established (reaction 5) [27].

3.6. The Rubber Industry in the First Half of the Showa Period

Let us now outline the state of the rubber industry in the early Showa Period.

3.6.1. The Rubber Industry in the Early Showa Period

(1) Use of Organic Accelerators

While organic accelerators gained popularity considerably at the end of the Taisho and start of the Showa Period, it appears that they were not readily mastered. Even a source published in 1940 [14] notes that accelerators were used in token small amounts and not very effectively. Furthermore, small amounts of accelerators made the rubber harder to scorch (burn; prevulcanization) and easier to extrude; some compounds were researched out to that end [14].

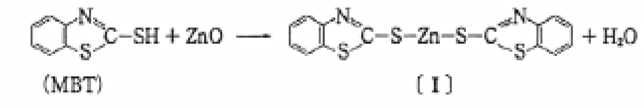
Research divisions of major factories used an academic approach to come up with compounds. Ninety per cent of smaller factories used the old methods of secretly stealing, memorising or otherwise learning compounds [33].

(2) The “Academic” Movement

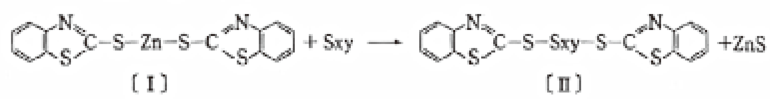
However, the academic initiatives appeared to be reliable and The Society of Rubber Science and Technology, Japan was established in 1928. *Gomu Seizō-Hō [Rubber Manufacturing Methods]* recorded basic sample compounds, such as those given in Table 3.6, that are still used today.

While research on compounds progressed, the aforementioned *Gomu Seizō-Hō [Rubber Manufacturing Methods]* [25] also recorded sample compounds for automobile tyres, such as those given in Table 3.7, that are still used today.

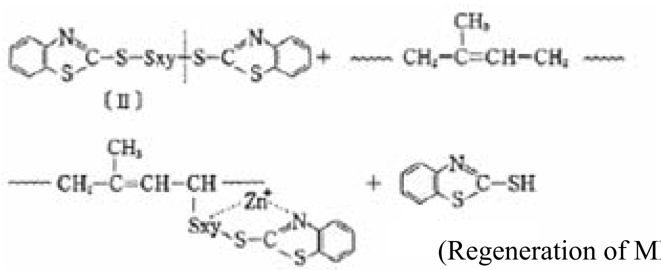
1) Generation of ZnMBT [I] by reaction between vulcanisation accelerator MBT and zinc oxide (ZnO)



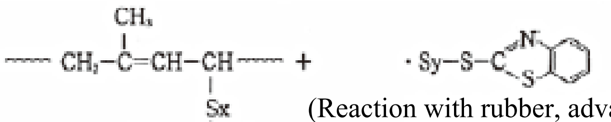
2) Reaction between ZnMBT and Sulphur (Sxy)



3) Reaction with rubber



4) Sx-Sy separation through coordination of Zn^+ ions



5) Generation of cross-links and cross-linking precursors

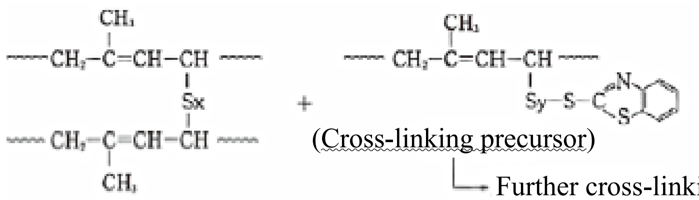


Fig. 3.2. Mechanism of Action of Vulcanisation Accelerator MBT [27)]

Table 3.6. Basic Compound from *Gomu Seizō-Hō [Rubber Manufacturing Methods]*

Raw Rubber	100
Sulphur	0.5-3.5
Accelerator	0.5-1.5
Zinc oxide (ZnO)	1.0-10
Stearic acid	0.5-2
Anti-ageing agent	0.25-1.5
Other, reinforcing agent (carbon black, magnesium carbonate, clay)	
Filler, softener, colourant	

Table 3.7. Automobile Tyre Compound

Smoked sheet (natural rubber)	100
Mineral rubber	5
Carbon black	40
Zinc oxide (ZnO)	5
Stearic acid	1
Binder	1
Anti-ageing agent	1
DM (organic vulcanisation accelerator)	0.8
Sulphur	3

(Probably an early Showa Period compound; Yamada comment)

Here, an accelerator is used in an actual compound for automobile tyres. The compound in the table is almost identical to the compound in *Gomu Haigō-Hō [Rubber Compounding Methods]*, published in 1958 [24)]. It can thus be assumed that wartime compounding techniques had reached a reasonable level. DM (Benzothiazile disulphide) is a thiazile organic vulcanisation accelerator like the aforementioned MBT.

(Refer to) modern compound samples (natural rubber tyres)

Natural rubber 100, zinc oxide (ZnO) 5, stearic acid 1-2, carbon black 50-60, anti-ageing agent 1, oil 1-5, sulphur 1-2, vulcanisation accelerator (NS or CZ) 1-2.

NS: N-Oxydiethylene-2-benzothiazole sulfenamide

CZ: N-cyclohexyle-2-benzothiazole sulfenamide

3.7 Summary

Looking at these details, we can say that the invention of organic vulcanisation accelerators that allowed control over vulcanisation was a major breakthrough and revolution in the development of the rubber industry. The main points are as follows.

1. Improved productivity due to reduced vulcanisation time
2. Less deterioration of the rubber due to shorter exposure time during vulcanisation
3. Rubber shifted from an experience-based technology to a chemical-theory-based technology
4. Theorisation meant redundancy of compounding specialists, who had previously made their living from secret compounds

The above compound is thought to be

from the early Showa Period, indicating that compounding specialists had disappeared by the end of the Taisho Period.

Nevertheless, organic vulcanisation accelerators were an American invention; the major change in rubber technology following the introduction of this technology can be said to exemplify how the Japanese introduce technology, learn it and then improve it to make it their own.

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4. Stage of Growth: Creation of the Domestic Tyre Industry

The Age of Imported Technology from Overseas and Domestically Produced Technology (Taisho-Showa Periods to the End of the War)

Japanese tyre companies (Dunlop, Yokohama Rubber, Bridgestone, Toyo Rubber) were founded during this period. Following the acquisition of compounding techniques, this period saw the successive creation of domestic tyre companies.

The first half of this period was a time of domestic production of overseas manufacturers' technology or domestic production using domestic technology. The latter half was a time of wartime regime, the end of overseas technology imports and the development of independent technology. Ultimately, this period was a time devoted to building up technological strength to improve durability (long life), a fundamental performance for tyres.

4.1. The First Half (Time of Imports; 1912-c.1930): The Beginning of Japan's Tyre Industry

4.1.1. The Beginnings of Dunlop (Far East) Technology

As mentioned previously, Dunlop (Far East), the Japanese branch of Dunlop UK, had a lot do with the start of tyre technology in Japan [1].

In 1909, 20 years after the Dunlop tyre company was launched in Dublin, Dunlop UK planned to expand into the Far East, first establishing a company in Hong Kong, then six months later, with the outlook for the Japanese market looking sufficiently promising, establishing a Japanese branch and building the Dunlop Rubber Co. (Far East) factory [3].

The factory in Wakinohama was around one-third of the size of the grounds of the headquarters (now Sumitomo Rubber) and factory before the Great Hanshin-Awaji Earthquake, with a two-storied brick building occupying a site of around 16,000m^2 (5,000 *tsubo*). A copy of the registration of establishment of Dunlop (Far East) (Fig. 4.1; dated 4 October 1909) is shown in the company history *Sumitomo Gomu Hachijūnen-shi [The Eighty-Year History of Sumitomo Rubber]* [2].

The arrival of Dunlop with its full-scale facilities and superior technology was a major stimulus and influence on the Japanese rubber industry at the time, with its technology still hovering in a state of infancy. This built up momentum for the rise of the rubber industry, triggered by the First World War. Inspired by Dunlop, other rubber manufacturing companies were established one after another from the end of the Meiji Period to the start of the Taisho Period, mainly in Kobe, like satellites gravitating around Dunlop [3].

Thus, this period saw Dunlop (Far East) take the lead in rubber technology and rubber business, starting the first automobile tyre production in 1913. The first domestically-produced automobile tyre is still preserved at Sumitomo Rubber [1]. See Fig. 4.2.

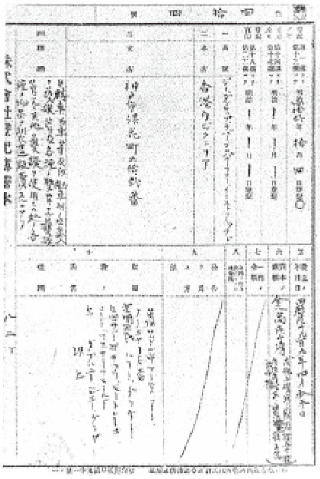


Fig. 4.1. A Copy of the Registration of Establishment of Dunlop (Far East) [2]
1909

Fig. 4.2. The First Automobile Tyre Produced in Japan, 1913, Dunlop (Far East) [5]
Sumitomo Gomu Hyakunen-shi [The Hundred-Year History of Sumitomo Rubber] [4], p. 44

Around this time, tyres were very obviously hand-made in nature. These "fabric tyres" or "canvas tyres" were produced by overlapping cotton fabric. This method continued until around 1921 [4].

The demand for tyres grew substantially at this time, accompanied by a growing demand for durability. A major reform in technology took place in relation to this – a transition from canvas tyres (fabric tyres) to cord tyres.

4.1.2. Yokohama Rubber (now the Yokohama Rubber Company) Pre-War Technology

While Japanese automobile tyres were all still fabric tyres, the United States was shifting into an age of cord tyres. This technology first appeared as the result of an invention in 1908 by American J. F. Palmer. The "cord tyre" made of blind fabric was developed by Silvertown Cable of the United Kingdom and perfected into a commercial product by US company Goodrich.

Early pneumatic tyres had a frame of rubber-coated canvas (fabric), but the threads would often chafe and break while running due to the flexure of the tyre, since the canvas had a warp and weft like any other fabric.

Cord tyres (blind-fabric tyres) did not have the horizontal and vertical threads interwoven but laid in parallel, forming a kind of mesh superimposed in the direction in which the two layers of adjoining threads crossed. These tyres were successfully commercialised by Goodrich in 1910, immediately after Palmer's invention.

Yokohama Rubber Company started out making fabric tyres but began production of cord tyres in 1921. This was the beginning of cord tyre production in Japan. The invention of cord tyres made tyres three times more durable than fabric tyres [6] (see Fig. 4.3).

4.1.3. The Establishment of Bridgestone (now Bridgestone Corporation)

(1) The details leading up to the establishment

of the company are based on *Buridjisuton Shijūgonen-shi [The 75-Year History of Bridgestone]*.

The distinguishing characteristic of Bridgestone's pre-war tyre technology was that it was domestically produced and independently developed and manufactured. Until that point, other companies were either Japan-based manufacturing branches of overseas companies or were importing technology developed by overseas partners.

In 1928, when Bridgestone's founder Shōjirō Ishibashi was setting up mass production and mass production systems for Japanese work shoes and rubber boots, the main player in the rubber industry in the West was automobile tyres, consuming around 60% of the available natural rubber. Thinking that Japan's future would be similar, Ishibashi took the lead and decided to produce automobile tyres domestically [7)].

Given that this decision to take on the challenge of producing automobile tyres using local production technology came at a time when automobile parts such as tyres and even automobiles themselves were highly revered imports and there was no question of domestic production, Ishibashi potentially stood no chance for success in domestic tyre production.

Since Ford Japan and General Motors Japan would only use tyres that had passed strict quality testing at their overseas headquarters, the technologically-inferior Japanese-made tyres had no chance of being fitted on new automobiles, while the reverence for imported goods seemingly presented too much of a barrier to their commercial use (replacements/repairs) [7)].

In April 1929, in absolute secrecy, Bridgestone placed an order with the Akron Standard Mold Company in Ohio, USA, via Healing & Co. in Osaka, for a complete set of equipment needed to produce 300 tyres in one day [7)].

"It contained two banner machines (tyre moulding equipment), five watch case heaters (vertical vulcanisers), two moulds (one for each tyre size: 29x4.50 and 30x4.50) and other equipment, as well as materials such as blind fabric cord, breakers and bead wire" [7)].

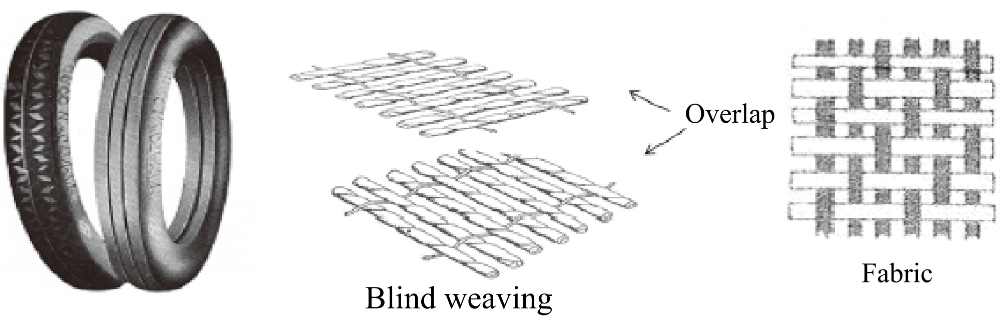
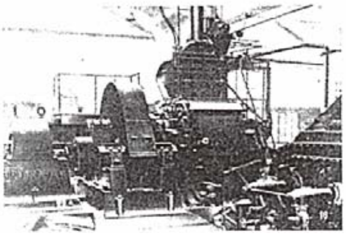
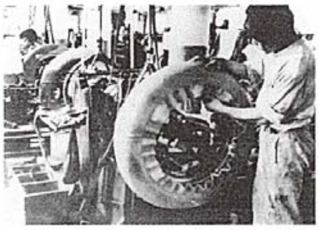


Fig. 4.3 Cord Tyre "made by Hamatown Cord in 1921" [6)], Blind Weaving (for Cord Tyres) and Ordinary Fabric

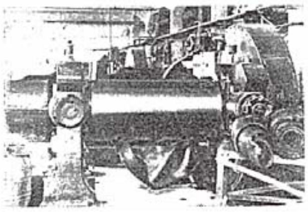
Page 32 of *Buridjisuton Shijūgonen-shi [The 75-Year History of Bridgestone]* shows photographs of the factory facilities (see Fig. 4.4 below); fundamentally, these are little different from modern-day facilities, which means that they must have been state-of-the-art at the time (there is also a photograph of a Banbury mixer, still commonly used today).



Contemporary Banbury mixer



Tyre prototype at the temporary factory



Contemporary 22-inch roll

Interior of a tyre factory from this period. Many women in aprons were employed in manufacturing.

Fig. 4.4. Contemporary Factory Facilities [7)]

Starting out with domestically-produced technology, having a foundation laid on independent research and using cutting-edge facilities for the time probably led to success later on.

It was a hard struggle leading up to the production of the first tyre. The work did not go smoothly. One very difficult challenge was manufacturing the ply cord that formed the skeleton reinforcing layer of the tyre. Vulcanisation was also done completely by hand [7)].

Amidst these hardships one on top of another, a successful tyre prototype was finally produced at 4 PM, 9 April 1930. This was the birth of the first “Bridgestone tyre” (29 x 4.50 in size, 4-ply). It was a tyre for a small passenger vehicle. The second tyre was completed on 11 May [7)].

Fig. 4.5 shows the commemorative tyres; Fig. 4.6 shows a replica. Domestic production technology had manufactured its first tyre.

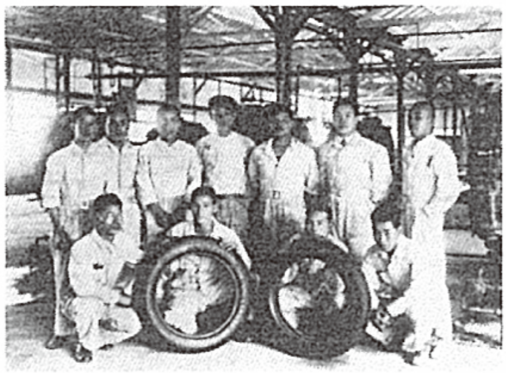


Fig. 4.5. Commemorative No. 1 Tyre [7)]

Fig. 4.6. Replica of the No. 1 Tyre (BS Museum Collection) [8)]

The initial idea was crucial to starting business with domestic production technology. The founder had a huge impact on this.

(2) Embodiment of Ishibashi-ism (*Risō to Dokusō [Ideals and Creation]* by Shōjirō Ishibashi)

According to Shōjirō Ishibashi, while mass production of Japanese work shoes and rubber boots was already under way around 1928, what he wanted to make in the future was automobile tyres [9)], as he felt that tyres were of utmost importance.

His perception proved to be very sharp indeed, right from the start [9)]. Despite Japan having only a few automobiles at the time, a time would come when automobiles would be domestically produced; having five to ten million cars on the road would mean a consumption of ten to twenty million tyres. Accordingly, making purely Japanese tyres and selling them at affordable prices would be essential to the development of the automotive industry.

While still continuing to mass produce Japanese work shoes and rubber boots, Ishibashi quietly studied rubber, the main raw material. He considered all the special properties of rubber and meditated on the future of rubber itself [10)].

According to *Risō to Dokusō [Ideals and Creation]*, Shōjirō Ishibashi had breadth of vision and a sense of duty; when going about his work, he had insight into technological development and took the point of view of a company existing within society.

As discussed above, the three main Japanese companies made different contributions to early tyre production; tyres were birthed out of the early struggle. As war became imminent, it became harder to import overseas technology; in the end it seems that there were no significant differences between the three main companies in terms of their technology.

4.1.4. Contributions Towards the First Domestically-Produced Tyre

The three main Japanese companies made the following contributions towards the first domestically-produced tyre.

Dunlop (Far East) (now Sumitomo Rubber Industries, Ltd.)

> The Japanese factory (in Kobe) of Dunlop UK manufactured the first domestically-produced tyre in 1913. Dunlop Rubber (Far East) was established in 1909.

Yokohama Rubber (now Yokohama Rubber Company)

Imported technology from Goodrich (partner). Manufactured the first domestically-produced cord tyre in 1921. Yokohama Rubber was established in 1917.

Bridgestone (now Bridgestone Corporation)

Japan's first tyre produced with domestic technology in 1930 by the Japan "Tabi" socks Tire Division, one year before the founding of Bridgestone. Bridgestone was established in 1931.

4.1.5. Toyo Rubber, Founded in Wartime

Establishment of Toyo Rubber

The following account is from *Tōyō Gomu Kōgyō Gojūnen-shi [The Fifty-Year History of Toyo Tire & Rubber]*.[11]

Toyo Tire & Rubber Company was established under two parent companies, Toyo Rubber Industrial and Hirano Rubber Manufacturing. Toyo Rubber Industrial was established in May 1938 by Toyo Boseki for automobile tyre production as Naigai Saisei Rubber Company (*Naigai Saisei Gomu Kabushikigaisya*), but changed its name in October that year. While both companies were built up under Toyo Boseki, they merged and were re-launched as Toyo Tire & Rubber Company on 1 August 1945, right before the end of the war.

From this description, it seems that Toyo Rubber was established in 1943. According to the chronological tables in *Taiya no Hanashi [The Story of the Tyre]* [12], "1943: Toyo Tire & Rubber was established".

4.1.6. Establishment of Other Tyre Companies [12]

According to the chronological tables in *Taiya no Hanashi [The Story of the Tyre]* (pp. 232-233), the other manufacturers given below entered the tyre business either during wartime or post-war.

1944: Dai-Nippon Aircraft Tyres(*Dai-Nippon Kōkūki Taiya*) (later Ohtsu Tyre & Rubber) established

1949: Nitto Tyres(*Nittō Taiya*) (later Ryoto Tyres(*Ryōtō Taiya*)) established

1964: Okamoto Riken enters the tyre business

4.2. The Second Half (Time of Domestic Production; Wartime Technology, 1930-1945)

From the outbreak of war to the end of the war (technology through wartime production expansion and control)

The times grew dark in the 1930s and the sounds of war could be heard approaching. Military colours flew high. As Japan entered a wartime regime, tyre companies set up systems for supplying military goods. There was a demand for improved tyre performance in harsh conditions in areas such as durability. With it eventually becoming increasingly difficult to import overseas technology, research began on domestic production technology and independent technology began to be developed. Especially after the Pacific War, everything was in military colours; tyre factories were designated as war factories. Despite initial emergency wartime procurements, there was a shortage of raw materials and production became difficult.

Let us examine how tyre companies handled such circumstances in the area of technology.

4.2.1. Dunlop Japan (now Sumitomo Rubber)

During this period, the munitions supply of Dunlop (Far East), supplied exclusively to the army and navy, was on the brink of crisis and certain steps had to be taken to continue supplies. In 1933, despite ongoing fierce competition in the tyre market, the decline in yen exchange meant very few automobile tyre imports; Japan entered an age of self-reliance for automobile tyres.

The entry of Dunlop (Far East) entry into automobile tyre [13] self-reliance around this time was as follows.

Politically, 1932 was a dark year and there was a sense of uneasiness about the future. There was a sudden rising clamour about rejecting foreign investment; the munitions supply of Dunlop (Far East), supplied exclusively to the army and navy, was on the brink of crisis and certain steps had to be taken to continue supplies.

Dunlop (Far East) sought to strengthen its ties with the navy as a means of breaking out of this deadlock.

It had begun construction on a new factory in 1929 to expand its production and sales structure. Three years after construction started, the facility was complete, with the existing buildings having been renovated.

"The new factory was a four-storey building; there was an 84-inch open mill in the basement where rubber compounding was performed for carbon compounding tread. The basement was segregated to prevent carbon from spreading.

The ground floor was the mill room, for measuring chemicals, peptising and mixing non-black rubber; it was equipped with 84- and 60- inch mills and other rubber kneading rolls, as well as various calenders.

The first floor was the automobile tyre factory, equipped with tread extruders and bead moulding machines, as well as tyre moulding machines and vulcanisers." [13]

This facility had basically the same layout as those of today, other than the compounding machines using rolls instead of the internal mixers used today; this indicates that this was a state-of-the-art facility at the time.

Dunlop (Far East) changed its name to Dunlop Rubber (Japan) in 1937; on 29 January 1943, it changed again to Central Rubber Industries. At this point, aircraft production was held as the key to victory; increasing efforts were devoted to this industry, along with the army and navy. The previous year (1942), aircraft production had increased to 8,800 machines; in 1943, it doubled to 17,000.

Central Rubber drove the development of aircraft tyres, succeeding at this with its own technology. These were supplied to the army, but requests were also fielded from the navy. The 1944 proceeds from aircraft tyre sales reached ¥5.7 million, making them the second-place flagship product second only to bulletproof tanks, even outselling truck and bus tyres [28].

The 35th anniversary of Dunlop's founding fell in 1944; under a total war regime, Central Rubber became concealed war plant "Factory Jinmu 7176" by order of the *Munitions Companies Act* [23].

It had achieved the supply of munitions under an all-out regime despite a shortage of raw materials.

4.2.2. Yokohama Rubber (now Yokohama Rubber Company) [14]

The Manchurian Incident in September 1931 led to a rise in demand for military vehicles. The government and military authorities also concentrated their efforts on protecting and developing the domestic automobile industry. Increased automobile production meant a sudden rise in demand for tyres. From March 1934, Yokohama Rubber set about expanding its primary tyre factory.

The most important technical issue was durability. Tyres had to be developed to meet the increased demand in order to survive the fierce competition. Yokohama Rubber's technical team devoted itself to increasing tyre durability. In April 1937, Yokohama changed its trademark on all its tyres and other products from "Goodrich" to "Y" for Yokohama and announced its "New Y Tyre" with a Y on the tread. This tyre was characterised by a continuous Y shaped pattern; with its unique, newly-developed tyre cord (patent granted in 1939), it was more than twice as durable as existing products and gained a very good reputation.

Perhaps due to wartime demand, other companies also made significant improvements to durability.

4.2.3. Technology Examples

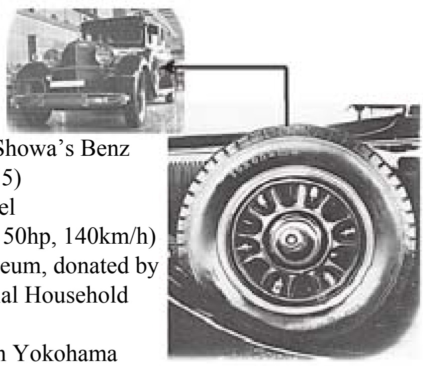
(1) Providing Tyres for Emperor Showa's Benz (Grosser Mercedes)and Domestically-Produced Cars

The Grosser Mercedes was an ultra-luxury passenger car made for world leaders and multi-millionaires. With an engine capacity of 7700cc, 150hp output and top speed of 140km/h, it had an enormous engine and was surprisingly high performance for its time. In 1937, Yokohama Rubber was commissioned by the Imperial Household Department at the time to produce tyres to be fitted to the vehicle; these were completed after one and half a year of development. These tyres were specially designed with cloth-inserted sealant pasted inside the tube so that air would not escape even if punctured. Their size was 7.50-20 [15].

The durability of the tyres fitted to this high performance vehicle would have been comparable to those of today. This means that domestic production technology must have already reached a considerable level at this time. This is one example of the level attained by Japanese engineers having to take creative steps to achieve things on their own, with it becoming increasingly difficult to import overseas technology (see Fig. 4.7) [15].

At this time, significant progress was also made on passenger vehicle technology and domestically-produced passenger vehicles were also being developed. Fig. 4.8 shows the first passenger vehicle produced by Toyota (Toyota Model AA; replica). The tyres were made by Bridgestone.

In light of the circumstances, it must be said that Japanese engineers had already mastered the imported overseas technology and attained a high level of domestic production technology, especially in terms of durability. This was the age of application.



Emperor Showa's Benz
(1935-1955)
1935 model
(7700cc, 150hp, 140km/h)
Benz Museum, donated by the Imperial Household Agency
Fitted with Yokohama tyres (made in 1938)

Fig. 4.7. His Imperial Majesty's Car (from *Yokohama Rubber News*) [15]

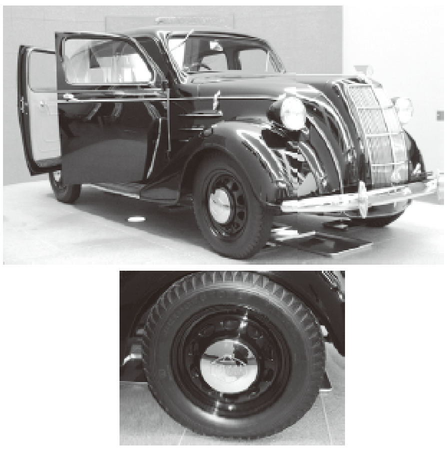


Fig. 4.8. Toyota Model AA, 1936; Toyota's First Passenger Vehicle (Replica) [16]

550-17 Tyres (Bridgestone)

Toyota Automobile Museum Collection

(2) Aircraft Tyres

Demand for military rubber products steadily increased at Yokohama Rubber since the outbreak of the Second World War against Japan in 1941. Since aircraft tyres in particular had a significant impact on the course of the war, there was a rush to expand that division [17].

Accordingly, in 1943, the Yokohama factory fell completely under the supervision and control of the army and navy [18].

In these circumstances, tyres were also produced for the Zero fighters.

A Zero fighter discovered in Guam in 1963 is said to have been fitted with Yokohama tyres. Having gone through 20 years of typhoons, the aircraft was damaged beyond recognition, but the tyres were still in a useable state [17]. This indicates the high durability capable through independently-developed Japanese technology (see Fig. 4.9).

Fig. 4.9. Zero Fighter Tyre [17]

Held by Yokohama Rubber Company Hiratsuka Factory

(made in May 2006)

4.2.4. Bridgestone [19)]

(1) Wartime Regime

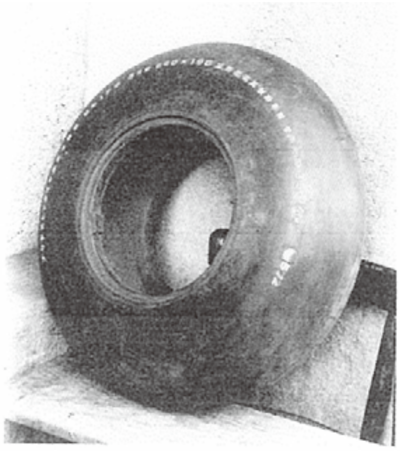
A directive from the Minister of Commerce and Industry in January 1939 prohibited the manufacture of passenger vehicles other than for military use; the production of small trucks was also mostly prohibited. Accordingly, production of automobile tyres was also limited to ordinary trucks, most of which were military vehicles [19)].

Meanwhile, full-scale production and supply of aircraft tyres started in 1939. As the war intensified, production rapidly increased. The annual production number of around 3,000 in 1939 is estimated to have grown around 60 times to 176,000 in 1944.

Bridgestone also progressed into wheel manufacturing as part of its wartime aircraft-related operations. This corresponds with an order from the army in 1942 to supply combined wheels and tyres for aircraft.

(2) Tyres for the “Falcon” Fighter

While tyres for the Hayabusa “Falcon” fighter are mentioned in the company history (Fig. 4.10), an actual tyre for the Falcon is held in the Bridgestone Museum (see Fig. 4.11). It is in good shape with hardly any deterioration [8)].



Tyre for the “Falcon” fighter ‘560 x 190’
(manufactured in March 1942)
Fig. 4.10. Tyre for the “Falcon” Fighter [20)]
Buridjisuton 75-nen-shi [The 75-Year History of Bridgestone]

Fig. 4.11. Tyre for the “Falcon” Fighter [8)]
Size: 570-190; made in February 1944 by Nippon Tire Company
Bridgestone Museum Collection

While wartime technology was munitions-focused, it had come a long way on its own efforts. On 20 February 1942, the company changed its name to Nippon Tire Company at a request from military authorities to amend the English name. The Bridgestone

Tire company name disappeared for ten years, until 25 February 1951.

(3) Level of Aircraft Tyre Technology at the Time

Taiya no Hanashi [The Story of the Tyre], by Rokurō Hattori, records the following regarding wartime development of aircraft tyres.

“Looking back, the time before and during the war was a time of suffering for Japanese aircraft tyres; many aircraft designers thought only of flying faster and further – tyres and other things that weren’t used in the air were nothing more than a necessary evil. Tyre manufacturers were requested to produce a tyre that could support such and such a weight within certain dimensions. … Such poor design and underdeveloped manufacturing technology resulted in frequent serious accidents from tyres bursting.

However, while it had seemed like every effort had been in vain, light began to dawn on improvements in tyre durability. Various elements in tyre design somehow made it possible to estimate tyre durability.” [21)]

This account has some credibility, as these are the words of someone at the site of development (Hattori was a former Bridgestone engineer, employed in naval aircraft design during the war).

By the end of the war, a reasonable level of durability had presumably been attained.

4.2.5. Toyo Tire & Rubber [22)]

According to *Tōyō Gomu Kōgyō 50-nen-shi [The 50-Year History of Toyo Tire & Rubber]* the following circumstances occurred.

“At the time [around 1941; author note], tyre production at Toyo Rubber Industrial [predecessor organisation; author note] was still in its infancy. As the war intensified, ensuring tyres for the military became top priority and the company had to respond.

Related to this, trucks manufactured by Kawasaki Rolling Stock Manufacturing Company (now Kawasaki Heavy Industries) were fitted with tyres by Toyo Rubber Industrial and other companies and given a five-day road test. The route went out of Kobe from Okayama to Tottori; while it was a rigorous test for the time, the results demonstrated that Toyo tyres were more durable than those of other companies. With these outstanding results, Toyo Rubber Industrial products were highly rated by Kawasaki Rolling Stock Manufacturing Company; Toyo then received its first order for military truck tyres and tubes.”

This account indicates that highly durable tyres had been developed by Toyo Tire & Rubber as well.

From the above, it can be considered that there was a rising level of interest in tyre durability as a basic performance factor from around this time.

4.3. Industry Response to the Wartime Regime

At this time, there was a form of technical cooperation in the industry.

According to Bridgestone, in January 1938, Dunlop Rubber Company (Japan), Yokohama Rubber and Nippon Tire (Bridgestone; author note) anticipated the expected regulation of rubber distribution in that coming July and established the Japan Automobile Tyre Industry Association(*Nihon Jidōsha Taiya Kōgyō Kumiai*), gaining government approval in April. The Association carried out business in cooperation with the Japan Tyre Association(*Nihon Taiya Kyōkai*), but when that Association dissolved in March 1939, the Japan Automobile Tyre Industry Association inherited all of its operations. [20)]

The Japan Automobile Tyre Industry Association dissolved after ceding its operations to the Rubber Control Association(*Gomu Tōsēkai*) launched in January 1943.

4.3.1. Wartime Technology

By the end of the war, the aforementioned Control Association was engaging in operations (1944).

According to *Nihon Gomu Kōgyō-shi [The History of the Japanese Rubber Industry]*, the following circumstances were in place.

The aim of the Rubber Control Association was to “provide comprehensive regulation and administration of operations related to marketing as well as production and sales of rubber products (hereinafter as Rubber Production) in order to provide an advanced state defence system and to collaborate in the drafting and execution of state policies related to Rubber Production” (Articles of Incorporation, Article 1). The Association was to carry out various operations in order to achieve this aim.

These operations can be divided into two broad categories: directly and indirectly taking part in government planning and cooperating with government policy execution. Above all, the basic mission of the Control Association was to cooperate with the execution of government policies.

(i) Taking part in government planning

(ii) Cooperating with regulation execution

There were seven aspects to cooperating with regulation execution: 1. production regulation; 2. regulation of supply of raw materials; 3. regulation of product distribution; 4. price regulation; 5. labour regulation; 6. technology regulation; 7. curtailment of business operations.

Of these, the most important task was to do with technology regulation: improving the technology of the rubber industry and improving and promoting efficiency in the industry in order to increase production during wartime.

The Rubber Control Association designated members, provided mediation and established technical committees in addition to its technology division for the purposes of researching and improving technology as well as exchange and disclosure. It had a product subcommittee to ensure technology regulation. In April 1944, nine articles of regulations on technology exchange and disclosure were drawn up; these stipulated specific agreements regarding technology exchange and disclosure, as well as an accompanying compensation system. Decisions were made to meet the demands for increased production [24].

Accounts such as the following state that effective technological advances were made in the field of rubber.

4.3.2. Specific Advances in Rubber Technology [25]

According to *Nihon Gomu Kōgyō-shi [The History of the Japanese Rubber Industry]*, as the Pacific War intensified, there was a shortage of raw materials accompanied by a decline in the quality of rubber products. With an increasing demand to ensure rubber products high in both quantity and quality, the technology division of the Rubber Control Association planned and implemented an open exchange for superior technology.

This rapidly lifted the overall level of technology in the rubber industry, making it very significant in the history of rubber technology. In other words, it would not be exaggerating to say that this rise in the level of technology provided the basis for the rapid restoration and development of the rubber industry in Japan after the war [25].

The following is based on research on various raw materials.

1. Raw materials

(1)Natural rubber; (2) latex; (3) reclaimed rubber

2. Secondary materials

(1)Domestic production of carbon black (reinforcing agent)

There were successive instances of domestic production of carbon black

(2) Fibres

Despite a temporary ease of access to resources in the south following the onset of the Pacific War, fibres were still in short supply.

In 1942, a directive was issued to produce reinforced rayon and Toyobo and other companies entered an era of finding practical applications for reinforced rayon. It was found that 20-30% rayon cord was suitable for use in automobile tyres. Yokohama Rubber, Nippon Tire and Central Rubber each joined forces with rayon companies to produce prototypes and performed running tests on these fitted to trucks and passenger vehicles, reporting very good results. In 1943, the technology division of the newly-established Rayon Control Association(*Jinken Tōsēkai*) proposed and established provisional standards for reinforced rayon for use in tyre cord. According to a report by Automobile Division 3 of the administration bureau of the Ministry of Railways, which had carried out practical testing for a year from August 1942 to July 1943, “of the 12 tyres, 6 exceeded the life expectancy of the existing Egyptian cotton cord tyres (24,141km in 1942), 2 by 90% or more, 3 by 80% or more and 1 by 68%.” This was a good result, acknowledging that the average number of kilometres of 25,228 was better than the ordinary product [27].

As indicated above, it was an age of regulations; technology advanced rapidly as companies worked together, sharing technology for the sake of development. There are many accounts regarding the outcome of this technology disclosure. Technology develops when a country has to get by on its own technology.

Taiya no Hanashi [The Story of the Tyre] [26] by Rokurō Hattori has the following account regarding cotton tyre cord technology.

"Since spun yarn transmits force by means of entwined short fibres, the longer raw cotton fibres are, the better quality they are. Raw cotton was graded by an expert who would take a pinch of it between the thumb and index finger of both hands and tear it several times, then lay the pieces out on black velvet to form a kind of fibre length spectrum to judge its quality.

Later on, to maintain strength, low stretch processing was carried out to prevent any excess stretching. This was a method of winding which provided a strong tensile strength in the winding process; adding water and using fixative would prevent the yarn from stretching back. This process significantly improved the quality of cotton cord. During the Second World War, there were concerns about variation in the lifespan of the company's [Nippon Tire, Bridgestone; author note] aircraft tyres, but the introduction of Yokohama Rubber's low stretch production method through technology disclosure led by the navy greatly improved the lifespan of the tyres and reduced the variation. This is a true story I heard from my immediate supervisor."

This actually also shows the effects of the technology control associations.

This technology is thought to have been applied to aircraft such as the "Zero" and the "Falcon". As mentioned previously, the Nippon Tire (Bridgestone) tyre on the Falcon fighter and the Yokohama Rubber tyre on the Zero fighter show little outward sign of deterioration, indicating the high level of technology at the time.

This is surely the result of incorporating improved product quality through technology disclosure.

4.4. Summary

As seen above, the period spanning the Taisho Period to the end of the war can be divided two ways.

1. The age of Japanese factories for overseas tyre companies or introducing overseas technology (Dunlop, Yokohama)

   These companies imported overseas technology, but also studied it for themselves and went on to develop their own technology.

2. The age of starting independent technology from the beginning (Bridgestone, Toyo)

As the Pacific War era approached, other countries started to be boycotted and Japanese companies had to get by on their own technology. There was little difference between 1 and 2 at this point; both rapidly advanced in performance and production technology. The technology evidently reached a very high level during the war, as they also had to produce all of their own technology despite an extreme shortage of raw materials and expand their adaptive abilities to produce goods for the military, with rigorous usage conditions. The level of durability would have increased rapidly during this period.

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14)*Yokohama Gomu Sōritsu 50-Shūnen [Yokohama Rubber 50-Year Jubilee]*, Yokohama Rubber Company, October 1967, p. 27.

15) “His Imperial Majesty’s Car”, *Yokohama Rubber News*, No. 34, October 1972, p. 10.

16) Toyota Automobile Museum Collection, 41-100 Yokomichi, Nagakute, Aichi. Originally released as “Toyoda” with the voiced sound indicators included on the final character in the Japanese script. Changed to “Toyota”

without the voiced sound indicators in October 1936. (Discussion with Toyota Automobile Museum.)

17)*Yokohama Gomu Sōritsu 50-Shūnen [Yokohama Rubber 50-Year Jubilee]*, Yokohama Rubber Company, October 1967, p. 31.

18) *80 Shūnen Kinen We Tokubetsu-gō [80-Year Anniversary We Special Edition]*, Yokohama Rubber Company, October 1997, p. 53.

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22) *Tōyō Gomu Kōgyō 50-nen-shi [The 50-Year History of Toyo Tire & Rubber]*, Toyo Tire & Rubber Company, 21 March 1996, p. 70.

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5. Stage of Maturity: The Age of Motorisation

5.1. Stage 1: Technology in the Posr-War Rebuilding Period

5.1.1. The Age of New Materials – the Rise of the Post-War Motorisation Age

(1) Post-War Situation

The recovery from the chaotic post-war aftermath [1)] (the age of new materials) was as follows.

Although the rubber industry had taken a major hit from war damage, its recovery was comparatively quick, given the state of other post-war industries. Reasons for this included the fact that the industry had had training in collective control and had taken to collective behaviour before and during the war, the fact that raw rubber and fibres that had been held by the army and navy during the war were released into the private sector at the end of the war in greater amounts than had been expected during the war, and the fact that military demand could be converted to private demand relatively simply; but the main reason was a prompt and relevant directive to all rubber factories in the country from the Rubber Control Association based on government policy at the end of August 1945, outlining "matters on provisional measures on handling the new situation in the rubber industry" [1)].

To put it simply, this directive put an immediate end to the exclusive production of military goods and allowed private sector production to continue or increase.

This period was the entry point into the age of motorisation (see Fig. 5.1) [2)]; later, as society suddenly became motorised, major changes happened with tyres as well. The distinguishing characteristic of this period was the appearance of new materials.

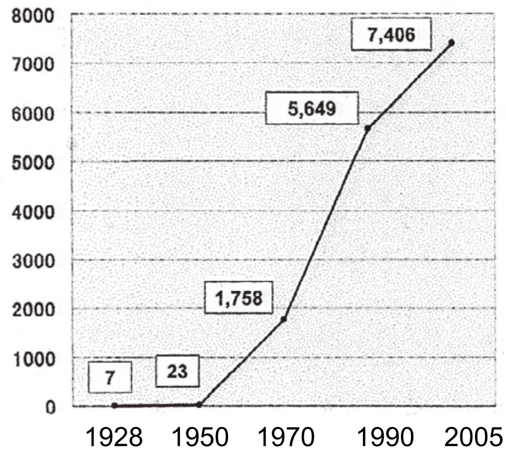


Fig. 5.1. Ownership of Four-Wheeled Vehicles in Japan (unit: 10,000 vehicles) [2)]
(*Sekai Jidōsha Tōkei [World Motor Vehicle Statistics]*, Vol. 6, 2007)

(2) The Appearance of New Materials

For the Japanese tyre industry, this period was a time of importing and learning overseas technology once the country reopened after the war.

The greatest change was the introduction of new materials. This included the transition in reinforcing material from cotton to synthetic fibres such as rayon and nylon and the emergence of synthetic rubber as a raw polymer. Consequently, difficulty arose in this period in adopting new materials without changing bias processing machines. There are tales of hard times learning to use nylon and SBR. In other words, this period was a time of changes in raw materials.

(3) Reinforcing material (tyre cord)

(i) Changes in tyre cord

In modern terms, tyres are made of fibre reinforced rubber (FRR). This structure was implemented because tyres are pressure vessels. Tyres are a kind of balloon; natural rubber on its own cannot counteract the internal pressure and needs to be wrapped in a strong, non-stretch material. It needs reinforcing fibre to do that. With internal pressure in the tyre, tension is applied to the tyre cord. Actual tyres are wrapped in reinforcing materials such as fibre and steel cords. The tension applied to the reinforcing layer is determined by the balance between internal pressure and external shape. Consequently, the tension applied to the cord on a turning tyre fluctuates. Therefore, tyre cord must be rated not only on strength and breaking elongation, but also from the perspective of fatigue, deterioration and adhesion between the rubber and the cord.

Rayon started to be used in the United States from around the 1940s; nylon appeared in the 1950s and gradually grew in popularity, while cheaper polyester also began to be used. Rayon cord was replaced by nylon in post-war Japan. Looking at the volume of consumption, as shown in Fig. 5.2, we see that nylon took over as the main cord fibre in the mid-1960s. Nylon's replacement of rayon in the United States is thought to be around 10 years earlier. This means that the tyres on the B-29 bombers that bombed Kyushu towards the end of the war contained nylon, something previously not seen in Japan. These were ideal for aircraft tyres in terms of impact resistance and fatigue resistance and accordingly were already in use during the war [5].

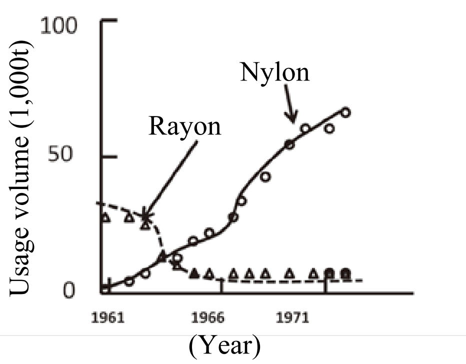


Fig. 5.2. Post-War Changes in Tyre Cord [10]

(ii) Details on tyre cord [4]

1) Cotton cord

Until regenerated and synthetic fibres appeared, cotton was the only fibre with the adequate performance, cost, availability, and other factors to be used as an industrial fibre. Most tyre cord was also cotton. Since cotton has short fibres, it has to go through a spinning process that pulls and twists the fibres together.

2) Rayon cord

Fibre made by chemically extracting and re-forming natural fibres (cellulose). The tyre cord is made using the viscose method, in which a pulp of wood or other material is treated with caustic soda, dissolved in carbon disulphide and aged to form a sticky liquid called viscose, which is pushed through a nozzle to form threads. Increasingly higher quality tyre cords emerged, while and rayon and reinforced rayon have even recently been rated as having no noise, vibration or flat spots (a phenomenon in which the part of a tyre in contact with the road changes shape after the car has stopped and cooled) when production conditions are good and have been used in high performance tyres. Following the appearance of radial tyres, it continued to be used in the carcasses of high performance tyres, mainly in Europe. In Japan, there has not been much success with stable fibres, made by cutting spun thread into short fibres and twisting them.

3) Nylon cord

Synthetic nylon tyre cord appeared on the market in Japan around 1950. This was made by melt spinning a dissolved liquid. As it was highly stretchy in that state, it had to undergo a stretching operation to align the crystals and make it stronger; the stretch also had to be within an appropriate range.

Most tyres at the time were for trucks and buses, but nylon matched that need. Nylon is still used today in bias tyres for heavy services such as trucks, buses, construction machinery and aircraft. Nylon is stronger than rayon and does not lose its strength when wet like rayon does. However, nylon shrinks in the heat and requires a process of cooling while still inflated after vulcanisation.

Later, reinforcing layers for passenger vehicle tyres were made of combinations of steel cord and polyester. With that change, nylon appeared to have lost its main function; however, an increasing number of tyres had another layer of reinforcing material in the circumferential direction above the belt and nylon was often used as reinforcement for this layer, thereby winning back a major field of use for it to date. This layer heats up while the vehicle is in operation and forms another layer over the steel belt due to thermal contraction, thereby improving high speed durability. Nylon clearly exemplifies the rise and fall of a material in a very short time.

(4) Organic fibre tyre cord adhesion

(i) RFL adhesive

RFL is a fibre adhesive made up of a combination of resorcinol (R), formaldehyde (F) and latex (L). In the 1940s, Church and Manny et al. discovered that a liquid adhesive made by adding resorcinol formaldehyde resin to an aqueous solution of rubber latex had superior adhesion properties. For the next half century, RFL has been the main adhesive used on fibres such as rayon, nylon, polyester, aramid and glass fibre.

The adhesion mechanism is thought to be as shown in Fig. 5.3. The figure shows nylon on the left, rubber on the right and resorcinol and formaldehyde simply in between, causing a three-dimensional resinification reaction. The main cause of adhesion is the resin fundamentally forming a secondary bond (hydrogen bond) rather than a primary bond (chemical bond) with the nylon and the rubber. As shown in the figure, a resinification reaction occurs in the resorcinol between the rubber and the nylon, producing a resin between the rubber and nylon. The adhesive is produced along with the resinification reaction between the rubber and the nylon.

RFL resin is a significant invention that can be used generically on most fibres. It also made a very significant contribution to the tyre industry.

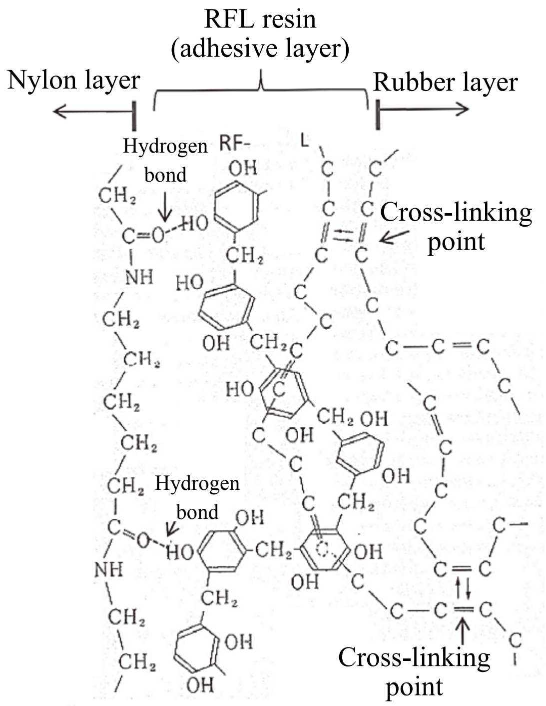


Fig. 5.3. RFL Adhesion Mechanism between Nylon and Rubber [8)]

(5) Changes in Cord by Companies

According to the history of Bridgestone, changes in cord happened as follows. By the 1950s, the United States was mostly using rayon instead of cotton; Bridgestone also recommended a change to rayon due to its low cost. This change took place rapidly, as by 1952, rayon was being used in 80% of their tyres.

Later, there was a change to nylon cord (initially for aircraft tyres); this change also happened quickly, with sales commencing in 1959. Major changes were happening with cord at this time [18)].

Yokohama Rubber Company developed a rayon tyre in 1950. By 1955, it had domestically produced an aircraft tyre with nylon cord in it [13)].

Toyo Rubber switched to rayon in the same period. According to its company history, various tyre manufacturers had started using rayon cord by 1951, while Toyo itself completed a dipping machine, put separation countermeasures in place and put rayon tyres on the market in February 1952 [12)].

Research on nylon tyres was carried out in earnest from the spring of 1954; from December 1958, they were marketed all over the country for trucks and buses [12)].

As outlined above, major changes in cord happened at around the same time.

(6) Composition of Rubber Compounds

The rubber used in tyres is a compound of various compounding agents. In other words, it is basically a compound of natural rubber, styrene-butadiene rubber (SBR) or other synthetic rubber (raw rubber) with reinforcing agents such as carbon black added to it, as well as compounding agents such as vulcanizing agents (to cause a cross-linking reaction to produce elastic rubber) and anti-ageing agents (for durability) mixed in. By changing the ratio of the raw rubber, reinforcing agents and vulcanizing agents, these compounds can form the required rubber; in other words, various kinds of rubber from hard to soft can be produced for use in various components. The greater the capacity, the greater the impact on the properties of the rubber; natural rubber (polymer) has the greatest impact.

(i) Adoption of synthetic rubber (natural polymers)

Right before the Second World War, the Japanese government noted the importance of synthetic rubber as a military resource. In 1938, it set up a 10-year plan to establish a synthetic rubber industry; in 1941, it issued the *Organic Synthesis Businesses Act*(*Yūki Gōsē Jigyō Hō*) to protect and develop it [16].

Research on the industrialisation of butadiene rubber in Japan grew more prolific as the war started. Through its occupation of southern territories, Japan was able to secure sources of natural rubber, which meant that SBR was no longer necessary. Focus shifted to the production of oil resistant NBR (acrylonitrile butadiene rubber) [16].

As the war ended, the Allied Forces Headquarters prohibited the production of synthetic rubber, providing a minor setback. However, from around 1950, the Ministry of International Trade and Industry, The Japan Rubber Manufacturers Association and the private sector began discussing the need to domestically produce synthetic rubber once more. Later, as the plans for the petrochemical industry began to take shape in Japan, a plan was proposed around 1955 requiring synthetic rubber for B-B fraction in oil-cracked gas rather than from alcohol. In 1957, the *Act on Special Measures for Synthetic Rubber Production Businesses*(*Gōsē Gomu Seizō Jigyō Tokubetsu Sochi Hō*) was issued and Japan Synthetic Rubber established through ¥1 billion of government funding and ¥2.5 billion in capital. Technology was imported from Goodyear in the United States and a factory started operating in Yokkaichi in 1960, producing 45,000 tons of SBR per year [11) 16)].

Meanwhile, "Nippon Zeon imported technology from Goodrich Chemical in the United States and started operating a factory in Kawasaki in 1959, producing 8,500 tons per year of mainly special non-SBR rubber, such as NBR and high styrene rubber. Production of SBR started in 1962, with production expanding to a total of 30,000 tons, including 10,000 tons of SBR and 20,000 tons of NBR and other special rubber. In 1965, a second plant opened in Tokuyama, producing a total of 45,000 tons per year, including 20,000 tons of SBR and 15,000 tons of BR. It supplied its own raw butadiene using its own extractive distillation methods." [16]

The change from natural rubber to SBR involved a struggle with reduced tack. In the moulding process during manufacture, tyres are moulded from layers of unvulcanised rubber, which requires tack (stickiness). Since SBR is less tacky than natural rubber, it was more difficult to mould. The invention of tackifiers in the United States solved this issue and paved the way for later widespread use [17].

Changes were taking place in compounding technology, with large amounts of fillers and oils being compounded as well as SBR.

When Japan Synthetic Rubber Company was established, the majority of the members of the Bridgestone Research Division Tokyo Office transferred there and successfully produced SBR. Meanwhile, the "Bridgestone catalyst" was perfected for cis polybutadiene rubber and patented in 1959; this catalyst provided a successful cis polybutadiene compound. In 1963 a pilot plant started operation; the main factory was completed in 1964 and started operating in 1965. This was Japan's first cis polybutadiene and was rated very highly; the technology was exported many times [15].

One account on the introduction of synthetic rubber tyres states that "the Passenger Vehicle Tyre Division perfected the country's first synthetic rubber tyre, throwing new light onto the devotion to natural rubber and greatly improving the durability of truck and bus tyres by using reinforced rayon." [13] New product development, which had seemed to stall for a while in the turbulent times following the war, gradually revived from around the time that rubber regulation ended (1950).

Yokohama Rubber Company announced a synthetic rubber tyre in 1957 [14].

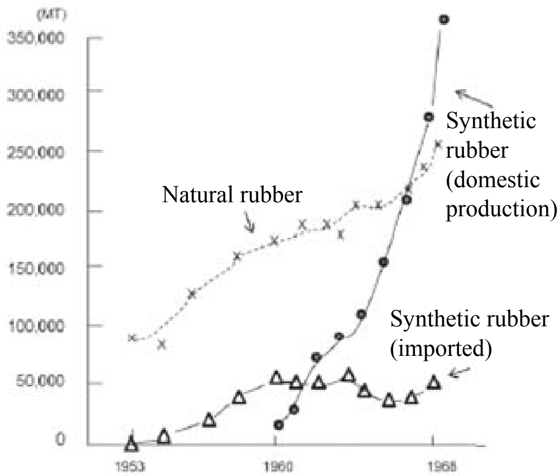


Fig. 5.4. Transitions in Raw Rubber Volumes (Domestic Production) in Post-War (1953-1968) Japan [3] (MT = metric ton)

The post-war raw rubber situation is shown in Fig. 5.4. It is clear how rapid the changes in raw materials were during this period. From around 1960 in particular, there was a rapid increase in the volume of domestically produced synthetic rubber used.

Looking at the above post-war initiatives in synthetic rubber, the two things that later undergirded Japan's tyre industry were the fact that some knowledge and experience in compounding existed before the war and the fact that even though Japan imported American technology after the war, it had the ability to develop its own technology in a coordinated fashion.

Pre-war compounding research is thought to have aided the progress of post-war polymer compounding technology. In other words, past experience made a significant contribution. This was one type of technology import in modern Japan.

As shown in the figure above, the demand for rubber grew rapidly with the rapid spread of motorisation up until around 1970. There was a rapid increase in domestically produced synthetic rubber from around 1960 in particular. Around half of this synthetic rubber was used in tyres.

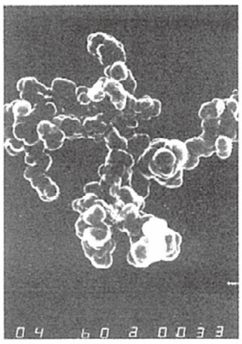
(ii) Carbon Black

Carbon black was produced by a US company in the 1870s. Later, the channel process of making it from natural gas was devised and became the main method used. During the Second World War, the furnace process emerged along with synthetic rubber; the oil furnace method used today, using heavy liquid oil instead of natural gas, became the main method used.

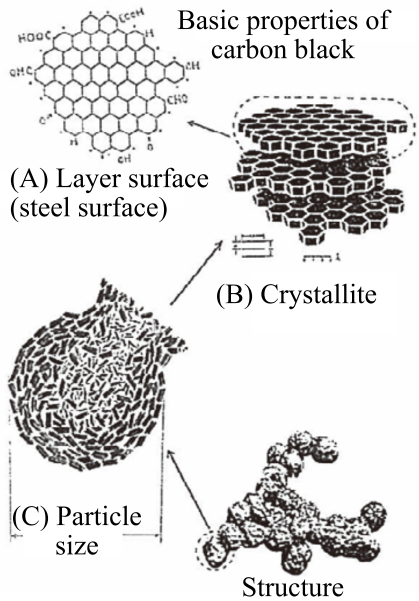
Carbon black is a type of soot found in the early 20th century to have a reinforcing effect on rubber. It became an essential reinforcing agent because it rapidly improves the strength of the rubber when added as such.

With the appearance of synthetic rubber, furnace black became the carbon black used due to its high reinforcing properties.

While carbon black is a stratified substance composed of carbon, it is particulate in form; the surface of the particles react with the polymers, causing a reinforcing effect (see Fig. 5.5). The larger the size of the particles, the smaller the surface area and the lesser the reinforcing effect. However, the smaller the particles, the greater the surface area and the greater the reinforcing effect. During this period, carbon particles were made smaller in size to increase the reinforcing effect.



Electron micrograph of carbon black (provided by Mitsubishi Chemical Corporation)



Carbon black structure (provided by Mitsubishi Chemical Corporation)

Fig. 5.5. Form of Carbon Black [6)]

Properties of Carbon Black

Particle Size	Large	Small
Breaking strength	Low	High
Hardness	Low	High
Wear resistance	Low	High
Heat build-up (lower is better)	Low	High

As an overall trend, small-particle carbon black is used on tread, the area of the tyre in contact with the road, where wear resistance is important. Large-particle carbon black is used in the rubber covering the internal cord in order to reduce the heat build-up.

Fig. 5.6 shows how tyre production volumes have increased. As seen in this figure, production increased by 50 times in a 30 year period from 1955. The figure shows a rapid post-war increase. This period was a time of rapid increase in production and challenges in keeping up with and mastering rapid changes in raw materials.

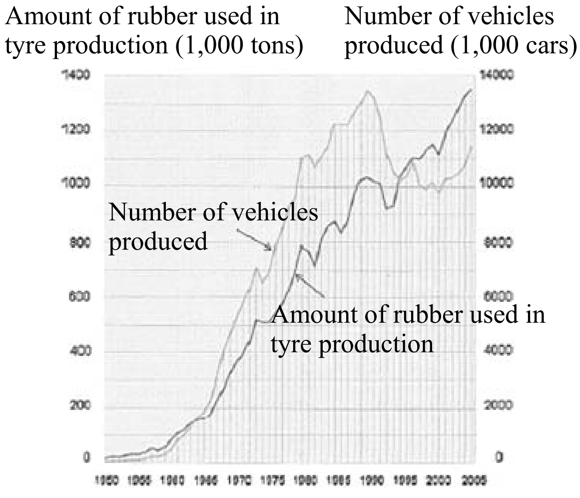
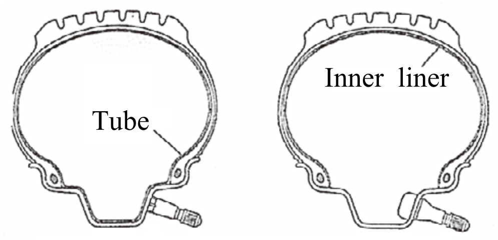


Fig. 5.6. Transitions in Japanese Vehicle Production Numbers and Amount of in Tyre Production (Amount of Rubber Used) [9)]

(7) Development of Tubeless Tyres

Tubeless tyres were developed by US company Goodrich in 1947; these have an inner liner of low-air-permeable rubber on the internal surface of the tyre, which plays the part of the tube, as shown in Fig. 5.7. Besides having fewer components and attaching to and detaching from the rim more easily, tubeless tyres also serve to improve safety at high speeds, since the air does not all escape at once if the tyre incurs a small puncture, such as would be incurred by running over a nail. Further, there is no need to separately manufacture a troublesome tube. This epoch-breaking technology advanced rapidly to Japan and was adopted in passenger vehicles from the 1970s onwards; by the 1990s, almost all vehicles had tubeless tyres. Only a few tube-type tyres remain for trucks and buses. While this technology involving fixing an inner liner of low-air-permeable rubber onto the internal surface of the tyre was a key technology, the decisive blow was the emergence of halogenated butyl rubber. Butyl rubber was already known as a low-air-permeable rubber and was used in tubes.

However, butyl rubber could not be fixed directly onto the inner liner of the tyre, as it does not co-vulcanise with other rubbers. Halogenated butyl rubber, developed in the United States in 1960, made it possible to co-vulcanize it with other rubbers and accordingly made it possible to attach it directly to the inner liner area of the tyre. It is still in use today. Brominated butyl is the usual type of halogenated butyl rubber used today.



a) Ordinary tyre b) Tubeless tyre

Fig. 5.7. Comparison of the Structure of Passenger Vehicle Tyres [7)]

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2) *Buridjisuton Nanajūgo-nen-shi [The 75-Year History of Bridgestone]*, Bridgestone Corporation, May 2008, p. 30. (Source) *Sekai Jidōsha Tōkei [World Motor Vehicle Statistics]*, Vol. 6, 2007

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9) Material from Japan Automobile Tyre Manufacturers Association (from *Nihon no Taiya Sangyō 2007 [Japan's Tyre Industry 2007]*).

10) Figure based on *Gomu Kōgyō Binran [Rubber Industry Handbook]*, fourth edition, The Society of Rubber Science and Technology, Japan, ed., January 1994, p. 549.

11) *Buridjisuton Nanajūgo-nen-shi [The 75-Year History of Bridgestone]*, Bridgestone Corporation, May 2008, p. 105.

12) *Tōyō Gomu Kōgyō 50-nen-shi [The 50-Year History of Toyo Tire & Rubber]*, Toyo Tire & Rubber Company, March 1996, rayon p. 99, nylon p. 117.

13) *Sōritsu 50-Shūnen Yokohama Gomu [50-Year Jubilee of Yokohama Rubber]*, Yokohama Rubber Company, October 1967, p. 38.

14) *80 Shūnen Kinen We Tokubetsu-gō [80-Year Anniversary We Special Edition]*, Yokohama Rubber Company, October 1997, p. 55.

15) *Buridjisuton Nanajūgo-nen-shi [The 75-Year History of Bridgestone]*, Bridgestone Corporation, May 2008, p. 106.

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5.2. Stage 2: From Bias Tyres to Radial Tyres

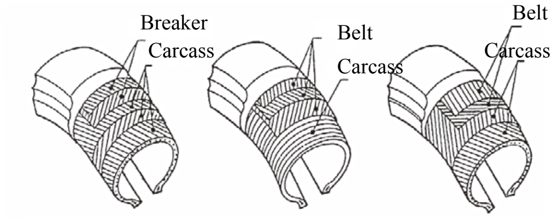
5.2.1. Change in Structure: The History of Changes in Production Technology

Following the post-war high economic growth period from the 1970s onwards, there was a rapid transition in Japan from bias tyres to radial tyres. This is thought to be the greatest change in tyre technology both before and after the war. As well as changes in tyre structure, steel cord also appeared as a reinforcing material, meaning all-out changes in manufacturing methods and facilities and equipment. This brought improved performance and revolutionary changes in all directions.

Steel radial tyres with steel cord reinforcement were developed by Michelin in France. A passenger vehicle tyre was announced in 1948, followed by a truck/bus tyre in 1953. These are the most widely used tyres today.

(1) Changes in Tyre Structure

The following figure shows the difference between bias tyres and radial tyres. Bias tyre carcass ply overlaps with the direction of the cords running in alternate directions on a bias, hence it is called a bias structure. Radial tyre carcass ply has the cords running radially from the centre to the outside when viewed from the side, hence it is called a radial structure. Belted bias tyres are somewhere between the two (see Fig. 5.8).



a) Bias tyre b) Radial tyre c) Belted bias tyre

Fig. 5.8. A Comparison of Bias, Radial and Belted Bias Tyre Structures [1)]

Fig. 5.9 shows the transition in the proportion of radial tyres produced in comparison to other tyres in Japan. The reason radial tyres became popular so suddenly was that the expansion of highway networks and improved car performance demanded better tyre performance and radial tyres met the needs of users in terms of stability and controllability (cornering power, etc.) at high speeds, as well as better durability, better wear resistance and lower fuel consumption at high speeds.

The drawback to radial tyres was that they offered poor riding comfort on bad roads; however, this was not a major problem in Japan as the rapid expansion of highway networks at the time (see Fig. 5.12) meant road conditions were improving.

As seen in Fig. 5.9, radial tyres were used in passenger vehicles in the 1990s and for most truck and bus tyres in the 2000s.

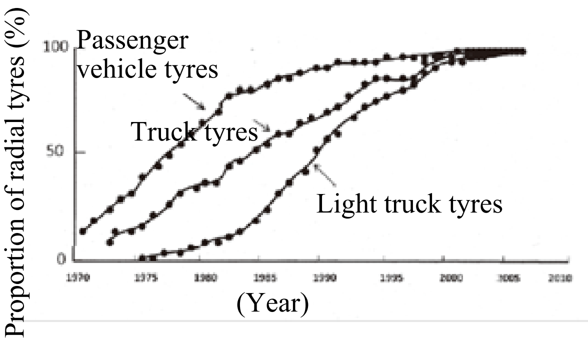


Fig. 5.9. Proportion of Radial Tyre Production in Japan [2)]

Radial tyres gained popularity in Japan later than in France and other countries in Europe, but earlier than in the United States (see Fig. 5.10).

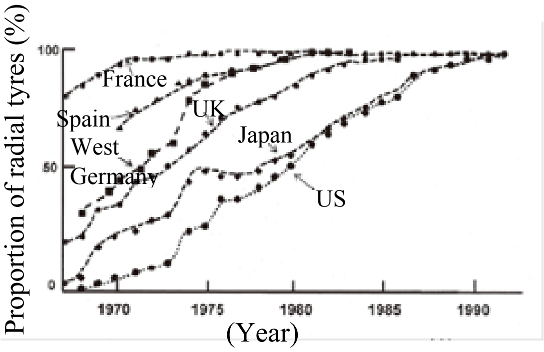


Fig. 5.10. Proportion of Radial Tyres for Passenger Vehicles (Sales for Vehicle Maintenance) [3)]

The transition from bias to steel radial tyres was not a sudden change; there was a transition period in which two structures emerged: belted bias tyres and textile radial tyres.

Belted bias tyres could be manufactured on existing facilities and equipment and thus avoided the issue of having to make changes to manufacturing facilities and equipment. Textile radial tyres offered the same poor ride comfort as steel radial tyres. Belted bias tyres came about in the United States as a result of the issue of having to make changes to manufacturing facilities and equipment. Textile radial tyres were actively produced in Japan and other countries where road conditions were less than ideal.

There were repeated discussions at the time in the United States whether to continue on with the existing belted bias tyres or to transition to radial tyres like Europe. The reality was that belted bias tyres had taken a firm hold and the demand for them was continuing to grow [12)].

Later, radial tyres gained a firm position in the United States as well.

The period of transition from bias to radial tyres saw temporary structures such as belted bias tyres in the United States and textile radial tyres in Europe and Japan, but in the end everyone settled on steel radial tyres.

In terms of facilities and equipment, Japan had entered a time of high economic growth and various tyre companies were building new factories anyway, so they established these as radial tyre factories. Motorisation was already fully fledged in the United States and so the transition from bias to radial and the accompanying major facilities and equipment changes were somewhat delayed, so belted bias tyres were a proposed compromise.

The greatest differences between radial tyres, bias tyres and belted bias tyres are the number of layers of ply and breakers (belts) and the angle of the cord (see the figure below); however, there were various different cord materials and bead structures [21)].

	Ply angle (˚)	Belt angle (˚)
Radial ply tyre	70-90	10-60
Bias ply tyre	30-40	30-40
Belted bias ply tyre	30-40	20-30

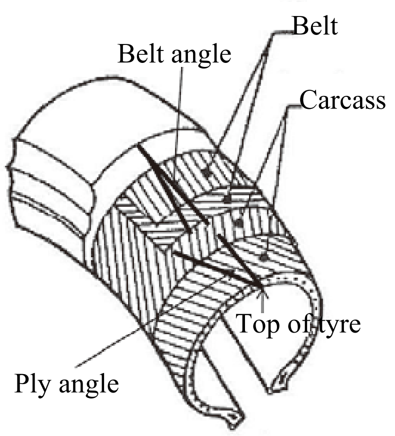


Fig. 5.11. Tyre Ply/Belt Structure

As previously mentioned, radial tyres had issues with ride comfort, but this was solved by the development of highways.

Radial tyres were also more suited to travelling at high speed than bias tyres. From these two factors, the development of highways can be said to line up with the change to radial tyres (Fig. 5.12).

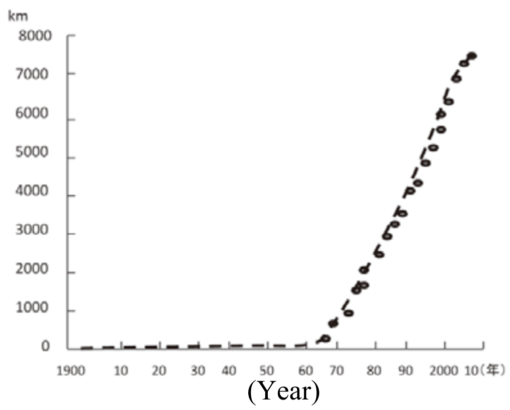


Fig. 5.12. Transitions in Highway Extension Distances in Japan [11)]

(2) Manufacturing Methods

Radial tyre factories required major changes to bias tyre factory facilities and equipment. Let us now discuss factory facilities and equipment.

Manufacturing Facilities and Equipment (Radial Tyre Factory)

Fig. 5.13 shows manufacturing facilities and equipment [4)]. Broadly speaking, tyre production involves the following five processes.

(i) Compounding (Mixing and kneading the raw rubber and various kinds of compounding agents in a mixer. Fig.5.14 shows a mixer.)

(ii) Extruding (Extruding the kneaded rubber from an extruder in a predetermined size and shape.)

(iii) Rolling (Topping the rubber with fibre, steel cord and other reinforcing materials.)

(iv) Moulding (Doubling together the materials prepared in (ii) and (iii) and forming a tyre shape.)

(v) Vulcanising (Making it into a finished product by adding heat.)

The facilities and equipment for this have remained basically unchanged since the 1970s.

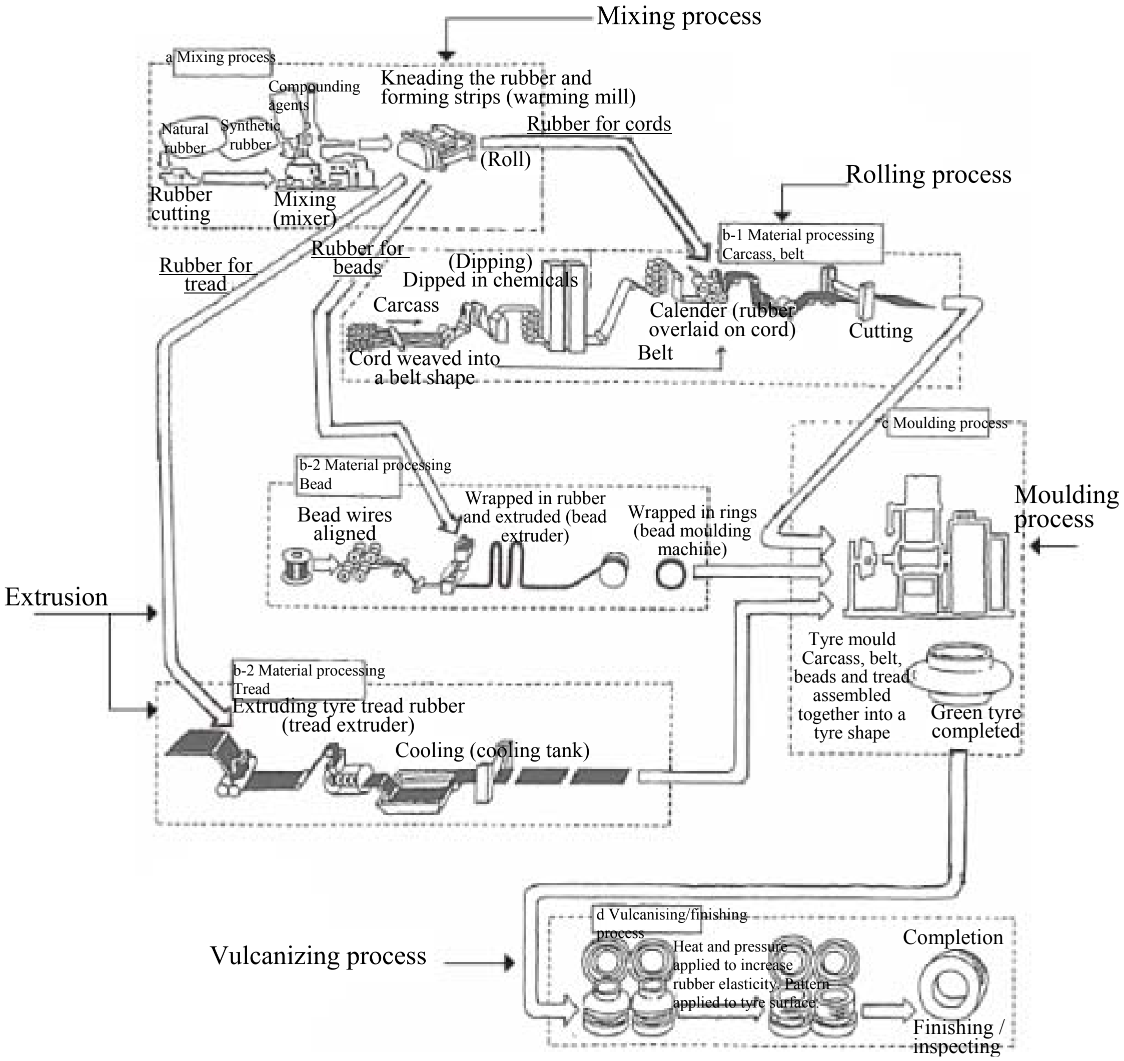


Fig. 5.13. Tyre Production Process [4)]

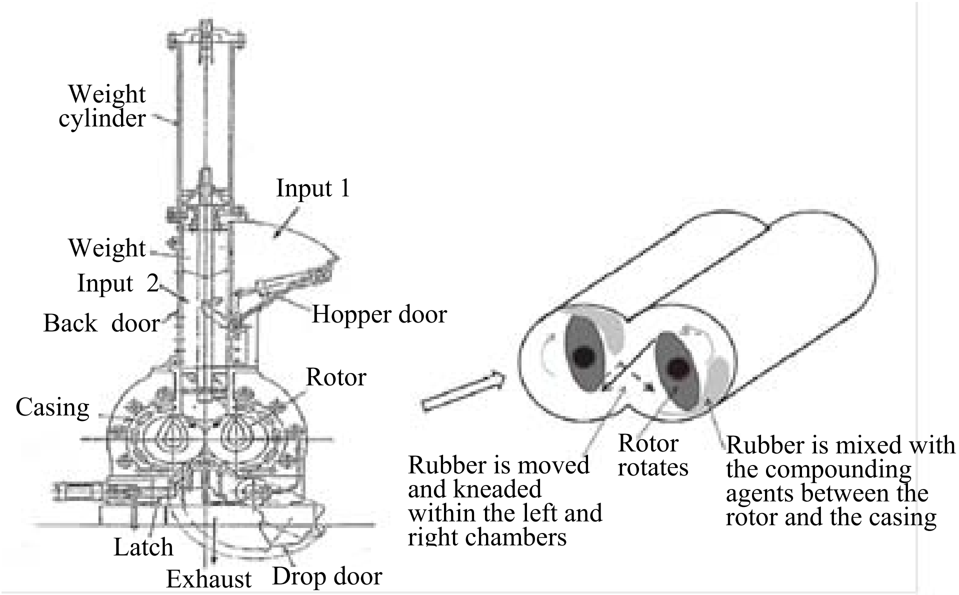


Fig. 5.14. Mixer (Banbury Mixer) [5] and Model of the Interior of a Mixer

(3) Details on the Tyre Manufacturing Process

(i) Mixing (Kneading)

The process of making un-vulcanised rubber by combining the various compounding agents weighed according to a recipe. This is a very important task that affects the properties of the final product.

Fig. 5.14 shows a Banbury mixer.

These are internal mixers. The material goes into a central area called a mixing chamber. A rotor with two blades side by side rotates within the chamber to create a shearing force between the opening and the chamber wall. The raw rubber, carbon black and other fillers placed into the input are rubbed together and blended. The blades on the rotor are designed to mix the materials evenly [5].

(ii) Extruding Process (see Fig. 5.15)

Areas with a predetermined cross-section such as the tread (the area that comes into contact with the surface of the road) are achieved by an extruding process. After being kneaded in the mixer, the tread rubber is plasticised with a warming mill and then fed into an extruder, where it is extruded through a nozzle in a pre-set tread shape, thereby forming a predetermined cross-sectional shape. The extrusion area is then cooled and the tread rubber is cut to the required lengths and stored.

(iii) Calender Process (see Fig. 5.16)

The calender process produces breakers, belts and other materials by coating fibres and wire cords with a thin layer of rubber on both sides (topping). For steel cord, a creel containing the necessary number of steel cords to fit the width of the calender is set in a stand. The wire cords are unwound from each creel, collected together and aligned at intervals like a comb. A sheet of rolled rubber is then pasted on top of them. For fibre, the fibre cords are lined up with a coarse weft and put in the calender. Steel cord calender processing has become an essential manufacturing process in the age of radial tyres.

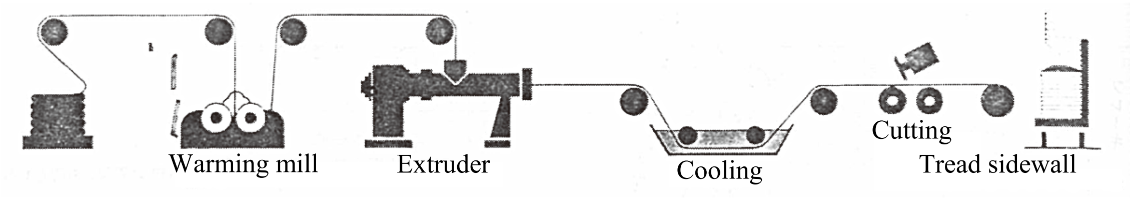


Fig. 5.15. Extruding Process [14)]

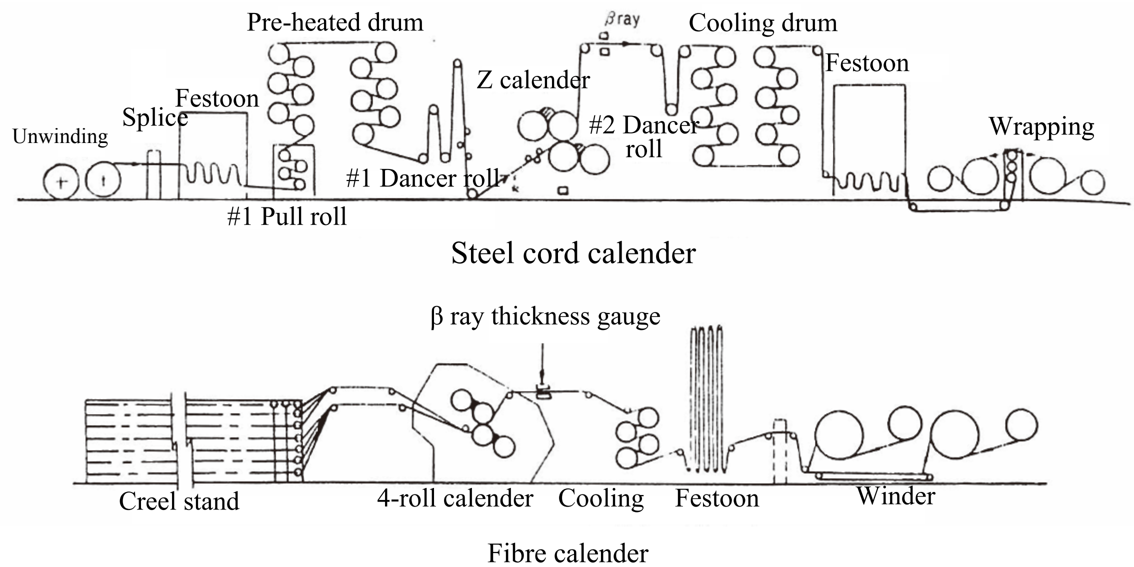


Fig. 5.16. Calender Process [15)]

(iv) Moulding Process

This process differs the most between bias and radial tyres. Fig. 5.17 below shows the difference in moulding methods between bias and radial tyres [6].

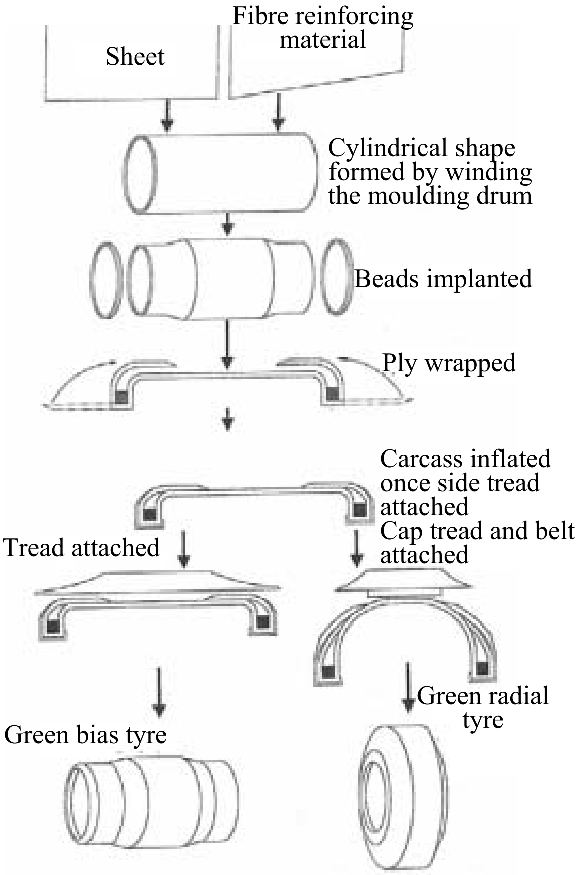


Fig. 5.17. Tyre Moulding Process [6]

Tyre production involves a number of components being overlaid, shaped into a tyre, put into a mould and heated (vulcanised) to form the final product. While the transition to radial tyres meant changes had to be made in all processes, the greatest change was in the tyre moulding process. The pre-vulcanisation (pre-heating) state differs for radial and bias tyres (see Fig. 5.17). From the figure, we see that the pre-vulcanisation shape of bias tyres is quite different from the shape of the finished product after vulcanisation, while the pre-vulcanisation shape of radial tyres is quite similar to the shape of the finished product after vulcanisation.

(v) Vulcanisation Process

This process also differs significantly between bias and radial tyres, because the shape of the tyres is quite different prior to vulcanisation. Tyres that have finished the moulding process (un-vulcanised tyres) are called green tyres. These tyres are pressed into a tyre mould by internal pressure and then vulcanised. At this point, the tread pattern, side design and stamped characters on the surface of the mould are imprinted on the tyre. At the same time, the tyre is heated inside and out through a medium such as steam, water or gas and the entire tyre is undergoes a vulcanisation reaction, turning it into elastic, vulcanised rubber and the tyre is completed. Heating is done internally and externally. There are two methods of external heating: using a jacket-type hot plate or shutting the mould in a pressure vessel and pumping in steam around it. Internal heating is achieved by inserting an airtight pouch (vulcanisation bladder or air pack) injected with steam, water or gas. Since tyres do not have uniform thickness, heat is not supplied evenly to all areas, making it difficult to achieve a uniform degree of vulcanisation. It is important to complete vulcanisation in such a way to avoid excessive heating and consequent deterioration of the rubber. The Bag-O-Matic

(BOM) press (Fig. 5.18) is a popular vulcaniser currently in use.

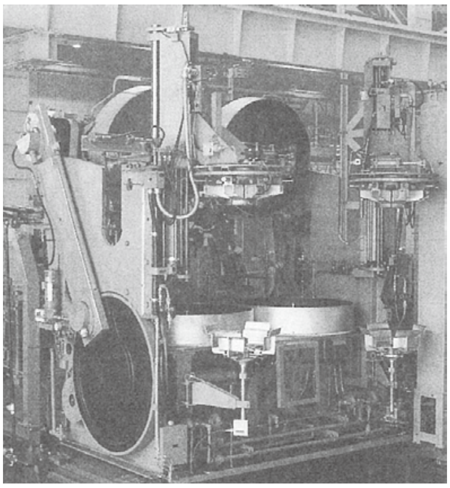


Fig. 5.18. BOM Vulcaniser (When Open) [20]

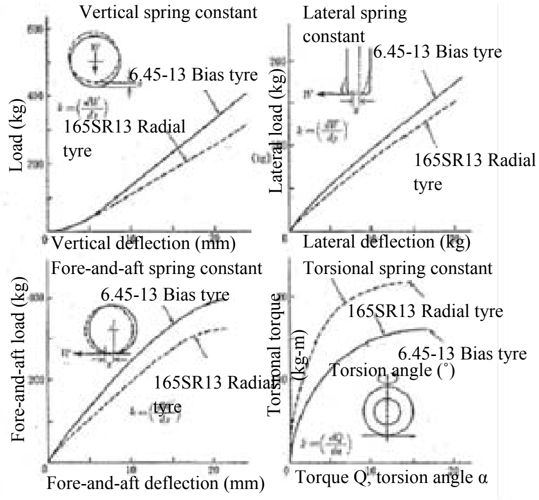


Fig. 5.19. How to Measure Various Static Spring Constants and Sample Load-Displacement Curves [18]

(4) Bias and Radial Tyre Performance Comparison

(i) Spring Constant [18]

The spring characteristic of tyre function is the property that allows the tyre to change shape while resisting external forces acting on it and then return to its original shape once the force is removed. This is usually denoted as a "spring constant", comprising the ratio between the external force and the direction of the change in shape. The following are four static spring constants (see Fig. 5.19).

1) Vertical Spring Constant (Z direction)

The vertical spring constant is the slope of the curve between the vertical load on the tyre and the vertical deflection. This spring constant mainly relates to tyre vibration and ride comfort (frequency range of around 30Hz or less). The lower the vertical spring constant, the better the ride comfort.

2) Lateral Spring Constant (Y direction)

The lateral spring constant is the slope of the curve between the pulling force and the lateral displacement where a vertical load is applied to the tyre and it is pulled laterally on the road surface. This spring constant relates to the cornering properties of the tyre.

3) Fore-and-Aft Spring Constant (X direction)

The fore-and-aft spring constant is the slope of the curve between the pulling force and the fore-and-aft displacement where a vertical load is applied to the tyre and it is pulled forwards on the road surface. This spring constant relates to the oscillation of the tyre in the fore-and-aft direction.

4) Torsional Spring Constant (Z rotation)

The torsional spring constant is the slope of the curve between the torque and the torsional angle where a vertical load is applied to the tyre and the contact area of the tyre rotates on the road surface with the centre of the contact area as the centre of rotation. This spring constant is an indicator of tyre torsional stiffness. This property is higher in radial tyres than in bias tyres. The increased stiffness demonstrates the effect of the change to radial tyres in the age of highway travelling.

The radial tyre structure has less rigid sidewalls and more rigid belts, meaning less flexibility in the tread area due to the load and a direction of deflection causing overall eccentricity. Since the vertical spring constant is measured with the tyres inflated, radial tyres have a lower vertical spring constant, but they offer poor ride comfort over bumps because of the high rigidity of the belts.

(ii) Rolling Resistance

When comparing the performance of radial and bias tyres, there is a clear difference in loss due to deformation because of the degree of deformation from stress. The difference in the degree of deformation of the overall tyre is expressed as a difference in rolling resistance (related to fuel consumption). Since radial tyres have a little amount of deformation, they have a low rolling resistance (good fuel consumption). As shown in Fig. 5.20, rolling resistance relative to speed is higher in bias tyres and the difference increases with speed. As shown in Fig. 5.21, radial tyres have lower rolling resistance compared to bias tyres even relative to load.

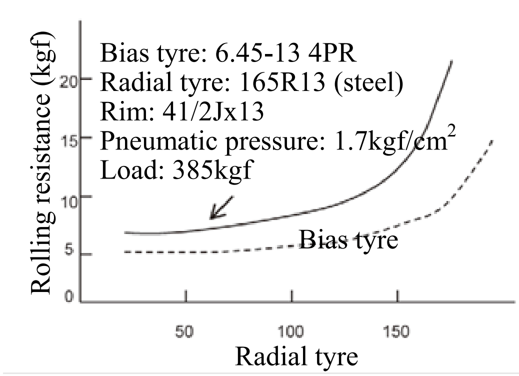


Fig. 5.20. Rolling Resistance of Radial and Bias Tyres [7] Speed (km/h)

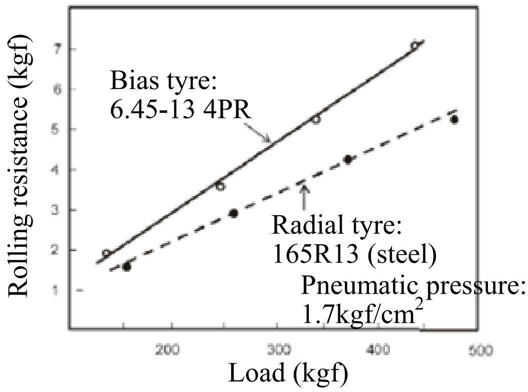


Fig. 5.21. Load and Rolling Resistance [7]

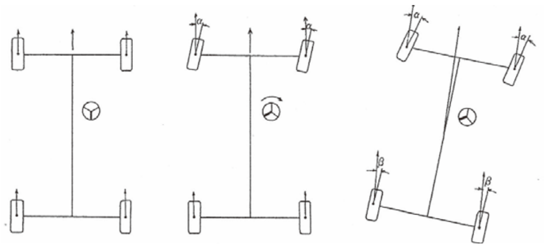
While radial tyres had better fuel consumption, as shown above, fuel (gasoline) was inexpensive in the United States at the time, and the change to radial tyres progressed more slowly there than in Europe.

(iii) Cornering

Two aspects of tyre performance relate to manoeuvrability: braking and controllability (cornering). Let us discuss cornering.

Consider a skidding tyre.

When the steering wheel is turned to the right while the vehicle is in motion, as shown in Fig. 5.22, the operation of the steering wheel puts the rotational plane of the wheels at an angle to the direction of travel of the car. Because the car tries to keep going straight ahead due to inertia, a disconnection occurs between the rotational plane of the tyres and the direction of travel of the car. The angle of this disconnection is called the slip angle [16].



(a) Travelling straight	(b) The moment the steering wheel is turned α: Slip angle of the front wheels	(c) Turning α: Slip angle of the front wheels β: Slip angle of the rear wheels

Fig. 5.22. Relationship Between the Direction of Travel of the Car and the Direction of Rotation of the Tyres [16]

(iv) Cornering Force and Self-Aligning Torque

When slipping sideways, the tyres themselves contort against the surface of the road (see Fig. 5.23). The sideways force exerted on the vehicle is called the cornering force and causes the vehicle to move in a curve. The force that rightens this is called self-aligning torque.

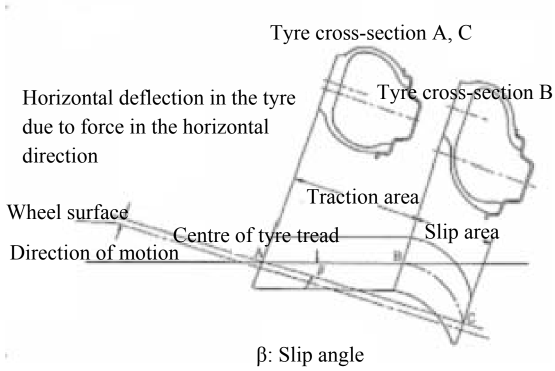


Fig. 5.23. Tyre Slipping Sideways [16]

(v) Difference in Manoeuvrability

When a vehicle is cornering around a bend, a cornering force is generated to oppose the centrifugal force on the tyres (see Fig. 5.24). The cornering force increases in a linear fashion as the slip angle increases, reaching its maximum value when the slip angle reaches or exceeds a certain value. The structural element with the greatest effect on the cornering force is the flexural rigidity of the tread area. Radial tyres have a belt layer with high flexural rigidity in the tread area, which means that they offer far greater cornering force than bias tyres. The slope of the straight-line portion of the cornering force is called cornering power and is often used as a property value to indicate cornering performance. One reason for the change to radial tyres was their manoeuvrability. As shown in Fig. 5.25, radial tyres have greater cornering power than bias tyres. This means that radial tyres are easier to drive on and better to manoeuvre.

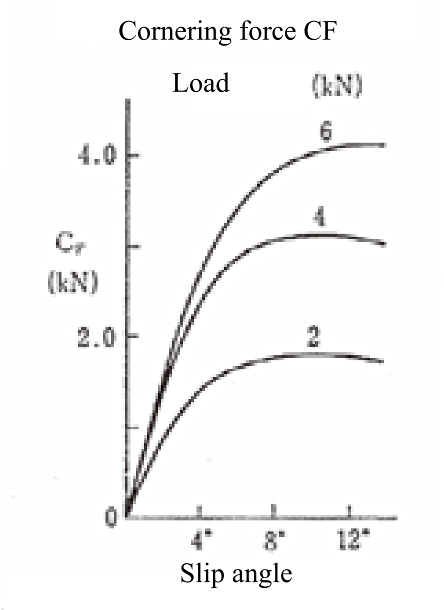


Fig. 5.24. Cornering Force [17)]

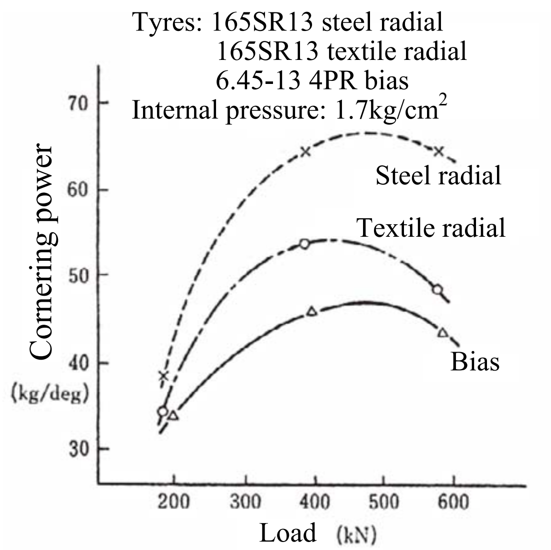


Fig. 5.25. Cornering Power and Tyre Structure[8)]

As given above, the appearance of steel radial tyres dramatically improved automobile turning performance and high-speed straight-line stability. This is a major factor enabling today's safe highway travel for everyone.

The tread area (the area in contact with the surface of the road) also has the highest contribution factor to rolling resistance. When this area is in contact with the surface of the road, radial tyres fluctuate less and so require less work. This also means that the area in contact with the surface of the road fluctuates less, meaning that radial tyres are also better in terms of wear resistance.

(vi) Tyre Functions

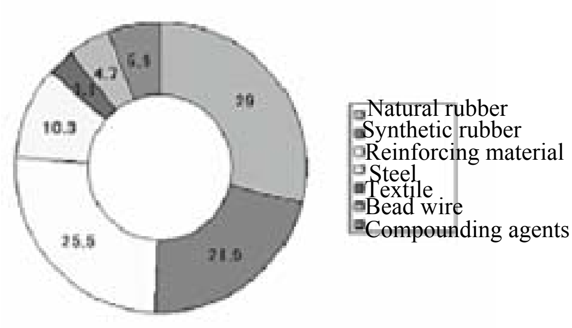
As mentioned in the introduction, tyres have the following four functions.

- Bearing a load (support)
- Acting as a spring (absorption)
- Conveying driving and braking forces (transmission)
- Facilitating steering of the vehicle (turning)

These are vital functions in which the tyres as part of the vehicle serve as an intermediary in establishing a mutual relationship between the vehicle and the surface of the road. However, it was not until the transition to radial tyres that these functions started to be clearly manifested in tyre development, thanks to easier turning and transmission with increased rigidity and other radial tyre characteristics. This also coincided with the advent of the age of high speed travel.

5.2.2. Change of Materials

The transition from bias to radial tyres meant a change in materials as well.
(Polyester, steel cord)



Rubber/filler/chemicals 80%

Basic Composition	Example of Main Composition Type	Weight Composition Ratio (%)
Rubber	Natural rubber, synthetic rubber	50.5
Reinforcing agent	Carbon black Silica	25.5
Tyre cord	Steel cord Textile cord	13.4
Compounding agents	Vulcaniser, vulcanisation accelerator, vulcanisation agent, anti-ageing agent, filler, softener	10.6

Source: Japan Automobile Tire Manufacturers Association

http://www.jatma.or.jp/index.html

Fig. 5.26. Radial Tyre Composition and Materials Used in Each Part

(1) Radial Tyre Materials

As previously mentioned, tyres are generally composed of more than 10 components (see Fig. 1.3 in Chapter 1). Each component has its respective function; suitable materials are selected, combined and systematised to fulfil those functions. Generally, the area that comes in contact with the surface of the road and the bead area that comes in contact with the rim are made of hard rubber, while the sidewall between these areas is made of soft rubber. The raw materials consist of rubber and reinforcing (tyre cord). As shown in Fig. 5.26, the rubber portion, including rubber, reinforcing agents such as carbon black, and compounding agents, accounts for at least 80% of the tyre.

(2) Rubber for Each Component

(i) Tread and Sidewall

Tread rubber (the part that comes in contact with the surface of the road) plays the role of transferring the forces applied to the tyre to the surface of the road. Of all the rubber used in the tyre, tread rubber has to withstand the most external mechanical force to protect the tyre from the road surface so that the pressure-vessel carcass is not damaged. In terms of rubber properties, it has to have superior strength, tearing force and wear resistance. Accordingly, it is usually a selection of natural rubber, SBR or BR polymers blended with fine-grained, high-reinforcing carbon black. However, while fine-grained carbon black is highly reinforcing, it generates a lot of heat when restraining polymer movement. This is a major issue because it is a fuel-inefficient behaviour.

Natural rubber has a high balance of performance; in particular, it is lower in heat generation than synthetic rubber and is still often used today in tyres with higher heat generation during operation, such as truck and bus tyres, construction machinery tyres and aircraft tyres.

An increasing amount of SBR was being used for passenger vehicle tyres, but the SBR itself was difficult to process. Use of oil-extended SBR (oil included during polymer manufacture) became adopted as standard. This method was effective for compounds with oil added to improve processability. Oil-extended SBR was patented in 1950 by US company General Tire and was later used throughout the world.

SBR was the ideal technology for tyre tread for passenger vehicles, but it took second place to natural rubber for truck tyres, bus tyres and other heavy duty vehicle tyres.

Sidewalls do not come into contact with the ground, but they are subjected to repeated bending and so must be fatigue resistant. They are usually made of NR/BR polymer and soft carbon and are also often combined with anti-ageing agents because they are exposed to sunlight. To perform their necessary function, sidewalls must be flexible, fatigue-resistant, age-resistant and ozone-resistant.

(ii) Carcass Rubber

Carcass rubber must adhere well to cord, have low heat build-up and be able to withstand shear stress. Natural rubber is the main rubber used because of its superior adhesive properties and heat generation.

(iii) Belt Rubber

Belt rubber is the rubber that covers the reinforcing steel cord; natural rubber is mainly used for this. This rubber must be adhesive to the steel cord and also age-resistant. This adhesion and age-resistance are discussed in more detail in Chapter 6.1.

(iv) Bead Area Rubber

Since the bead area contains a steel wire to connect the rim and the rubber tyre, the coated surface of the cord and the rubber must adhere together. Since this area also has to stay firm, natural rubber is often used with a lot of carbon black, with consideration given to heat build-up and adhesion.

(v) Tubeless Tyre Inner Liner

Solved by using halogenated butyl to maintain stable tyre pressure (discussed in Chapter 5.1).

(3) Reinforcing Material

The change from bias to radial was not a simple change in structure; it was also combined with a change in materials in a very short space of time. This was particularly evident in reinforcing material: belts were switched to steel and carcasses were switched to polyester (for passenger vehicles). For truck and bus tyres, both belts and carcasses were eventually switched to steel.

Passenger vehicle tyres also had a further layer of fibre reinforcing (cover material) over the belt. Nylon was often used for this and in some cases aramid fibre was also used. Fig. 5.27 shows the relationship between tensile strength and stretch for various fibres.

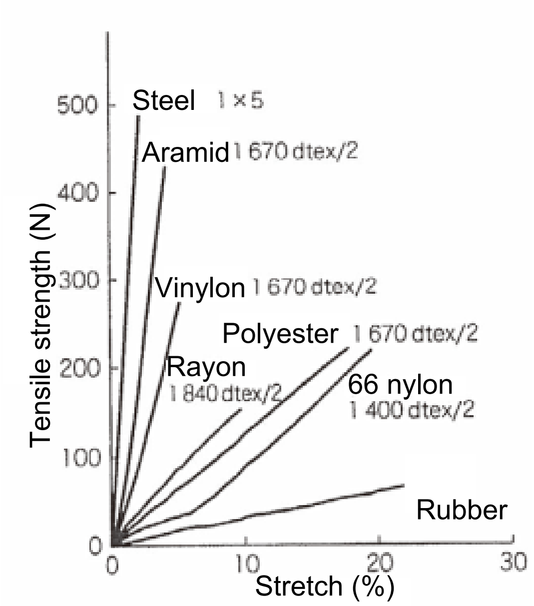


Fig. 5.27. Tensile Properties of Various Cords

As shown above, the change from bias to radial was a significant change, encompassing a change in structure as well as a change in materials.

(i) Development of Polyester Cord Carcasses for Passenger Vehicle Tyres

Polyester is somewhere between nylon and rayon in nature; it performs better against various drawbacks of nylon cord, especially in the areas of flat spots (a temporary flat area on a tyre against the road having cooled down after travelling), dimensional stability and manoeuvrability in smaller tyres such as passenger vehicle tyres. In other words, in terms of firmness, it has more rayon-like properties. Since it is also cheaper than rayon in price, it could be said in some ways to have spelled the end of rayon. However, high quality rayon is still used in top quality tyres where high manoeuvrability is required.

The drawback with polyester cord is that it has a greater decrease in strength due to twisting than nylon or rayon and is less adhesive to rubber than nylon or rayon. Before RFL adhesive, now commonly used, it required two-step processing, needing a primer-like pre-treatment.

Consequently, it is used in passenger vehicle tyre carcasses but not on truck and bus tyres and other tyres with greater shear stress between the ply. Since the fibre itself is susceptible to heat build-up, the rubber material is susceptible to deterioration; furthermore, the polyester itself can lose strength when the ester bonds hydrolyse.

(ii) Aramid Cord

Aramid cord was announced as a dream fibre with twice the strength per weight as nylon and around eight times the elastic modulus. An aromatic polyamide in structure, it has the drawbacks of being expensive, weakening with repeated compression strain (fibrillisation) and being difficult to adhere to rubber. Consequently, it has not been used as a main reinforcing material.

(iii) Steel Cord

Steel cord wire is high-carbon steel (0.7%) made into thin strands using a die. This process hardens it, so it is heat-treated, tempered and then coated with brass plating to provide a lubricating effect on the die to make it possible to draw it. Heat is applied in the vulcanization process during tyre production; a reaction between the rubber and the coating during this

process causes the cord and rubber to adhere together. In other words, the brass plating not only acts as an adhesive between the steel cord and the rubber, but also acts as a lubricant to prevent friction between the cord and the die during cord production. The final stage of drawing is carried out and the strands are complete. The strands range in thickness from 0.15mm to around 0.38mm. These strands are twisted together to form the cord. While the steel cord used varies between tyres, the more complex the structure, the more is involved in the twisting process and the greater the cost. In other words, steel cord with thinner strands and more twists has better flexural fatigue resistance, but since this makes the processing more complicated and increases the price, cord with a simpler structure is usually used instead. The plating process, drawing, twisting and other technologies are essential to development and much research and development went into these while radial tyres were being developed.
Japanese steel cord is top-level throughout the world; it has been highly regarded as having fewer impurities in the steel wire, meaning fewer breaks during the drawing process, as well as other performance factors.

(4) Cord / Rubber Combination

(i) Example Steel Cord Structures

The structures (twist structures) of steel cord for truck and bus tyres are as shown in Fig. 5.28 (single-layered twist, two-layered twist and three-layered twist). There are also structures for larger tyres that have multiple layers of twists. As seen from these structures, the single-layered twist structure has 2-5 filaments twisted together; this is often used for passenger vehicle tyres. The two-layered twist structure has a 2-3 filament cord in the centre with 6-9 filaments twisted around it; this is mainly used in truck and bus tyres. The three-layered twist structure comprises the two-layered twist structure with a further 14-15 filaments twisted around it; this is often used for larger tyres, from truck and bus tyres to construction machinery tyres

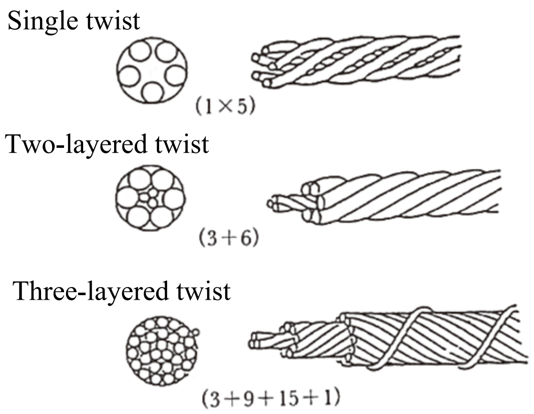


Fig. 5.28. Basic Steel Cord Structures for Passenger Vehicles, Trucks and Buses [9)]

As shown in Fig. 5.29, the structure of steel cord used in tyres increases in size from that used in passenger vehicle tyres and that used in truck and bus tyres. Tyres with heavier loads, such as truck and bus tyres, have a thicker structure. Construction vehicle tyres use an even stronger cord. These steel cords are used for different purposes according to the size of the tyre and the site of use.

Cross-Section of Steel Cord for a Passenger Vehicle		Cross-Section of Steel Cord for Trucks and Buses	
1 × 2		3 + 6	
1 × 4		3 + 9 + 1	
2 + 2		12CC + 1	
2 + 7 + 1		3 + 9 + 15 + 1	

Fig. 5.29. Example Structures of Steel Cord for Tyres (Cross-Section) [9)]

(5) Post-War Tyre Cord Trends and the Change to Radial Tyres

Fig. 5.30 shows the changes in tyre cord usage from the 1960s in the post-war era to the year 2000. As can be seen from these results, there were major changes within a short space of time: rayon had been replaced by nylon by the 1960s, while the transition to steel cord and polyester accompanied the shift to radial tyres from the 1970s onwards.

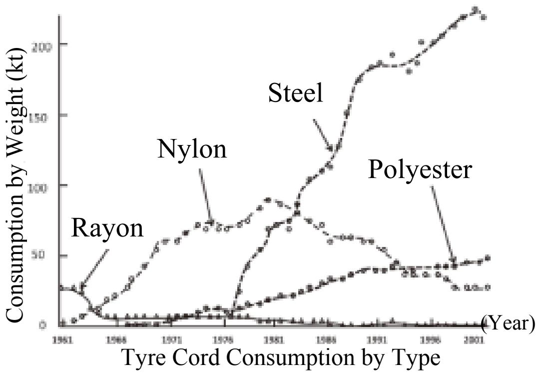


Fig. 5.30. Tyre Cord Consumption by Type [10)]

Fig. 5.31 shows the changes in the amount of tyre cord used in the United States. By contrast, the decline in rayon use and start of nylon use took place about ten years later in Japan. Polyester usage also started later in Japan than in the United States. As there is little difference between the two countries in terms of when steel cord came into use, it is fair to say that as passenger vehicles changed to steel radial tyres, polyester started being used in carcasses in Japan [19)].

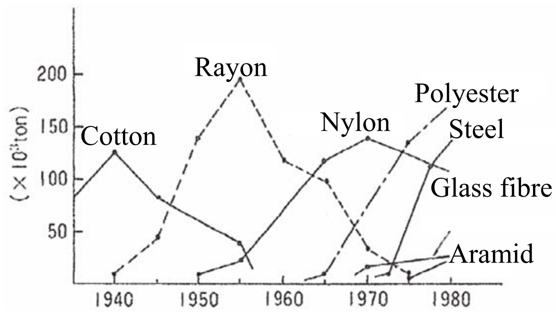


Fig. 5.31. Changes in Tyre Cord Usage in the United States [19)]

Thus, the transition to radial tyres was accompanied by major changes in cord along within a short space of time.

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2) Watanabe, Tetsuo: *Taiya no O-Hanashi [The Story of the Tyre]*, Japan Standards Association, October 2002, p. 35. Rewritten to include the latest data from documentation published by the Japan Automobile Tire Manufacturers Association.

3) Rewritten to combine Watanabe, Tetsuo: *Taiya no O-Hanashi [The Story of the Tyre]*, Japan Standards Association, October 2002, p. 36, Fig. 1.19 (b) and Hirata, Yasushi: *Taiya no Hensen ni tsuite* [Changes in Tyres], *Journal of The Society of Rubber Science and Technology, Japan*, Vol. 68, 1995, p. 25, Fig. 7.

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11) Drawn up from the Ministry of Land, Infrastructure, Transport and Tourism *Road Statistics Yearbook*. (See *Buridjisuton Nanajūgo-nen-shi [The 75-Year History of Bridgestone]*, p. 221.)

12) *Sumitomo Gomu Hyakunen-shi [Hundred-year History of Sumitomo Rubber]*, Sumitomo Rubber Industries, Ltd., December 2009, p. 176.

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6.1. The Age of Durability: The Coming of Age of Radial Tyres in the Age of Durability

Even for radial tyres, the basic area of performance is durability. Tyres must fulfil their lifespan. Accordingly, with the transition to the radial tyre structure, durability was the first thing that had to be achieved. The early radial tyre era in particular was a time of significant durability issues, such as the adhesion between the steel and the rubber, but these were overcome as time progressed.

6.1.1. Tyre Breakdown

Two things cause tyres to lose the strength they had when new: mechanical strain and generated heat. The extent of this varies according to how the tyre is used, from uneven terrain and unpaved roads causing major impact and deflection to highway-like conditions enabling high speeds on unobstructed roads with few bends, stops or starts. Tyres will break down if they encounter any abnormality that pushes beyond the limits of their remaining strength. Care must be taken so that the rubber from which tyres are composed does not reach that limit while running. Consequently, it is necessary to make it harder for the rubber to lose its strength. This requires a structure that prevents heat build-up both structurally and locally.

(1) An Examination of Strain [1)]

There are two types of tyre strain: strain generated by tension from internal pressure (static) and strain from rolling on the road surface while supporting a load (dynamic).

(i) Static Strain

Strain generated by tension from internal pressure differs between radial and bias tyre structure. In the radial tyre structure commonly used today, the carcass cord follows a radial path along the surface of the tyre and has a fairly uniform level of strain at any given point, while the strain is reduced slightly in the crown area due to the hoop effect of the belt. Along the belt cord, the strain is greatest at the centre of the crown, while a free end is formed at the shoulder area with zero strain. By contrast, the shear strain to counter planar deformation is greatest at the ends of the cords. Shear strain at the edges of the radial tyre belt is related to separation faults (faults in which the rubber splits and layers peel away) in this area. Belt edges in truck and bus tyres running with particularly heavy loads are also a factor for breakdowns under this same strain (see Figs. 6.1 and 6.2).

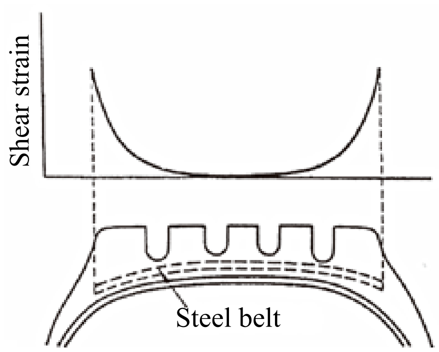


Fig. 6.1. Shear Strain on Radial Tyre Belt [1)]
(greater at the edges of the belt)

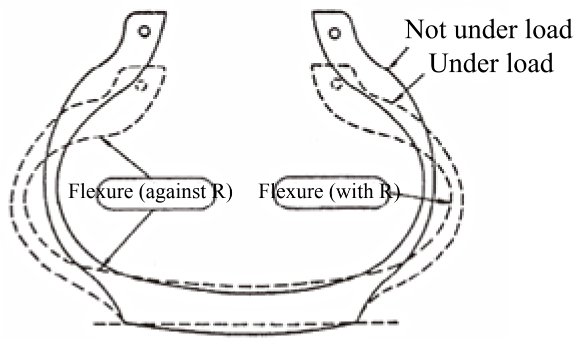


Fig. 6.2. Change in Tyre Shape When Under Load [1)]

(ii) Dynamic Strain [1)]

When a tyre is made to roll under load, the formerly solid torus shape is pressed against a plane at the part in contact with the ground. Viewed from either the cross-section or the circumference of the tyre, the curvature of the tyre wall changes shape and flexural strain occurs. In other words, it changes from the shape it had with only internal pressure applied to it. According to the cross-sectional diagram in Fig. 6.2, the side area is subjected to flexure in a direction that reduces the curvature R of the flexure, but in other areas (the crown, buttress and bead areas), the tyre is bent in a direction that increase the existing curvature R.

In the circumferential direction, the start and end of the area in contact with the ground are pressed by the surface of the road and a change in shape occurs, reducing R. This kind of flexural strain causes intensive strain on the ends of the belt and the folded edges of the bead, in the same way that the cord and rubber are of course subjected to stretching and compressive strain. Micro strains also occur, affecting the adhesion of the boundary layer between the rubber and the cord.

While the vertical and horizontal external forces acting on the tyre, namely, driving, braking and cornering forces, all incur strain, the lateral forces are particularly impacting. Fig. 6.3 represents this situation. The belt of a radial tyre is subjected to in-plane flexure from lateral forces; it is subject to stretching strain externally and subject to compressive strain internally. The edge of the radial tyre belt is faced with very harsh conditions, being subjected to overlapping strain from internal inflation pressure, strain under load and strain from lateral forces.

As seen from Fig. 6.3, compressive strain and stretching strain occur directly below the load, particularly when the belt is subjected to lateral deformation. This means that cracks are likely to occur when steel cord is present in the rubber at the edge, such as in the belt.

The belt edges in radial tyres are exposed to harsh conditions, being subject to overlapping strain from internal inflation pressure, strain under load and strain from lateral forces (see Fig. 6.4). In other words, easing the strain on the ends of radial tyre belts to prevent separation is an important durability factor.

With the transition to radial tyres, it has become a vital issue to prevent separation at the ends of highly structured reinforcing materials such as steel cord.

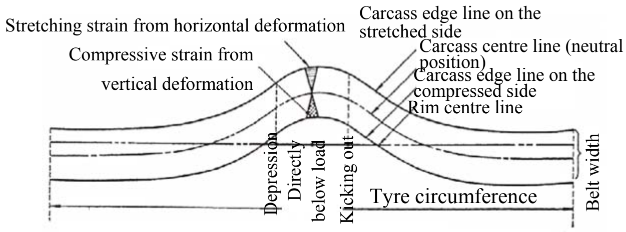


Fig. 6.3. Projected Diagram of the Change in Horizontal Shape of a Radial Tyre Belt and the Accompanying Stretching and Compressive Strain on the Belt Edge [1)]

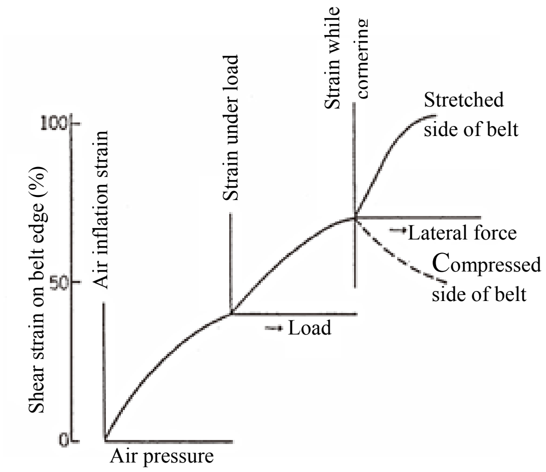


Fig. 6.4. Shear Strain on Belt Edge Generated While Cornering [1)]

6.1.2. Durability During the Transition to Radial Tyres

In terms of the factors that affected tyre durability in the time of transition to radial tyres, the major changes were the switch in structure from bias to radial and the use of steel cord as a belt material. (Of course, fibre textile cords were also produced for a while, but steel radial tyres gradually became the norm.)

The use of steel cord in the belt area of radial tyres led to a susceptibility to breakdown due to stress concentration in the boundary layer between the rubber and the steel cord, particularly at the edges of the belt, as mentioned above, due to differences in stiffness (by four digits on Young's modulus) between steel cord and the rubber used in the belt covering the steel cord (see Table 6.1). Durability is based on the breakdown phenomenon; breakdowns often start from microscopic defects, expanding from that point and developing into major breakdowns. Belt edges in particular are free ends and so are susceptible to cracking (edge separation). Withstanding breakdown around the steel cord is required as a basic performance factor.

Table 6.1. Comparison of Various Substances on Young's Modulus of Elasticity [17)]

Comparison of Various Substances on Young's Modulus of Elasticity Unit N/m^2 (Newtons per square metre) (multiplied by 10-7 to give approximate kgf/mm^2)	
Substance	$Ex10^{10}$
Iron	20-22
Copper	13
Aluminium	7
Lead	1.6
Wood (oak)	1.3
Glass	7-8
Polystyrene	0.38
Nylon 66	0.36
Polyethylene	0.076
Elastic rubber	$(1.5\text{-}5.0)x10^{-4}$

Durability using steel cord depended on the durability of the rubber coating to withstand stress concentration and the adhesion between the steel cord and the rubber.

Accordingly, let us discuss the durability of the rubber and the durability of the adhesion between the steel cord and the rubber. Generally, rubber loses its strength due to fatigue deterioration and heat deterioration as it runs. If it were to come under significant stress in that state, the rubber layer would break and the tyre would break down.

(1) Breakdown Due to Ageing of the Rubber Layer

The rubber covering the steel cord differs from ordinary rubber in that it has a higher sulphur content. Where ordinary rubber has a sulphur content of 1-2 parts per hundred rubber (phr), this covering rubber has a higher blend of 3-6 parts phr to make it adhere to the steel cord. This is because higher sulphur blends are better at adhering to steel cord. However, the higher the sulphur content, the more quickly the rubber ages. Also, the higher the heat to which it is exposed, the quicker the speed of the ageing. Since the onset of globalisation means that the same tyres are used throughout the world, there is a significant increase in the usage temperature range between hotter countries and colder countries from what there used to be. Age and deterioration happen more quickly in warmer regions. Generally, once the rubber ages, it becomes hard and its breaking elongation decreases. If there is a significant decrease in breaking elongation, the rubber can no longer handle deformation and the tyre breaks down. In this sense, how hard the rubber is during use and how much the stretch has decreased is an important factor in its durability. This is particularly important in high-sulphur blending.

This relationship has been the subject of much recent research. Fig. 6.5 below shows the state of ageing rubber.

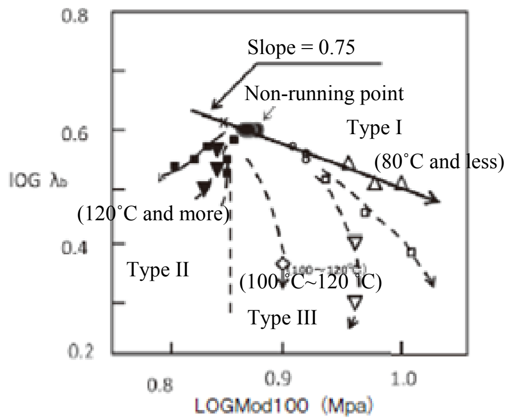
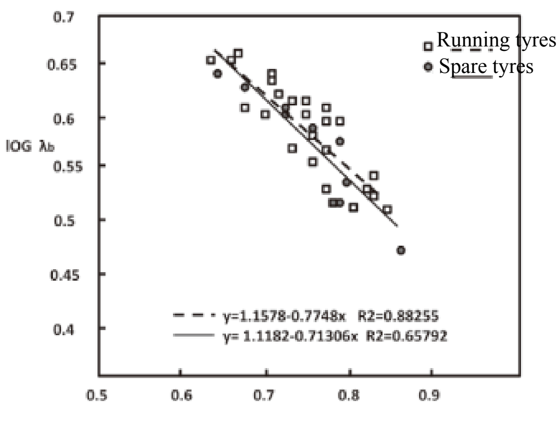


Fig. 6.5. Changes in Physical Properties (Modulus; 100% Mod.) During Rubber Ageing and Correlation to Breaking Elongation λ_b [2)]

The vertical axis in this chart represents the breaking elongation logarithm ($\log \lambda_b$) of rubber, while the horizontal axis represents the rigidity modulus (100% Mod) logarithm (Ahagon plot). Generally, the elongation decreases linearly with processing time, but if the processing heat is 80˚C or higher, the line moves by -0.75 (Type I on the chart). This indicates that as cross-linking continues, breaking elongation decreases. Further, as processing temperature increases, the slope of the line increases (Type III on the chart). Type III occurs in the range of 80˚C or over up to 120˚C. While rigidity does not increase in this range, breaking elongation decreases. This indicates that elongation decreases more than through the advancement of cross-linking; the main polymer chains being severed. In other words, there is a great decrease in break elongation compared to the amount of Mod change. When the amount of sulphur in the rubber increases, ageing becomes faster; consequently, the straight-line decrease speed increases. When it drops below a certain breaking elongation, there is an increased rate of tyre breakdown. Consequently, with high sulphur blends it is important to see how slowly they change; each company has its own special approaches to blending. Fig. 6.6 shows the results for actual cars on the market. Here, the elongation logarithm and Mod logarithm are over -0.75. Running tyres and spare tyres (not running) are shown on the same line, showing that heat has a major impact [3]. This method has made much recent progress as a measurable method of evaluating rubber durability, both for material in the laboratory and for rubber from actual car tyres. Type II is for cases of even higher temperatures.



LOGMod 100 (Mpa)

Fig. 6.6. Changes in Physical Properties for Cars on the Market [3]

6.1.3. Decrease in Durability Due to Deterioration of Adhesion Between the Steel Cord and the Rubber

Breakdown of tyres due to poor adhesion between composite layers of different materials such as fibre and rubber, steel cord and rubber has become a major issue.

In such cases, the area causing the breakdown is such a small area volumetrically, such as the reaction layer in the adhesive interface, that the phenomenon occurs discontinuously, but it causes major damage when it does happen. As the tyre runs, the bonding layer and reaction layer in the adhesive interface deteriorate and weaken, resulting in breakdown at some point in time. This deterioration is intensified by heat, moisture or a combination of both.

The steel cord and rubber are fastened together by means of a surface brass plating (copper (Cu) and zinc (Zn) alloy). When the tyre is vulcanised (heated), the copper (Cu) in the plating and the sulphur (S) blended into the rubber (or other intermediary products containing sulphur) undergo a chemical reaction, producing copper sulphide (CuxS (where x = 1 ~ 2; either copper (I) sulphide or copper (II) sulphide), zinc sulphide (ZnS), zinc oxide (ZnO), etc., while the sulphur (S) bonds with the rubber molecules, forming an adhesion between the steel and the rubber.

If the plating is thick or has a high proportion of copper (Cu), the presence of moisture promotes the production of CuxS, ZnS and ZnO, hindering adhesion due to a thick layer of brittle reaction products. If moisture penetrates during initial assessment (directly after vulcanisation) or during usage, the reactivity of the plating becomes less than optimal. While copper levels of around 70% are better for initial adhesion, lower copper levels of around 63-65% are better if moisture is present. Breakdown of adhesion occurs more often within the layer if the reaction layer is thick, such as in the model adhesion interface shown in Fig. 6.7.

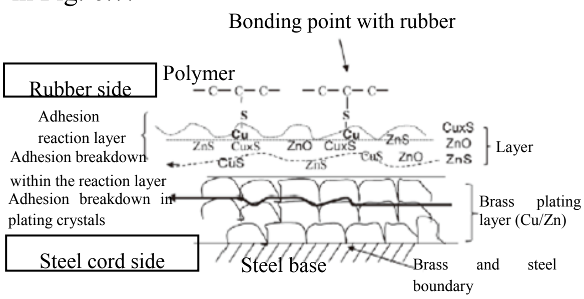


Fig. 6.7. Diagram of a Model Adhesion Interface

This figure is a combination of plausible models based on theories by van Ooij [4) 7)], Mori [10)], Pankaj [9)], Lievens [8)], Ishikawa [5) 6)] and others. As shown in the figure, there are multiple areas for potential breakdown in the adhesion reaction layer; these breakdown areas differ according to the usage conditions.

According to Watanabe, market issues with tyre breakdowns occurred from 1973 to around 1976, with many tyre companies around the world encountering problems with belt separation (peeling around the belt area) caused by poor adhesion in steel radial tyres for passenger vehicles. The main cause of the poor adhesion was thought to be the adhesion accelerator in the rubber. Two types of adhesion accelerators were in use: cobalt (Co) fatty-acid based and RHS (blends of R: resorcinol, H: hexamethylenetetramine and sometimes S: silica) based. Since the problematic brands of tyres more commonly used RHS based accelerators, this was thought to be the main cause of the issue. As later data was taken into consideration, the main culprit was found to be the over-reactivity of the plating, with the accelerators an accessory at most [16)]. The Cu/Zn plating at the time almost certainly had a 70% copper proportion; this would have had a markedly higher reactivity than the 63-64% proportion of today.

As shown in Fig. 6.7 above, the over-reactivity would have produced a thicker reaction layer, with breakdowns occurring both in the reaction layer and in the plating. This serious problem with steel radial tyres has now been almost completely resolved, through much effort.

Generally speaking, breakdowns in steel radial tyres commonly start at the belt edges. The most common direction of travel of the breakdown is shown in Fig. 6.8. Breakdown begins at the belt edge (i.e., the end of the steel cord) and progresses from there.

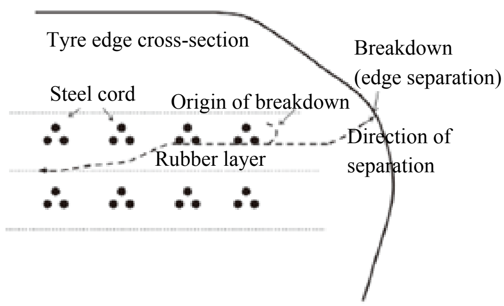


Fig. 6.8. Model Breakdown of Belt Edge

6.1.4. Organic Fibre Cord Adhesion and Fatigue Deterioration

While steel cord is used in the belts of radial passenger vehicle tyres, polyester or rayon are often used in the carcasses. Recently, nylon has also often been used as a covering material over the belt. In heavy vehicles (trucks and buses), it is common to use steel cord for both the belt and the carcass.

Carcass Adhesion

Polyester

Since this fibre has poor chemical reactivity on the surface and does not adequately adhere with RFL, it is treated with either (1) a two-bath method in which the surface is treated with epoxy and then with RFL, or (2) a one-bath method in which a special adhesive is added to RFL liquid and blends with the surface of the polyester (see Fig. 6.9).

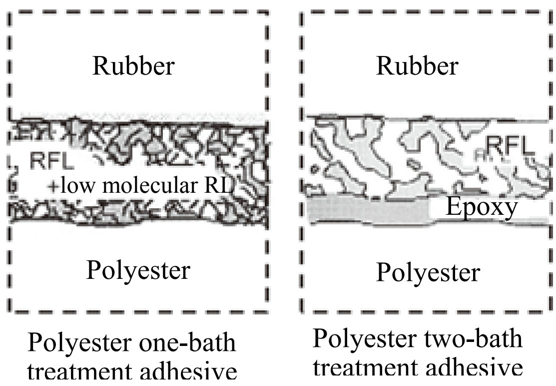


Fig. 6.9. Model Adhesion Mechanisms [11)]

6.1.5. Deterioration in Place Other than Around the Belt

Fatigue deterioration also occurs in rubber outside of the belt area. For each revolution the tyre makes, the entire area around the circumference of the tyre comes into contact with the ground each time, at which point the entire tread area moves against the ground, experiences fatigue and is worn away, albeit by a very tiny amount each time. The carcass is subjected to bending and deflects, while fluctuations in the tensile strength of the cord within the carcass cause repeated shear strain in the rubber layers between the ply.

Under this behaviour, heat is generated throughout the tyre, which is subjected to repeated deformation due to hysteresis loss; this heat gradually builds up. As a result, the entire tyre increases in temperature. Temperature increase has a doubly negative impact on the lifespan of the tyre.

The first negative impact is that as the temperature rises, the materials from which the tyre is composed are subjected to high temperature, which reduces the lifespan of the tyre. The second negative impact is that with continued high temperature, the tyre materials gradually deteriorate through fatigue. On one hand, the tyre is gradually losing its tread rubber; on the other hand, it is losing overall strength due to high temperature and fatigue.

As mentioned above, usage temperature is important for durability. The following are some considerations on usage temperature.

1. Rubber decreases in strength under high temperatures

2. Rubber ages more quickly under high temperatures, meaning its strength and breaking elongation decrease more quickly

Rubber naturally decreases in strength and deteriorates more when exposed to high temperature. This means that tyres must have a greater breadth of heat tolerance now that they are used throughout the world compared to when they were only used domestically. In other words, the scope of performance for use in just one country is no longer enough; tyres need a greater range of durability. In high temperature regions, there was often trouble with accelerated deterioration due to heat; it took time to resolve this.

6.1.6. Accidental Tyre Failure

(1) Cut Burst and Shock Burst

A cut burst is a burst caused by a stone or similar severing the cord and the tyre no longer being able to contain the air pressure. A shock burst is a burst caused by a significant force on the cord, such as an impact from travelling over a bump, and the cord layer breaking down without being severed.

Usually these occur on unpaved roads, but even on paved roads a tyre can run over an obstacle such as stone and, enveloping it, deform. If the obstacle is small, then the tread rubber can form a localised deformation around it, but if it is larger, even the carcass could deform around it. The tyre is affected by the size, shape and surface friction coefficient of the obstacle, which alters the degree of stress concentration, deformation, impact resistance and other factors applied to the tyre, depending on the level of air pressure in the tyre, the strength of the carcass, running speed and other conditions. This occurs in dump trucks, construction machinery and other vehicles currently running on unpaved roads.

6.1.7. Wear Resistance

As the tyre runs, the surface is worn away. The phenomenon of wear on the tread is extremely complex, as it varies according to many different contributing factors. Broadly speaking, however, it depends on the friction force on the wheel tread. A tyre travelling at a fixed speed without any accelerating/decelerating, cornering or other major friction on the tread incurs hardly any wear. In other words, the greater the friction force on the tread and the road surface, the greater the susceptibility to wear. The difference in wear life between vehicles is given as follows [12].

Approximate Wear Life Values [12]

	Category	Wear Life
Steel radial tyres for passenger vehicles	General purpose tyre	30,000-60,000km
	High performance tyre	20,000-30,000km
Steel radial tyres for trucks and buses	Transport truck	200,000-300,000km
	Bus	100,000-200,000km
	Dump truck	50,000-100,000km

The main causes of significant friction between tyres and the road surface are (1) accelerating/decelerating and (2) cornering (turning).

(1) Subjected to Acceleration/Deceleration

The distribution of contact pressure along the circumference of the tyre is shown in Figs. 6.10 and 6.11.

These figures indicate that the higher the load, the higher the contact pressure at both ends. Fig. 6.11 indicates that high contact pressure occurs during acceleration/deceleration in the longitudinal direction (fore-and-aft direction) when it is pressing in or pressing out. When the tyre is accelerating/decelerating, the entire tyre slips. The surface of the tread has traction areas and smooth areas; these are caused by wear.

In an extreme situation, such as the tyres locking and being dragged along, or the tyres are spinning, there are no traction areas. Wear on the tyre occurs on the smooth areas. Accordingly, conditions that increase the smooth areas, such as acceleration or sudden braking, make the wear on the tyre markedly prominent.

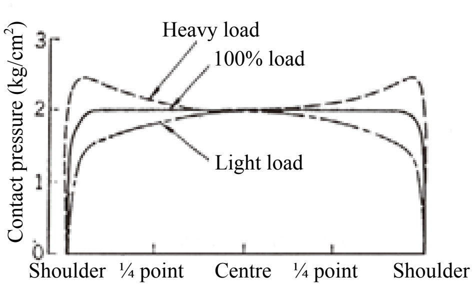


Fig. 6.10. Characteristics of Contact Pressure in Passenger Vehicle Tyres [13)]

(Horizontal) schematic view (the shoulder area is lower under lighter loads and higher under heavier loads)

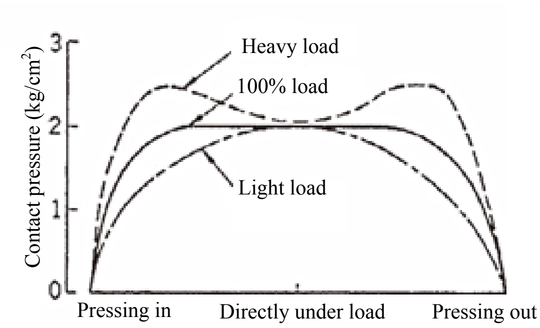


Fig. 6.11. Characteristics of Contact Pressure in Passenger Vehicle Tyres [13)]

(Horizontal) schematic view (the area directly after pressing in and directly before pressing out is lower under lighter loads and higher under heavier loads)

(2) Subjected to Lateral Forces Due to Cornering

When a car takes a corner while moving forward, the tyres slip sideways and lateral force is produced to counter the centrifugal force. Away from the contact surface, the lateral force is of course 0, but within the contact surface there is a disconnect between the direction of travel of the tyres and the surface of revolution due to the slip angle and the centre lines of these two factors separate. To begin with, the tread gains traction on the road surface and there is no relative displacement between it and the road surface. As the deformation of the tyre increases and the rightening force increases, the adhesive force between the tread and the road surface cannot be maintained and the tread starts to slip. At the rear end of the contact area, the carcass centre and the tread centre line up (see Fig. 6.12). This action is repeated at every point on the circumference of the tyre. Wear on the tyre is generated is the slip areas. The further the steering wheel is turned, the greater the slip angle, which increases the lateral force and also increases the wear on the tyres.

As this wear progresses, the pattern eventually disappears. It is desirable that the tyre fulfils its lifespan without the case, which is the skeletal structure comprising the belt and carcass, breaking down.

Since tyres are principally made of rubber, it should be possible to predict reasonable limits with an understanding of the stresses applied to each area. However, the rubber and the fibre are both high molecular substances and are subject to thermal and mechanical strength loss and fatigue deterioration due to increases in temperature from dynamic deformation as well as repeated mechanical loading; determining the allowable stresses is not straightforward.

Technology related to wear has mostly addressed the wear itself, involving developments to improve the constitution of materials, while irregular wear that involves partial wearing has largely been dealt with by measures taken in structural design.

Wear-related mechanisms are extremely complex and quite difficult to assess. Throughout the long history of tyre technology, this is one area that remains to be resolved. While various wear evaluating machines have been developed for use in laboratories in Japan and around the world, these are by no means conclusive.

Radial tyre durability is a major issue. In particular, the trouble with adhesion between the steel cord and the rubber has been a major problem worldwide. Many researchers have devoted much research into solving this.

6.1.8. Run-Flat Tyres

A New Proposal for Durability

Countermeasures against incidents such as punctures have always been considered with driver safety as an underlying issue

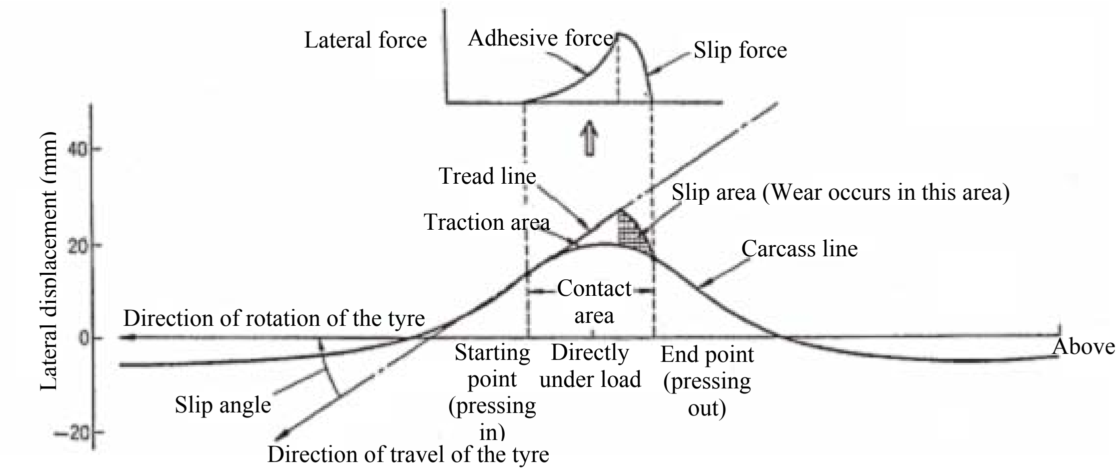


Fig. 6.12. Schematic Diagram of Lateral Deformation and Lateral Force Distribution on a Tyre While Cornering [14]

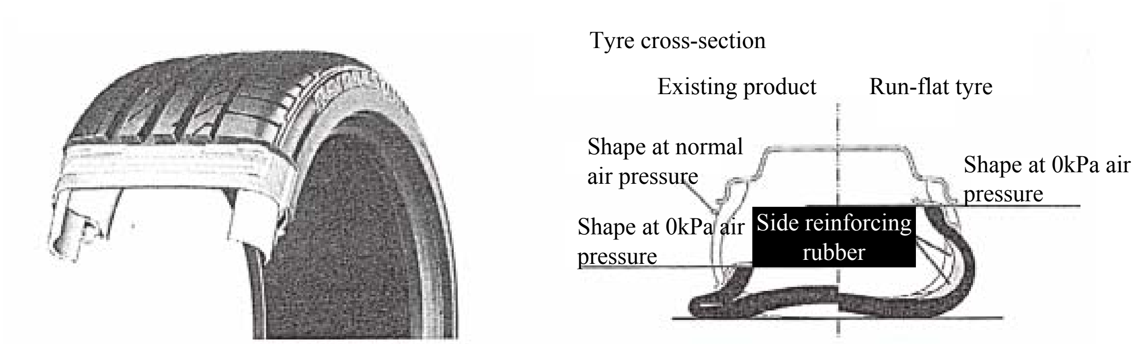


Fig. 6.13. Run-Flat Tyre [15)]

Run-flat tyres are tyres that can travel temporarily even with air pressure at 0 (see Fig. 6.13). This is made possible by means of side reinforcing rubber fitted into the inner tyre structure. While this method increases the weight of each tyre by the amount of reinforcing rubber used, the overall weight of the vehicle decreases as it does not require a spare tyre. There is also a significant benefit to the user in that not carrying a spare tyre means more space inside the vehicle.

6.1.9. Summary

As discussed above, the issue of durability is not unique to Japan alone. Accordingly, the countermeasures are not uniquely Japanese technology. Japanese technology in this area includes: (i) progress on the countermeasures against the significant problem of steel adhesion (of course, this happened in other countries as well); (ii) the proposal of the predominance of a rubber deterioration evaluation method (Ahagon plot); and (iii) progress on run-flat tyres, among others.

Durability is not an issue that changes with the demands of the times; it must of course be maintained. It is vital in the environmental age to prolong the lifespan of tyres; while it is not at the obvious forefront of performance, it is growing in importance.

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6.2. The Age of Manoevrability: The Coming of Age of Radial Tyres in the Age of Manoeuvrability

6.2.1. Rubber Development for Rolling Resistance

Since radial tyres are made using steel cord, which is quite a different material from rubber, poor adhesion made for significant durability issues. Many researchers worked to overcome this issue. The time that followed, from the 1980s onwards, was the age of manoeuvrability. It was from around this time that distinctly Japanese tyre products and technology began to emerge. Looking back at the course of tyre technology in the post-war era before that, it was a time of incorporating and learning overseas technology: overseas technology adopted after the war, new materials and new structures, the shift from bias to radial and the shift from tube to tubeless. In the new era, Japan made huge contributions by using its own technology to make fine optimisations.

Many design elements related to durability were material factors rather than structural design factors. However, manoeuvrability not only incorporates material elements such as rolling resistance (fuel consumption) and friction (grip), but also structural design elements for cornering performance, such as stability and controllability. In other words, manoeuvrability is an area encompassing both material factors and structural design factors.

(1) Contribution of Rubber to Rolling Resistance

As the rolling resistance of a tyre decreases, fuel consumption improves. In the environmental age, there is a demand to reduce rolling resistance to improve fuel consumption. The contribution of each part of the tyre to rolling resistance is as shown in the following figure. Since tread contributes half of the total, countermeasures have been focused on tread.

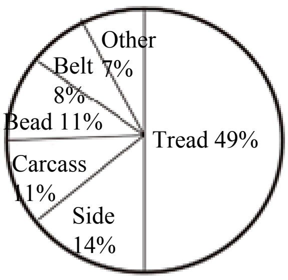

Fig. 6.14. Proportion of Contribution made by Each Part of a Tyre to Rolling Resistance [1] (according to the finite element method)

Accordingly, tread rubber has become important to developments related to rolling resistance. That is to say, a demand has grown for low energy loss materials to be used in tread rubber.

On the other hand, high energy loss is required for proper braking performance on wet roads and similar. Consequently, if low energy loss rubber were to be used in place of existing tyre rubber, braking performance would decrease. In other words, there is a trade-off in which the energy loss has to be as low as possible while running and as high as possible while braking.

From the perspective of tread rubber, braking performance is the issue of friction between the road surface and the tyre tread. Thus, let us consider rubber friction.

(2) Rubber Friction

The phenomenon of friction between rubber and a solid surface differs completely from that of friction between ordinary solid surfaces. Rubber has a friction coefficient that decreases as the contact pressure increases; it also relates to the relative sliding velocity and temperature. The friction coefficient is greatest when sliding at a relatively slow velocity rather than in a state of rest.

Fig. 6.15 shows a model of friction.

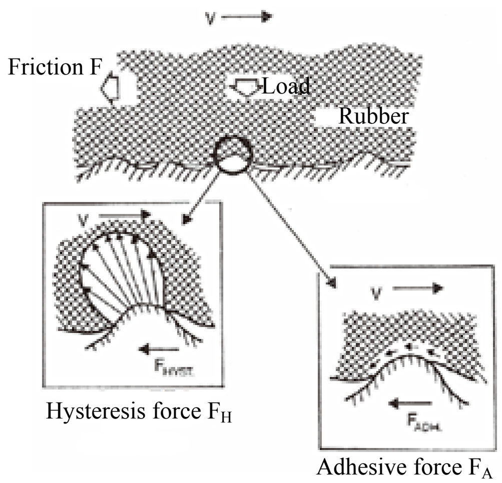

Fig. 6.15. Factors in Rubber Friction [3]

When a rubber mass presses against another solid mass under normal force and slides along the interface, an adhesive force acts between the masses through molecular attraction on the contact surface and resists sliding. If the surface of the solid mass is uneven, the rubber tries to fill out the unevenness by compressive deformation because of its low elasticity. Consequently, when sliding occurs along the interface, the areas on the rubber colliding with the convex areas on the solid surface are subjected to compression; when it encounters the other side of the convex areas or the concave areas, the rubber is released from that compression or stretches the opposite way. The difference in deformation energy coming and going through localised repetition, that is, hysteresis loss, acts as friction and is consumed in the form of heat energy; the corresponding frictional force acts on the interface.

In other words, total friction = hysteresis force (F_H) + adhesive force (F_A). Some friction, particularly Wet μ (friction coefficient of a wet road surface), has a very high hysteresis loss effect. Hysteresis friction is dependent on the viscoelastic properties of the rubber, such as its tan δ (hysteresis element; the tangent of the phase difference δ between vibration stress and vibration strain) and E' (modulus of elasticity). The viscoelastic property is not fundamentally a breakdown phenomenon, but rather a response to the strain (deformation) that is repeatedly applied to the rubber; it depends on the properties of the overall volume rather than on the properties of miniscule areas. With consideration for blending compounds, the greater the volume of a compounding element in relation to the whole, the greater the impact of that element. Usually, in sequence of volume, the most used material is natural or synthetic raw rubber (polymer), followed by carbon black, silica or other reinforcing agents. Accordingly, in an age where manoeuvrability is in demand, development is focused on raw polymers and reinforcing agents.

The greater the friction force, the more difficult rolling becomes; the higher the resistance to the rolling of the tyre, the worse the fuel efficiency. Fuel efficiency and safety are mutually exclusive phenomena. In other words, as mentioned above, there is a trade-off between low rolling resistance (LRR) and friction (particularly wet friction). Easier rolling means harder stopping. Currently, it is increasingly more common to aim for both summer/winter performance (high grip in high or low temperature regions in wet or dry conditions) and LRR wear resistance. Achieving both low fuel consumption (low rolling resistance) and high braking performance (grip) has been a major topic of research addressed by many researchers since the 1980s.

The time-temperature superposition principle was used to solve this trade-off. This principle follows the idea that temperature and time can be transferred in high molecular substances; the physical properties at low temperatures correspond to high-speed (high frequency) deformation, while the physical properties at high temperatures correspond to low-speed (low frequency) deformation. The objective function uses tan δ, the delay function of the response to stimulus. Since the rolling resistance is the resistance acting every time the tyre rotates, it is the resistance against one deformation per rotation. This equates to a frequency of 10Hz (low speed). Meanwhile, braking (grip) incurs a reciprocating motion in which deformations are restored against protuberances in the surface of the road. In this case, as the tyre follows minor unevenness in the road surface, the speed of deformation/reformation against the unevenness falls between several tens of thousands to several million Hz (high speed). Accordingly, since rolling resistance corresponds to tan δ of high temperatures and grip corresponds to tan δ of low temperatures, they are generally measured as tan δ at 50-60˚C (rolling resistance) and tan δ at 0˚C (Wet grip), which quickly developed into a tan δ curve. See Fig. 6.16.

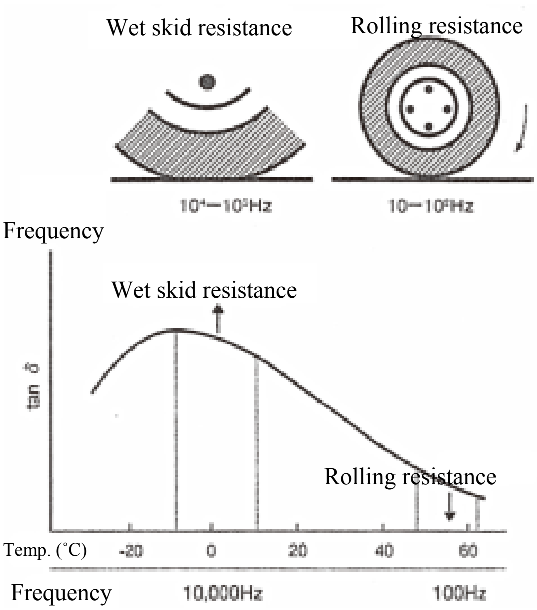

Fig. 6.16. Temperature and Frequency Dependency of tan δ and its Relationship to Required Tyre Properties [2)]

From the above, there is a need to reduce tan δ at 60˚C in order to reduce rolling resistance. To achieve this requires a low energy loss material. While using existing low energy loss tyre rubber such as natural rubber or polybutadiene (BR) rubber would lower tan δ at 60˚C, it would also lower tan δ at 0˚C. The peak of the tan δ curve lies at Tg (glass transition temperature; the temperature at which the rubber state starts to congeal into a glassy state). Consequently, if rubber with a high Tg is used, tan δ at 0˚C rises, but tan δ at 60˚C also rises. On the other hand, using a lower Tg, such as the aforementioned BR, lowers tan δ at 60˚C, but also lowers tan δ at 0˚C. SBR is often used to address both factors. While emulsion-SBR (E-SBR) (emulsion polymerisation; radical polymerisation) is generally used, another method is to use solution-SBR (S-SBR) (solution polymerisation; anionic polymerisation), which provides an even steeper tan δ curve at 0˚C and 60˚C (see Fig. 6.17).

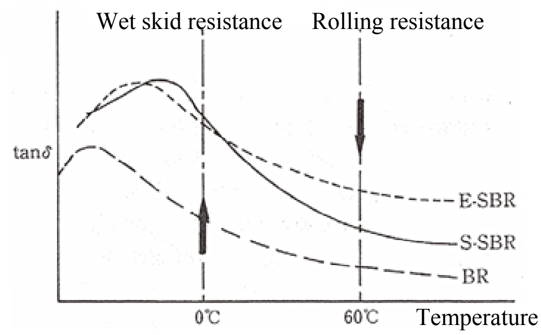

Fig. 6.17. Relationship between tan δ and Temperature for Various Kinds of Synthetic Rubber [6)]

Reducing the amount of carbon is another known method of steepening the tan δ curve that is widely used [5)].

(3) SBR plays a significant role in passenger vehicle tyres, such as in the development of

synthesis technology for passenger vehicle tyre rubber.

It has brought immeasurable diversity to rubber compounding. This is because SBR can be freely designed in terms of its microstructure, modification and other factors. Thus, SBR makes it possible to have a variety of molecular designs, ushering in an age of designer compounds through detailed molecular design in order to steepen the tan δ curve (1980s, see Fig. 6.18). The shift from radical polymerisation (emulsion polymerisation) to anionic polymerisation (solution polymerisation) during this time gave a greater degree of flexibility in molecular design, as follows.

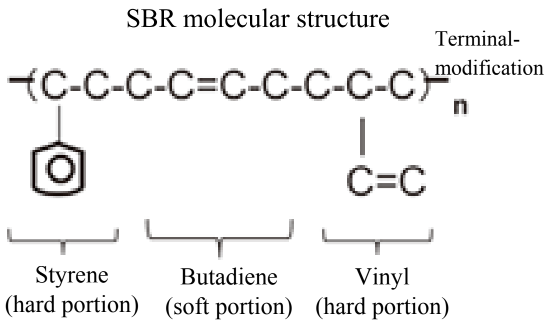

Fig. 6.18. SBR Microstructure

1. styrene content; 2. vinyl content; 3. molecular modification (terminal-modification); 4. molecule weight; 5. molecular weight distribution; 6. sequence distribution (styrene sequence distribution)

Since radical polymerisation allows for variation in styrene content, radical polymerisation could be used to control rolling resistance (fuel consumption) by using a low Tg polymer with a low styrene content; however, this also reduced tan δ near 0°C, meaning a decrease in Wet grip μ. The S-SBR (solution-polymerisation SBR) method was introduced as it offered a way to solve this trade-off using polymer molecular design. Incorporating molecular design with S-SBR made it possible to plan the tan δ curve. Acquisition of S-SBR technology and, by extension, terminal-modification technology, made a significant contribution to technology for reducing rolling resistance.

At this time, methods for steepening the tan δ curve were worked on together by researchers around the world. Tyre companies did not have their own individual theories. Competition focused on the different effects achieved through the choice of materials used and the mixing design.

During this time, Japan devoted much research to technology for optimising combinations. Japanese rubber technology made a significant contribution to this field. The two oil crises in the 1970s and later environmental issues resulted in the need for low fuel consumption, which in turn drove a flurry of research on modified SBR to improve fuel economy.

(4) Molecular Modification Technology

The catalyst for anionic polymerization is usually organolithium (alkyllithium; n-butylithium, etc.). Since these are living-polymerisable (the ends continue in a state of live catalytic activity during polymerisation), if polymerisation is not interrupted, it will continue its catalytic activity.

In binding mode, it is important to control the styrene content, which serves as a rigid element for modifying Tg, as well as the vinyl content (too much will raise the Tg). In anionic polymerization, the vinyl content can be controlled either by adding ether compounds, amine compounds (vinylation agents) or other compounds during polymerisation or by controlling the polymerisation temperature.

"Molecular terminal-modified rubber can be obtained by adding or reacting a modification agent to the active terminals at the final stage of anionic or living polymerization using alkyllithium as a medium, then stopping the reaction with ordinary methanol or similar. This binds with the surface of the carbon in the rubber, mutually binding carbon to carbon, thereby reducing the friction between carbons, lowering the tan δ and suppressing heat generation. N-alkyl benzophenones and N-alkyl lactams are effective modifiers." (Technology by Zeon Corporation et al. [8])

Further, during polymerisation, once 100% of the monomers have converted to polymers, it is possible to make use of the fact that the polymer terminals are active, adding tin, silicon or other halides or divinylbenzene to cause a coupling reaction and change the molecular weight distribution. This technology was largely researched and developed in Japan [9]. Fig. 6.19 shows a model of coupling and change in molecular weight distribution due to tin tetrachloride. (Technology based on Japan Synthetic Rubber, etc.)

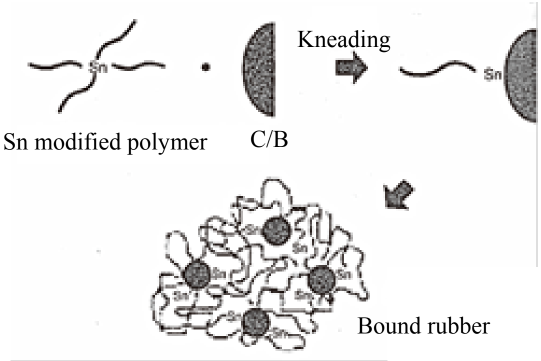

Fig. 6.19. Model of Improved Carbon Distribution with Sn Modified Polymer [9]

Modified polymer compounding techniques have become the axis of tread formulation for both fuel economy and wet grip. This technology was developed to provide a means of binding rubber molecules and carbon together to restrict free movement of the carbon, as the carbon/carbon friction needs to be reduced in order to lower the tan δ (reducing loss and heat generation) of carbon-containing rubber, as outlined above.

Accordingly, as discussed above, much research was devoted to technology that would introduce a functional group with affinity for carbon at the middle of the polymer and at the terminals. Noguchi [7], Nagata [8], Ohshima [12], Tsutsumi [13] and other researchers confirmed the effect of polymer terminal modification on lowering rolling resistance. As shown in Fig. 6.19, the idea was to efficiently modify the polymer terminals and increase the affinity of the polymer terminals to carbon. In any case, the idea was to reduce the main viscosity factor by removing the free terminals. Many patent applications have also been made in relation to this [14].

(5) The Age of Silica

Since 1990, an increasing amount of technology has switched some of the carbon for silica, for the purposes of both fuel economy and wet skid performance. Silica has a hydrophilic silanol surface, which makes it difficult to disperse through rubber and prone to clumping. Consequently, it is more difficult than carbon to distribute evenly throughout the rubber. To assist with this, a silane coupling agent is used to alter the surface of the silica, which improves its dispersion and also causes a reaction between the silica and the rubber to form a bond (primary bond). A lower rolling resistance is obtained by effectively reducing the heat generation caused by contact between silica. This method means the rubber is more rubbery, which gives tan δ a higher peak; it also raises tan δ at 0˚C from the perspective of Tg, which means that silica provides a steeper tan δ curve than carbon, improving both the rolling resistance and the wet grip at the same time. Fig. 6.20 shows a comparison of the viscoelastic properties of materials made from carbon compounds and from silica compounds.

Research has also continued on the viscoelasticity of silica [10]. Its use has expanded throughout the world since the early 1990s, when Michelin announced its use in green tyres. It also grew rapidly in popularity due to its conformity to environmental measures (reduced CO_2 due to lower fuel consumption). Many researchers have contributed research in relation to this [15) 16) 17) 18)]. Much research has also been carried out around the world on low-temperature kneading processes, because the silane coupling agent used has a cross-linking reagent structure and if it gets too hot during mixing it will react and become solidified (burning). To suppress this reaction, it was found that a mixer with a mesh rotor had a better cooling effect than existing mixers, so silica mixers are being switched to this type [10) 11)].

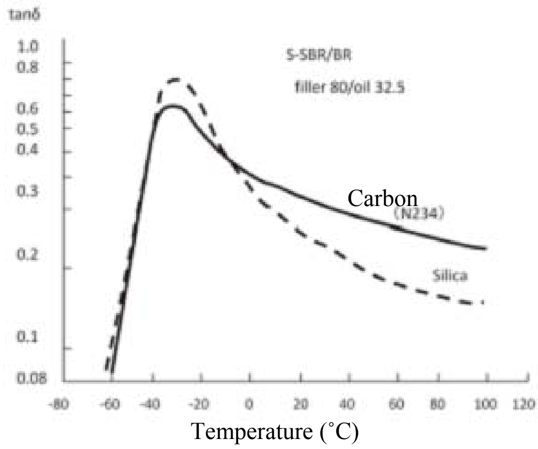

Fig. 6.20. Temperature Dependency of tan δ of Carbon and Silica [4)]

5% DSA 10Hz carbon; N234 silica (+TESPT; coupling agent) base mixture; S-SBR (high vinyl SBR75/BR25) filler 80 phr oil 32.5

(6) Silica Modification Technology [19)]

Technology was also developed to modify polymers to facilitate the bond with silica, like the bond between carbon and polymers.

(i) Modification for Silica

Research to introduce a functional group to SBR that would mutually interact or bond with silica particles resulted in the development of typical modified SBRs for blending with silica, such as diglycidyl amine compounds, cyclic imine compounds, halogenated alkoxysilane compounds at the living terminal or alkoxy-modified SBR. SBR with terminals processed by this functional group are confirmed to have an increased tan δ at 0˚C and a decrease at 50-60˚C [20].

Fig. 6.21 below shows the effect of modified polymer rubber on tan δ at 0˚C and at 50˚C. The effect of both terminal modifier processes is clearly seen against the unreacted substance [20].

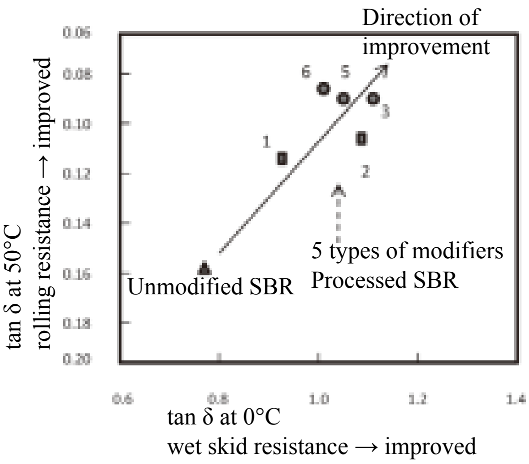

Fig. 6.21. Improved Fuel Economy and Wet Grip Performance of Various Kinds of Modified SBR [20]

This figure shows that SBR modified by reacting with a modifier by anionic polymerisation has a stronger mutual interaction with the silica, with better distribution of the silica particles. At present, the most effective method is a combination of switching carbon for silica and modifying the SBR. Fig. 6.22 shows a model of how these affect tan δ.

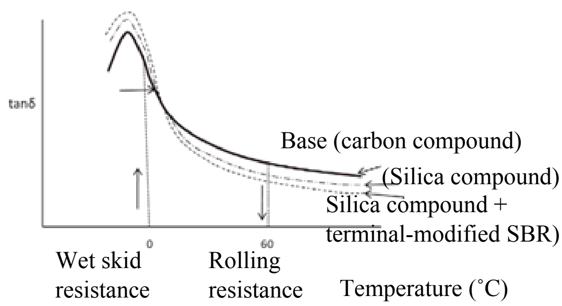

Fig. 6.22. Changes in tan δ Curve (Model) from Carbon Compounds → Silica Compounds → Modified Silica Compounds

Many patent applications for modifying polymers for silica have been filed from Japan [19].

It is fair to say that Japan was demonstrating its prowess in the technology at the time, particularly in terminal modification technology as a means of intricate mixing design. While the epoch-making technology of compounding solution-polymerised SBR and using silica did not originate in Japan, Japan was very quick in developing, optimising and implementing it.

6.2.2. Structural Design Elements for Manoeuvrability

(1) The Effect of Aspect Ratio

As the transition to radial tyres progressed, tyres with a low aspect ratio became more popular, particularly for high performance tyres, in order to improve manoeuvrability. All tyres came to adopt a lower aspect ratio, even non-high-performance tyres, as the wider width and lower height gave them better manoeuvrability (Fig. 6.23 (A) (B)).

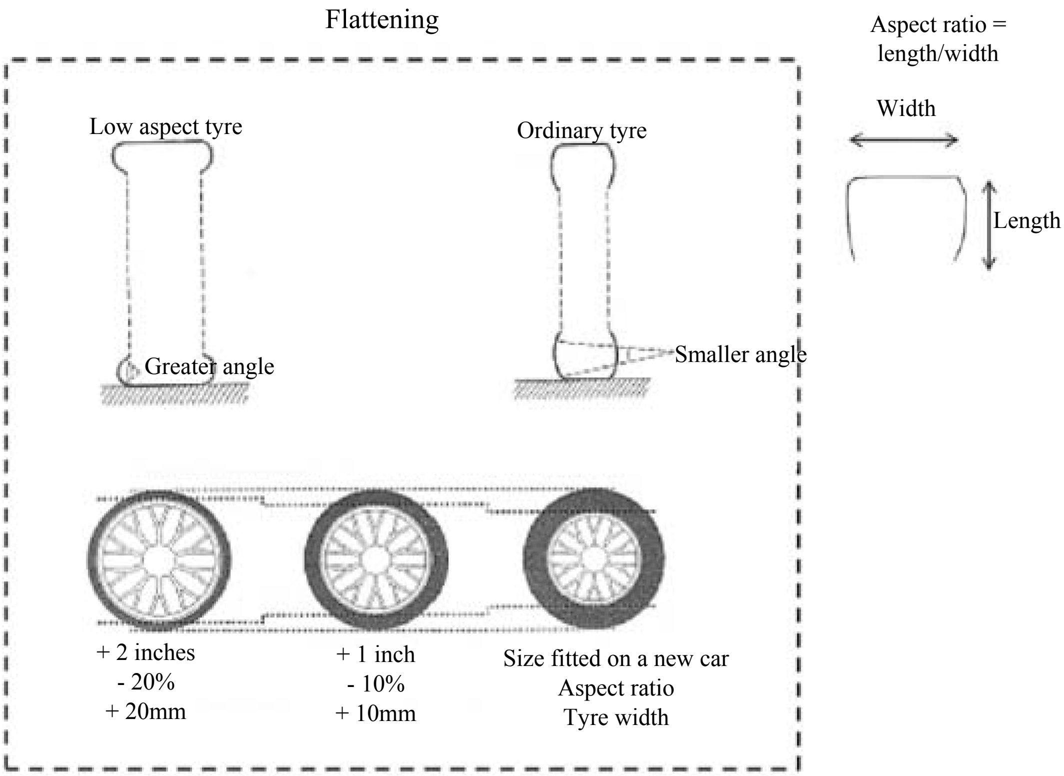

Fig. 6.23 (A) Effect of Aspect Ratio [21)]

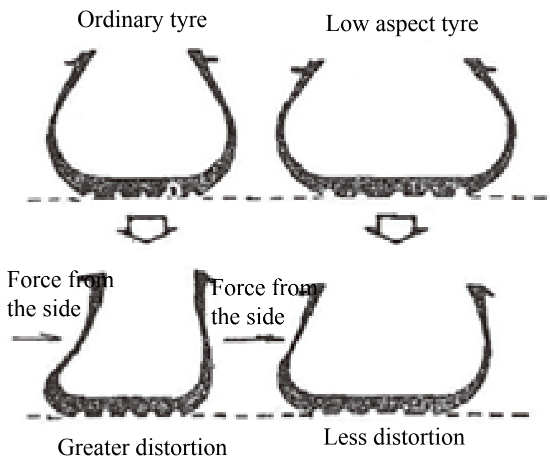

Fig. 6.23 (B) Structural Change due to a Lower Aspect Ratio [21)]

Flattening the cross-sectional shape of the tyre results in tyres with wider tread, producing greater cornering force. This is due to greater flexural rigidity of the tread, since the width of the belt area increases in accordance with the tread width. The cornering power (the slope of the straight line section of the cornering force) also increases.

Fig. 6.24 below shows aspect ratio and cornering power. The smaller the aspect ratio, the greater the cornering power. This gives the driver a sense of agility in the operation of the steering wheel while driving.

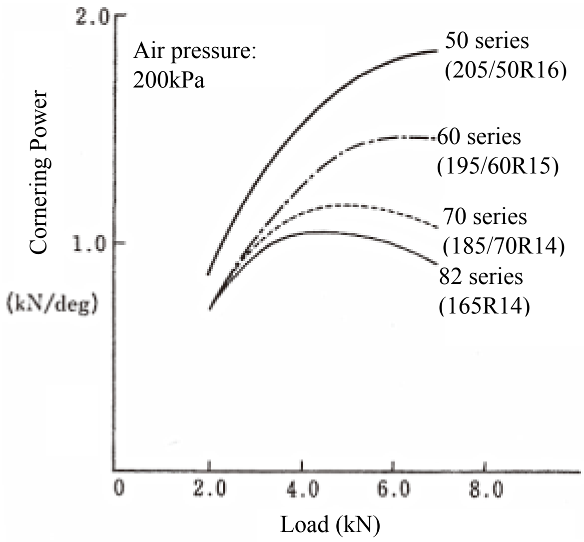

Fig. 6.24. Tyre Aspect Ratio and Cornering Power [22)]

Sports cars and other high performance vehicles are fitted with 50 series, 40 series and other tyres with a lower aspect ratio, as they require greater turning power, not only while turning at high speed, but also while travelling straight. A lower aspect ratio means a larger rim diameter for the same outer diameter, which means larger brake discs and other fittings can be fitted, which has the advantage of being good for braking performance. In review, developments in manoeuvrability performance are a combination of material development in the form of controlling viscoelasticity and structural development in the form of ratio flattening. In other words, this aspect of tyre technology development encompasses both materials and structure. Japan's contribution to tyre development prompted development in the high-performance tyre category, making advances in tyre flattening. However, tyre flattening brought with it a new problem: poor fuel economy.

As discussed in this section, while developments in manoeuvrability performance such as silica technology and anionic polymerization did not originate in Japan, Japan did absorb the technology and added to it in areas such as terminal modification, which made Japanese tyres world class.

In particular, there were major developments in polymerisation technology among polymer manufacturers. The material and structural designs of the time indicate that the level of technology was rapidly increasing, particularly among Japanese tyre manufacturers, who were becoming more well-balanced in all areas of performance.

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Abbreviations: Zeon: Nippon Zeon; BS: Bridgestone; JSR: Japan Synthetic Rubber; Sumitomo: Sumitomo Rubber; Yokohama: Yokohama Rubber Company; Toyo: Toyo Rubber; Ube: Ube Industries.

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Abbreviations: BS: Bridgestone; JSR: Japan Synthetic Rubber; Sumitomo: Sumitomo Rubber; Yokohama: Yokohama Rubber Company.

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6.3. The Age of Sensation and Sensitivity: The Coming of Age of Radial Tyres in the Age of Sensation and Sensitivity

6.3.1. Perception of the Times in the Age of Sensation and Sensitivity

The course of development of radial tyres discussed in the preceding sections has seen some remarkable progress, with a wealth of research resulting in significant improvements in durability, rolling resistance (fuel economy) and aspects of manoeuvrability, such as friction against the road surface in relation to braking performance. Durability, rolling resistance and braking performance are essential to the operation of the vehicle. There are also various other non-essential requirements, such as noise, vibration and ride comfort. While these are not as essential as durability and aspects of manoeuvrability performance, such as running, stopping and turning, as society has matured, cars have also come of age. Tyres, too, have become high-performance items with elements of sensation and sensitivity to them now, in the sense of eliminating sources of discomfort. While there always was a demand for these performance requirements, they grew in importance once the other more essential performance factors had been achieved.

In recent years there has been a growing demand to remove sources of discomfort, namely noise, vibration and harshness (NVH). There are two sides to these discomfort factors: the noise, vibration and ride comfort experienced by those in the vehicle; and the discomfort factors (environmental issues) inflicted on society by the running of the vehicle, such as noise in the surrounding environment. Technological development has advanced on both fronts and the component technology can be said to have reached a high level. This relates to the increasing focus on fuel economy and other environmental issues as society has advanced.

With the advent of the age of sensation and sensitivity, recent development has taken the form of durability + manoeuvrability + sensation/sensitivity elements. Let us discuss the technology related to noise, vibration and ride comfort developed after the war.

(1) Multiplicity in the Age of Sensation and Sensitivity

The path from durability → manoeuvrability performance → sensation/sensitivity has been a road to diversification. A single tyre has to fulfil various functions at the same time, which means there are issues that are very difficult to resolve, since there are a number of trade-offs that must be both avoided and accommodated at once. From a tyre design element perspective, the necessary performances have increased, from durability → manoeuvrability performance → sensation/sensitivity. According to this trend, there has been a shift in relative importance from material factors to structural factors. This relationship is shown as follows.

Target performance:	Durability	→	Manoeuvrability	→	Sensation/Sensitivity
(element)	(material)		(material/structural design)		(structural design)

Since we have entered an age of seeking relative comfort, the sensation/sensitivity factor has grown in importance. This has been reflected in the amount of research from many angles on tyres as transmitters of vibration. This is the age of learning how to control the physical viscoelastic properties of fibre reinforced rubber (FRR). Various studies have been carried out from that perspective with the aim of reducing discomfort.

(2) Vibration / Ride Comfort

While the noise, vibration and ride comfort experienced by those in the vehicle as well as the discomfort factors (environmental issues) inflicted on society by the running of the vehicle, such as noise in the surrounding environment, are both factors for consideration, let us examine harshness and road noise as sources of noise and vibration experienced by vehicle passengers.

(i) Harshness

Since radial tyres have a large, rigid belt, they are less able to encompass protuberances on the road surface (enveloping power) and are susceptible to joint shock (running over joins). In this respect, radial tyres offer poor ride comfort.

When travelling over uneven areas on road surfaces, such as joins and bumps, the shock vibration and noise are called harshness. Harshness was not such a significant issue while bias tyres were the norm; it is an issue that has accompanied the spread of radial tyres. While it improved somewhat with improvements to both tyres and vehicles, it has resurfaced with the popularisation of low-aspect-ratio radial tyres. The mechanisms that produce harshness are given as follows. Unevenness in the road surface causes vibration. Relatively large irregularities in the road surface, such as joins or bumps, cause a single strong jolt to the vehicle, the shock of which travels through the vehicle's suspension and into the car body. The shock noise at this point has a frequency of 200Hz or less; the problem with shocks that can be felt in the steering wheel or seats is the low frequency back-and-forth vibration at 30-60Hz. This evaluation is used for riding over protuberances. Fig. 6.25 shows data on velocity dependence while travelling over a protuberance. Radial tyres have a clear peak at 30-50km/h. The intensity (acoustic pressure) of the noise inside the vehicle coincides with the longitudinal acceleration of the floor. This is the cause of harshness.

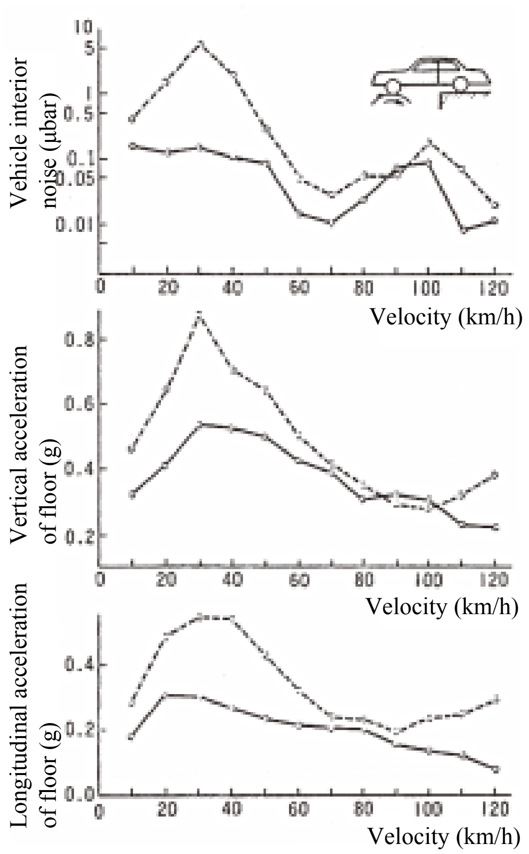


Fig. 6.25. Velocity Dependence of Acceleration and Noise While Travelling Over a Protuberance [1)]
(protuberance height 12mm, width 25mm)
Dotted line: radial tyre 165SR13; solid line: bias tyre 6.45-13

Fig. 6.26 shows the spectra of unsprung vibration and vehicle interior noise while travelling over a single protuberance at 40km/h. The vehicle interior noise peaks near 30-40Hz and 80-100Hz; each peak was found to correspond to the peaks of the unsprung vibration.

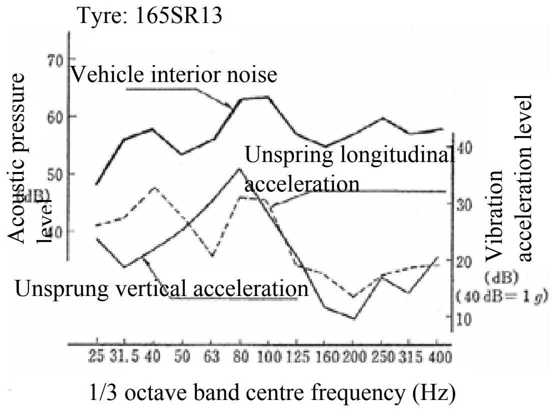


Fig. 6.26. Vehicle Interior Noise and Unsprung Vibration While Travelling Over a Protuberance [2)]

To improve harshness, the impact force must be reduced on the tyre itself. To achieve this, the tread area must decrease in rigidity to improve enveloping and reduce the vibration from the protuberance. Improving the longitudinal 40Hz (unsprung resonance fore-and-aft) and vertical 80Hz (tyre vertical primary) vibration transmissibility is also effective. However, since a decrease in the rigidity of the tread area means a decrease in manoeuvrability, stability, high-speed durability and wear resistance, work is being carried out on improving the vibration properties of tyre suspension so as to improve harshness while maintaining these other performance factors.

(ii) Road Noise

Road noise is low-frequency noise generated inside a vehicle when the vehicle is travelling on a rough road.

To reduce road noise, the main peaks of the passenger vehicle road noise spectrum, 100-200Hz and around 300Hz, must be reduced.

Various measures have been adopted to achieve this, including reducing the primary natural frequency in the radial direction and increasing the secondary natural frequency of the cross-section to reduce vibration transmissibility in the radial direction in the 100-300Hz range, or by reducing the vibration on the tread due to unevenness in the road by using softer rubber or thicker rubber.

Fig. 6.27 shows the improvements made by using these methods. However, although these methods improved the road noise, there were other effects, such as reduced manoeuvrability due to reduced rigidity of the side area, or poorer fuel economy due to thicker tread rubber; further countermeasures were needed to prevent this.

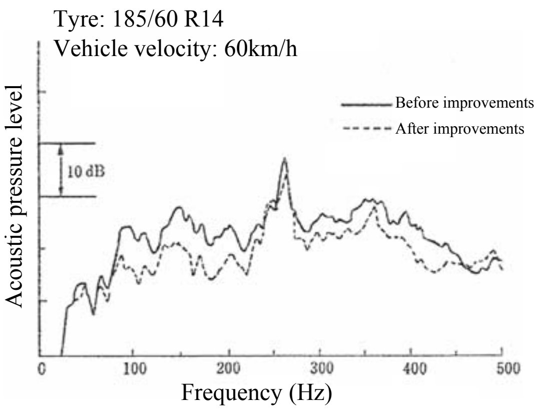


Fig. 6.27. Typical Reductions in Road Noise from Tyres [3)]

(iii) Cavity Resonance

Cavity resonance is resonance from the cavity within the tyre. In other words, a tyre is like a pipe that produces a resonant sound. The cavity resonant frequency equates to a sound wave frequency with a wavelength the same as the circumference of a circle with a diameter approximately halfway between that of the tyre and that of the wheel. Consequently, the cavity resonant frequency is determined by the size of the tyre and does not depend on the tyre structure. Recent countermeasures have been considered, such as placing obstacles in the tyre so that it does not resonate.

(iv) Uniformity Vibration

To improve vehicle vibration and ride comfort and to reduce noise, it is best if tyres are completely uniform on their circumference. Uniformity means uniformity in tyre dimensions, rigidity and weight. In terms of tyre uniformity, the change in force during a single rotation due to non-uniformity on the tyre axis while the tyre is travelling on a completely flat road surface is referred to as force variation. For testing, the following are measured with a fixed distance between the tyre and the road wheel (drum) axis.

(1) Radial force variation (RFV): changes in force in the longitudinal direction (direction of travel)
(2) Lateral force variation (LFV): changes in counterforce in the horizontal direction
(3) Tractive force variation (TFV): changes in force in the fore-and-aft direction; lateral force deviation (LFD): changes in force in the fore-and-aft direction (see Fig. 6.28).

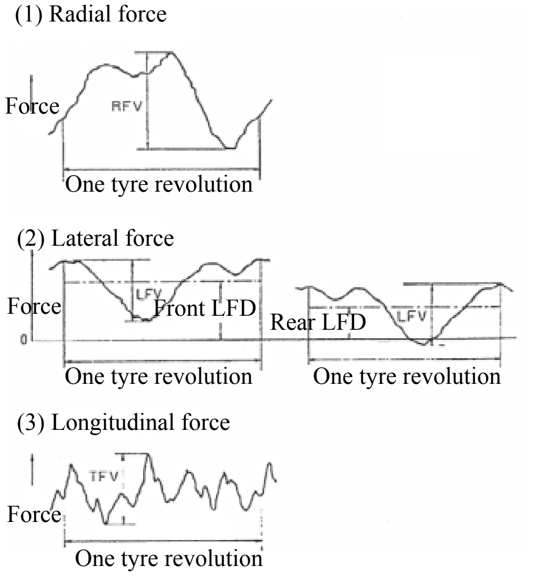


Fig. 6.28. Wavenumber Variations in Forces Generated by Tyres [4)]

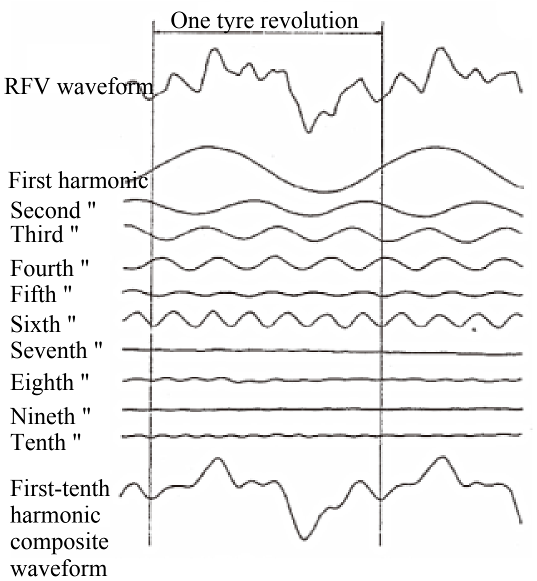


Fig. 6.29. Sample Fourier Analysis of FV Waveform [4)]

The measurements are shown above. These uniformity measurements make it possible to detect and estimate variations in tyre structural elements and their configuration and placement.

A Fourier analysis of the uniformity measurements shown in Fig. 6.29 above aims to determine the higher end of the variation waveform. The higher end is important to analysing the causes of unpleasant noise and vibration inside the vehicle. In other words, it is an analysis of the source of the discomfort from vibrations.

Vibrations caused by non-uniformity of the tyre are perceived as vibration or noise in the floor, seats, steering wheel or other areas in direct contact with the vehicle occupants.

Since uniformity manifests as the total sum of all the differences in tyre structure and variations during production, it indicates a basic level of discomfort and also indicates the level of completion of technology improvements. Various manufacturers have worked on various improvements, such as improving the degree of accuracy of factory components or adjusting the way the components adhere together, which has resulted in a rapid improvement.

(3) Tyre Noise

Let us now discuss the discomfort factors (environmental issues) inflicted on society by the running of the vehicle, such as noise in the surrounding environment.

The noise emitted directly by the tyre from the mutual interaction between it and the road can be categorised two ways: noise generated while the vehicle is travelling straight forward (tyre road noise); and noise generated while the vehicle suddenly brakes, takes off or turns (squeal). Tyre road noise is an issue from the perspective of noise pollution, in that it is one of the main contributors to vehicle exterior noise, which is the subject of legislation. It is also an issue in that it contributes to the vehicle interior noise, which compromises the comfort of the vehicle occupants. Once environmental issues came to the fore in Japan, manufacturers have put concentrated efforts into this issue, as it is a serious issue for the tyre industry.

Japan Automobile Tyre Manufactures Association (JATMA) and other members of the Japanese tyre industry carried out months and years of vital testing and research on how to reduce noise, from basic studies on tyre road noise generation mechanisms to investigating testing methods, ascertaining current road noise conditions and examining noise reduction technology and its impact on other performance factors. JATMA summarised these findings in *Taiya Dōro Sōon ni Tsuite [Tyre Road Noise]* [5].

Truck and bus tyres generate more noise than passenger vehicle tyres. Running trucks and buses in a small country during a time of growth, such as Japan's period of rapid economic growth, leads to major environmental issues, particularly in high-traffic areas; the entire country needed a solution.

In 1973, automobile standard JASO C606-86 "Methods for Testing Automotive Tyre Noise" was enacted, standardising two methods for testing tyre road noise: the vehicle coasting test method, in which tyre road noise was measured using a vehicle on an actual road, and the standalone bench test method.

For the vehicle coasting method, the vehicle was fitted on all four wheels with the tyres to be tested; it was then put in neutral with the engine turned off and made to coast at a predetermined speed past a microphone, which measured the maximum noise level.

(4) Types of Tyres and Noise

Causes of Tyre Noise

Pattern Noise

The most dominant tyre noise is pattern noise. This occurs due to a pump effect, in which air trapped in the grooves of the tread pattern is released when the tyre rolls and that area either loses contact with the ground or presses down against the ground. This is a major source of noise. Altering the pitch of the pattern disperses the frequency of the generated pattern noise. While this does not reduce the sound energy, it widely disperses the frequency of the generated noise to make it less noticeable. There is a relationship between the pitch of the pattern and the speed of revolution of the tyre. The noise is generated by a fundamental wave of around 200-1000Hz and a high frequency wave. Generally, the greater the number of grooves (ribs) parallel to the direction of travel, the quieter the noise; the greater the number of grooves (lugs/blocks) perpendicular to the direction of travel, the louder the noise. Bias tyres are also known to be louder than radial tyres.

Truck and bus tyre patterns are shown below.

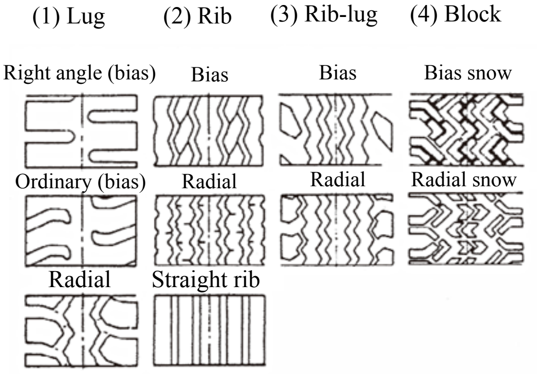


Fig. 6.30. Typical Truck and Bus Tyre Treads [6)]

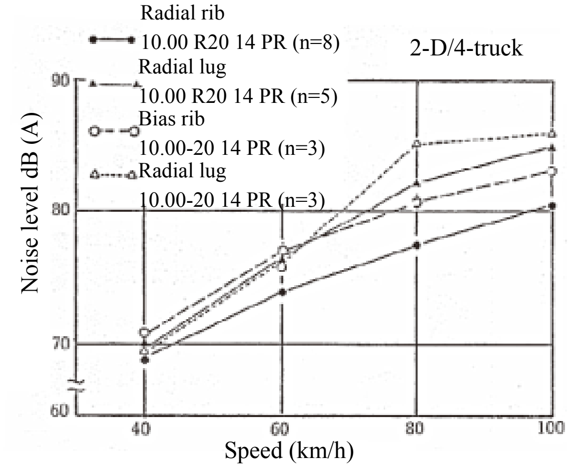


Fig. 6.31. Noise Levels of Various Truck and Bus Tyres [7)]

(measurements taken at various places offset with a reference tyre) (vehicle coasting test)

The following figure shows truck and bus noise levels. This indicates that lugs>ribs and bias>radial.

Fig. 6.32 shows passenger vehicle tyre noise. These results also indicate that lugs and blocks are louder than ribs, and that bias tyres are louder than radial tyres.

As indicated in Figs. 6.31 and 6.32, trucks and buses have more individual tyres and a higher noise level than passenger vehicles.

Accordingly, since trucks and buses are far louder than passenger vehicles, reducing their noise has become a significant issue. For this reason, many truck and bus tyres today have a rib pattern. This is a low-noise pattern to reduce noise pollution in built-up areas. It is one form of eliminating objectionable environmental elements.

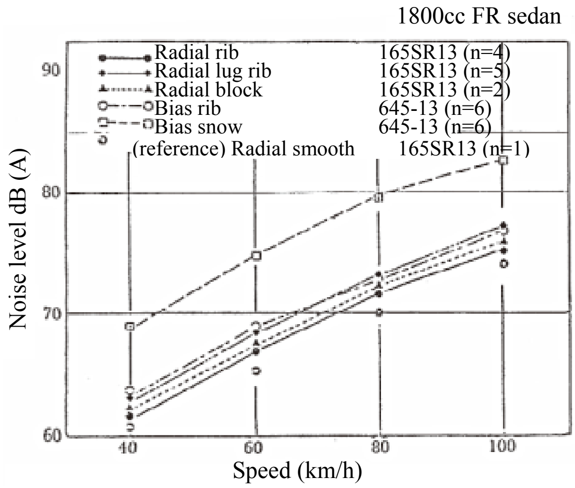


Fig. 6.32. Types of Tyres and Noise (vehicle coasting test) [8)]

6.3.2. Summary

As discussed above, in keeping with a growing demand to make life more comfortable, there was an increasing demand in post-war tyre technology development to remove sources of discomfort in terms of sensation and sensitivity factors, such as vibration and noise. Much progress has been made in this area in recent years as research techniques have improved. Examination of company patent applications to ascertain the kind of tyre developments being undertaken as sensation and sensitivity factors have grown in importance reveals that developments in the area of noise and ride comfort have mainly been design elements such as tread design and layout. A significant number of pattern design patents also related to noise. Most of the patents to do with noise and vibration given in the cited literature are for structural design technology [9].

In terms of the relationship between vibration, noise and frequency, an important task was to level out the average at a certain frequency to prevent it being excessively high. This was developed further with the development of computers. Research on the discomfort factors of noise, vibration and harshness has been an area of technology development that has completely matched the progress of society. It is fair to say that it resulted in the coming of age of tyres.

Cited references:

1) Hattori, Rokuro: *Taiya no Hanashi [The Story of the Tyre]*, Taiseisha, June 1992, p. 76.

2) *Jidōsha-yō Taiya no Kenkyū [Studies on Automobile Tyres]*, Yokohama Rubber Company, ed., Sankaido, April 1995, p. 197.

3) *Jidōsha-yō Taiya no Kenkyū [Studies on Automobile Tyres]*, Yokohama Rubber Company, ed., Sankaido, April 1995, p. 195.

4) Hattori, Rokuro: *Taiya no Hanashi [The Story of the Tyre]*, Taiseisha, June 1992, p. 82.

5) Japan Automobile Tyre Manufacturers Association: *Taiya Dōro Sōon ni Tsuite [Tyre Road Noise]*, fourth edition, June 1991.

6) Hattori, Rokuro: *Taiya no Hanashi [The Story of the Tyre]*, Taiseisha, June 1992, p. 79.

7) *Gomu Kōgyō Binran [Rubber Industry Handbook]*, fourth edition, January 1994, p. 761.

8) *Gomu Kōgyō Binran [Rubber Industry Handbook]*, fourth edition, January 1994, p. 762.

9) For example, patent applications related to structural design for noise/vibration. Patent numbers: Hei-05-058119 (BS) side area reinforcing layer arrangement; Hei-06-001109 (Sumitomo) optimum belt layer configuration; Hei-06-171315 (Yokohama) combination of block and lug grooves; Hei-06-262909 (BS) shoulder groove siping arrangement; Hei-07-061207 (Sumitomo) inner sidewall indent arrangement; Hei-07-205614 (BS) block land surface longitudinal groove control; Hei-08-337102 (BS) oriented low-gradient groove arrangement; Hei-07-276914 (Sumitomo) vibration damping by piezoelectric material; Hei-10-086611 (BS) groove side wall buffer wall arrangement; Hei-10-147113 (BS) indentation arrangement between side and shoulder; Hei-10-166809

(Yokohama) maximum width side indentation arrangement; Hei-10-291403 (Toyo) reinforcing layer arrangement over belt and under ribs; Hei-11-059136 (Toyo) side reinforcing layer arrangement; Hei-11-091314 (BS) arrangement of inclined grooves at an angle to the central groove; 2000-016030 (Yokohama) side area indentation arrangement; 2000-158916 (BS) siping groove arrangement; 2000-233609 (Toyo) dynamic vibration absorber protrusion arrangement; 2001-191743 (BS) carcass side area double-layer arrangement; 2001-239809 (BS) countermeasures against air column resonance by linking the tread cavity with the circumferential groove; 2002-019423 (BS) block arrangement design; 2003-011617 (BS) asymmetric centre block arrangement on the press-out and press-in sides; 2003-260906 (BS) width-direction intervals in the belt layer with specific widths; 2004-351970 (BS) pitch arrangement; 2005-145429 (Sumitomo) cushion rubber arrangement between the belt and carcass; 2006-199101 (Toyo) extending the block from the shoulder to the side; 2008-024256 (Yokohama) carcass bead area reinforcing layer arrangement; 2009-107448 (Yokohama) double-layer shoulder carcass arrangement
Abbreviation: BS: Bridgestone; Sumitomo: Sumitomo Rubber; Yokohama: Yokohama Rubber Company; Toyo: Toyo Rubber

6.4. The Age of Integration: the Coming of Age of Radial Tyres in the Age of Integration

6.4.1. Advent of the Age of Theory

(Theorisation for the simultaneous achievement of performance factors such as durability and manoeuvrability; fuel economy, grip and sensitivity; noise, vibration and ride comfort)

Underlying the shifting trend from durability → manoeuvrability performance → sensation/sensitivity has been a shift on emphasis from material elements to structural elements. Nevertheless, techniques to achieve these target outcomes have been narrow in scope, with durability limited to material factors and sense/sensitivity limited to structural design factors.

From the 1980s onwards, Japanese manufacturers starting publishing a succession of theories on tyre design. By establishing mutual connections between different areas, such as incorporating design elements into durability and rolling resistance, which had previously been considered as mainly involving material design issues, these studies enabled new developments, which provided breakthroughs for existing trade-offs. These theories were mainly to do with the geometric design of tyres with presuppositions closer actual running conditions, namely, filled with air and under load. In other words, the ideas that surfaced took into account the tension distribution during use, the changing shape of the tyre and other factors. In short, these theories proposed major strides in progress by using structural design elements to solve performance issues that had previously been viewed as falling into the material elements category. Furthermore, these were also being published by all companies.

Structural designers expanded their scope of investigation from their main areas of responsibility, namely, noise, vibration, ride comfort, driving stability, etc. to include durability and rolling resistance through carcass tension control.

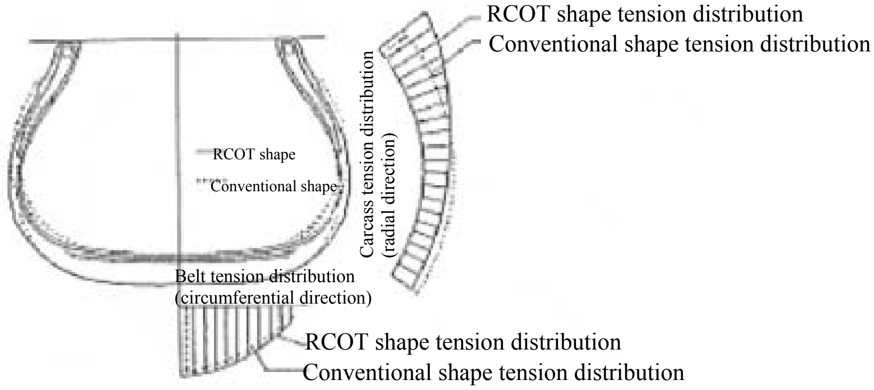
This theorisation coincided with the development of computers. The age of super-computers ushered in a drastic leap in complexity, combining all kinds of factors: examining what kind of materials to use and how to structure them, whether or not fibre reinforced rubber could work, and determining physical constants such as frequency and acoustic pressure for vibration, sound and other factors, particularly in the area of sensation and sensitivity. As these factors grew in importance, more advanced calculations were required, paving the way for large-scale computers and the finite element method.

With the advance of globalisation, tyres had to become more diverse to meet a broadening range of usage conditions. The technology also had to diversify, which required a multidisciplinary approach. This necessitated an integration of materials and design, given the mutual relationship between material design elements and structural design elements. This was an age of tyre design theory, encompassing durability and manoeuvrability performance factors as well as all aspects of sensation and sensitivity factors. The task of finding and balancing a compromise between factors without sacrificing any of them was a task well suited to the Japanese. Combined with advanced computer design technology, this worked to the advantage the overall situation. Consequently, the level of Japanese integration technology during this era was world class. The following are some of the theories by various companies.

Rolling Contour Optimisation Theory (RCOT), *Buridjisuton Nanajūgo-nen-shi [The 75-Year History of Bridgestone]*, p. 232

At the time, manufacturers around the world were designing tyres based on natural equilibrium shape theory. This shape is determined mathematically under conditions in which the tension of the air pressure is applied uniformly and is thought to be the most stable shape for a tyre.

A FEM model was created in which minute differences in tyre shape were deliberately emphasised and the energy loss predicted. The theory held that deformation could be absorbed by increasing tension to suppress deformation in areas susceptible to energy loss and reducing tension in areas not prone to energy loss. This is the main idea behind the RCOT theory, to "distribute the necessary tension to the necessary areas." Specifically, the theory proposed a non-equilibrium cross-section shape to increase the tension at the bead and belt areas (optimal travelling shape theory).



RCOT Carcass Shape and Tension Distribution

Jidōsha-yō Taiya no Kiso to Jissai [Foundation and Reality of Automobile Tyres], Bridgestone Corporation, Sankaido, p. 94.

Tension Control Optimisation Theory (TCOT), *Buridjisuton Nanajūgo-nen-shi [The 75-Year History of Bridgestone]*, p. 233; Watanabe, Tetsuo: *Taiya no O-Hanashi [The Story of the Tyre]*, (Japan Standards Association), p. 123.

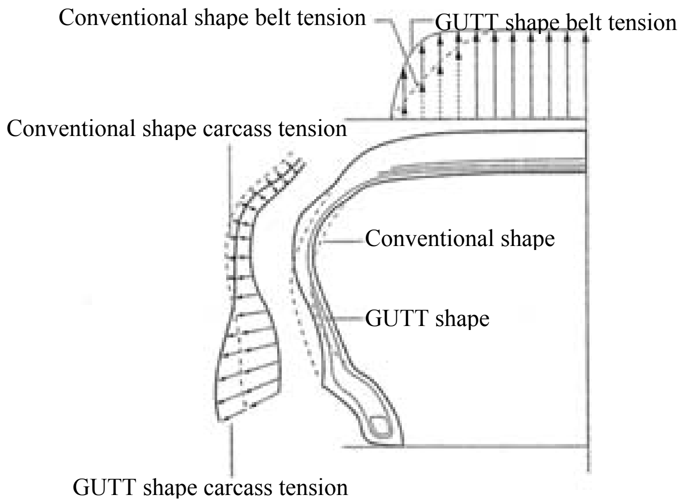
Clarifying the tyre distortions and their occurrence mechanisms and attaining a shape to suppress those distortions by TBR new shape design theory.

Since TCOT increases the radius of curvature of the carcass at the bead area and reduces the radius of curvature at the top of the sides, tension increases at the bead area, which reduces deformation, thereby improving the durability of the bead area. This increase in tension and reduction in deformation of the bead area improves durability by 20% and at the same time also improves rolling resistance, wear resistance, wet braking performance, driving stability and other trade-off performance factors.

Fig. 6.33. *Buridjisuton Nanajūgo-nen-shi [The 75-Year History of Bridgestone]*, (Bridgestone Corporation, May 2008) [1] pp. 232-233

Driver Oriented New Ultimate Tyre Science (DONUTS), *Buridjisuton Nanajūgo-nen-shi [The 75-Year History of Bridgestone]*, p. 305.
DONUTS is a technology comprising three other technologies: Grand Unified Tyre Technology (GUTT), an automated evolutionary design method; O-Bead, a bead with improved roundness; and Long Linkage (LL) carbon.
GUTT is a method of optimising target performance factors through computer simulation.
O-Bead is a shape of bead that fits the rim and tyre in a near-perfect circle, improving the straight running stability of the tyre. LL carbon is a new type of carbon that has an increased chain of carbon particles to achieve both improved wear resistance and reduced rolling resistance, previously thought to be mutually exclusive.

Advanced Quality of DONUTS (AQ DONUTS), ibid, p. 326.
Adoption of two technologies to prevent deterioration of performance due to on-going wear on the tyre, particularly when wet.
- AQ compound: use of compounding agents to suppress the hardening of the rubber
- Tread in tread: Once the tyre is worn to around half, rubber appears to suppress the gradual decline in performance, preventing the deterioration in wet performance and other performance factors.



Maximised Belt and Bead Tension Distribution using GUTT
Jidōsha-yō Taiya no Kiso to Jissai [Foundation and Reality of Automobile Tyres], Bridgestone Corporation, Sankaido, p. 96.

Fig. 6.34. *Buridjisuton Nanajūgo-nen-shi [The 75-Year History of Bridgestone]*, (Bridgestone Corporation, May 2008) 2) pp. 305, 326.

PSP-Y, (*Sumitomo Gomu Hyakunen-shi [Hundred-year History of Sumitomo Rubber]*), p. 376; 1996, fitted tyre sale, p. 376.

A new technology developed to address a change in required performance for truck and bus tyres from the conventional “strength to withstand heavy loads” to “mobility”, “maintenance” and “economy”.

- Adoption of particulate carbon to improve tyre life and travelling performance by strengthening the bond between the rubber and the carbon
- Flat, smooth, tread shape design to improve uneven wear resistance by suppressing dimensional changes in tyres from travelling
- Tread block layout design based on independent chaos theory to reduce noise by dispersing the noise generated by the tyre grooves, as well as to improve uneven wear resistance
- New bead structure design to improve rim insertion when fitting the tyre to the wheel and to improve air insertion when inflating the tyre

Evolution into Dunlop Energy Control Technologies (DECTES), p. 440.

Adjusting the distribution of ground contact area to evenly distribute wear energy and prevent uneven wear resulted in less maintenance; adopting highly active carbon in the tread rubber resulted in improved tyre life; suppressing the energy loss incurred with each revolution of the tyre resulted in lower fuel consumption.

Digital Rolling Simulation (DRS) → Digi-Tyre, ibid, p. 382.

Analysis of a rolling tyre model, reproduced exactly from the tread pattern to the detailed tyre structure.

Four type of simulations

(i) Contact shape / contact pressure simulation: “digital profile” allowing viewing of the contact surface of a tyre while travelling at 200/h

Led to the implementation of greater driving stability at high speeds with a wide ground contact surface at high speed.

(ii) Wear energy simulation: “digi-tyre pattern” allowing viewing of where the tyre is wearing away

Block shape enabled even wear energy across the ground contact surface of the tyre while rolling, reducing uneven wear and lengthening the life of the tyre.

(iii) Rubber compound simulation: “digi-tyre silica water-repellent rubber” enables the digi-tyre to run on any road surface

Proper blending of water-repellent rubber for summer, silica for wet use and particulate carbon for dry use, improving both wet grip and tyre life.

(iv) Noise / vibration simulation: “digi-tyre chaos array” allows hearing of tyre sounds while running

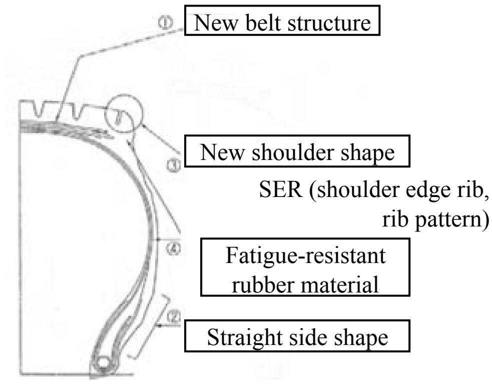
An array formed with an appropriate mix of regularity and irregularity, resulting in a balance between preventing uneven wear, which requires regularity, and reducing noise, which requires irregularity.

Fig. 6.35. *Sumitomo Gomu Hyakunen-shi [Hundred-year History of Sumitomo Rubber]* (Sumitomo Rubber Industries, Ltd., December 2009) [3)], p. 440, 382

Strain Energy Minimisation Theory on Loaded Tyre (STEM), Yokohama Rubber Company

The STEM shape uses a carcass line with the tyre inflated (FEM design theory). As opposed to an equilibrium carcass line derived from the balanced state of the membrane alone (only the belt and carcass), STEM uses a carcass line derived from the balanced state of the rigidity distributed across the entire tyre (very different from the equilibrium carcass line at the bead area). Accordingly, this successfully evens out the strain energy on the bead area and the belt edge. This is an under-load strain energy optimisation theory with a tyre shape based on the assumption that the tyre is travelling and the radius of curvature of the carcass line at the sidewall area is approximately the same as R with less deformation while inflated.

Four new designs support STEM

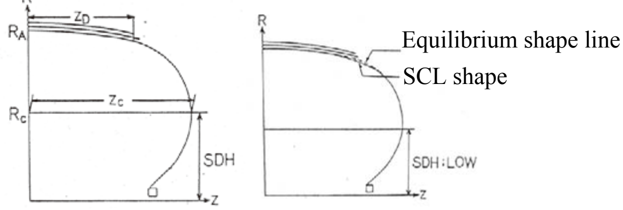


SCL driving stability theory, ibid.

Theoretical relationship between the yaw rate and vibration of a vehicle and the cornering force on the tyres while steering.

When the driver turns the steering wheel, a slip angle is applied to the tyres and they undergo significant deformation, generating cornering force.

When tyres are steered out of a straight line position, the tread area does not follow the movement of the rim immediately, but after a time lag. SCL theory holds that this feeling of delay can be made to match the feeling sensed by the vehicle occupants. The theory proposes the idea of matching the sensations of the driver with the movements of the vehicle. Accordingly, the SDH (side height) is lowered. Society of Automotive Engineers of Japan, Conference, October 1987, p. 527.



Tyre Shape Parameters SCL Shape

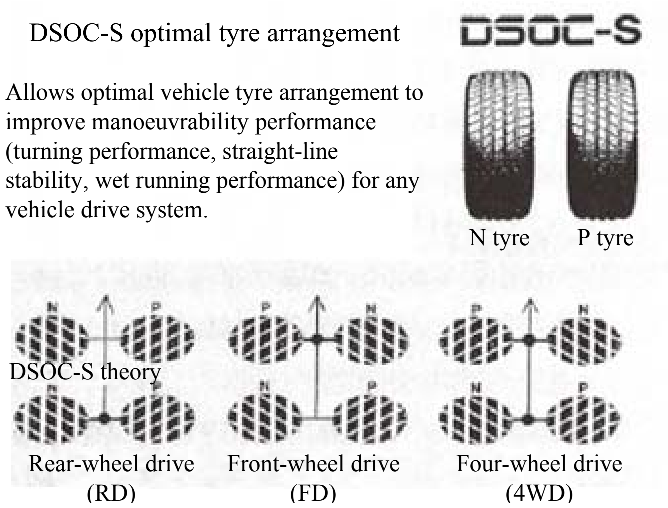
Fig. 6.36. Yokohama Rubber Company, *Motor Vehicle*, Vol. 38, No. 54 (STEM) [4]

Society of Automotive Engineers of Japan, Conference, October 1987 (SCL) [5]

DSOC Theory, (published August 1988) (*Tōyō Gomu Kōgyō 50-nen-shi [The 50-Year History of Toyo Tire & Rubber]*, 1996), p. 241.

DSOC theory enabled analyses of stress and strain while travelling using a supercomputer. It also enabled analysis of the contact area while travelling. This provided instant understanding of many performance factors that could not be known through conventional vehicle testing alone, which in turn made it possible to develop a better product in a short space of time. This resulted in the publication (in September the same year) of DSOC-S theory, a passenger vehicle tyre arrangement optimisation system that provided the optimal arrangements of two types of tyres with independent patterns and structures.

DSOC-S theory



DSOC II (*Tōyō Gomu Kōgyō 50-nen-shi [The 50-Year History of Toyo Tire & Rubber]*, 1996), p. 288.

DSOC II focuses on the space between the tyre and the road surface, which cannot be viewed using ordinary methods, but can be observed through computer simulation. This advanced technology optimises tyre performance and has been applied to passenger vehicle tyres as well as truck and bus tyres. As a further evolution of DSOC, the dynamic simulation tyre optimisation design theory, DSOC II incorporated cross-section shape, material properties and tread pattern to produce integrated, optimised designs.

Fig. 6.37. *Tōyō Gomu Kōgyō 50-nen-shi [The 50-Year History of Toyo Tire & Rubber]* (Toyo Tire & Rubber Company, March 1996), pp. 241, 288.

Cited references:

1) *Burdijisuton Nanajūgo-nen-shi [The 75-Year History of Bridgestone]*, Bridgestone Corporation, May 2008, p. 232.

2) *Buridjisuton Nanajūgo-nen-shi [The 75-Year History of Bridgestone]*, Bridgestone Corporation, May 2008, pp. 305, 326.

3) *Sumitomo Gomu Hyakunen-shi [Hundred-year History of Sumitomo Rubber]*, Sumitomo Rubber Industries, Ltd., December 2009, pp. 440, 382.

4) Yokohama Rubber Company, *Motor Vehicle*, Vol. 38, No. 54.

5) Hanada,Ryoji: Society of Automotive Engineers of Japan, Conference, October 1987, summary, p. 527.

6) *Tōyō Gomu Kōgyō 50-nen-shi [The 50-Year History of Toyo Tire & Rubber]*, Toyo Tire & Rubber Company, March 1996.

7. Detailed Description of Tyres Requiring Additional Performance

The preceding chapters have systematically discussed the ordinary properties of tyres. In other words, we have outlined the history and systematisation of technology related to performance factors that are ordinarily required in tyres, such as durability, manoeuvrability, noise and vibration. However, some tyres require additional, extreme performance factors. This chapter discusses the history of development of tyres requiring special performance factors, including aircraft tyres, construction vehicle tyres (high durability), two-wheeled vehicle tyres (structure) and studless tyres (snow and ice friction).

These tyres have presented challenges to meet the required performance factors.

7.1. High Demand for Durability

7.1.1. Aircraft Tyres: High Thermal Fatigue Resistance

Aircraft tyres are only required for take-off and landing.

Aircraft tyres must be able to soften the impact when the aircraft touches down on the runway and perform sufficiently to bring the aircraft to a safe stop. Accordingly, the tyres must have a structure capable of bearing sufficient load capacity, handling the speeds required for aircraft take-off and landing and adequately withstanding the wear from the surface of the runway. Aircraft tyres have a fixed number of uses, depending on the aircraft performance (weight, take-off and landing speeds), runway conditions, weather conditions and manner of braking. The tread pattern is usually a rib type, comprising four to six grooves running in the circumferential direction. After 200-300 take-offs and landings, the grooves wear away and the tyre is replaced. In many cases, the tyre is retreaded, with the worn tread removed and new tread put on. The retreading process can be repeated five to six times.

During landing, the tyres are subjected to significant vertical impact at the moment of contact with the ground. Since they go from not moving during flight to suddenly rotating, the tyres are subjected to major acceleration in the tangential direction against the runway surface on contact with the ground and are rubbed vigorously. Compared to ordinary tyres, aircraft tyres have the following distinguishing characteristics [9].

(i) Aircraft tyres have significant flexure. While the flexure under static load varies between tyre types, it is around 30% (within the range of 23.5-40%), two to three times more than automobile tyres. This helps to ease the shock during take-off and landing, particularly during landing.

(ii) Very high loading. Since the tyre size and weight are reduced as much as possible to lighten the weight of the fuselage as much as possible, the tyres carry a very high load in proportion to their size.

(iii) Superior high-speed performance. Since aircraft reach speeds of up to around

400km/h during take-off and landing, tyres must be stable and safe at high speeds.

(iv) Good cold tolerance. Tyres must be made of a material that can stand temperatures of -40 to -50˚C, since they are used at airports in cold regions and are stowed during flights through the stratosphere. Furthermore, when landing, the tyres are required to spin, despite having hardened due to the low temperatures.

Type of aircraft tyres include small and medium tyres, or low-pressure propeller aircraft tyres, high-pressure jet aircraft tyres, newly-designed flattened tyres and helicopter tyres, among others. There are also many different sizes of tyres, ranging from 56” (around 1.4m) tyres for large aircraft to 12” (around 30cm) tyres for small aircraft tyres.

While both bias and radial structures exist for aircraft tyres as well, the radial structure is on the way to becoming adopted as the main structure in use. However, on the whole, bias tyres are still the main structure in use, with more than 20 layers of nylon cord to ensure safety. Given the low temperature performance factor, natural rubber is used as the rubber material. This is because once a fuselage is developed, it is fitted with the same structure of tyres for 20-30 years until it is retired from service; there are no rapid changes made. In future, there will be a change to radial tyres, as radial tyres are becoming known for their high durability, light weight and good landing performance.

The high durability requirement for aircraft tyres means that they must have high rupture tolerance and low heat build-up. Accordingly, natural rubber is used for aircraft tyres. Aircraft tyres have a long history as far as tyres go, dating back to pre-war fighter aircraft, and the technology has been built up from that foundation. The strongest requirement is for safety; changes in specifications cannot be made quickly. Durability is also a very important area in tyre technology.

(See Chapter 1, Fig. 1.2 for an external view of an aircraft tyre.)

7.1.2. Tyres for Construction Vehicles: High Heat Resistance

Construction vehicle tyres (OR, off-road tyres) are tyres for scrapers, dump trucks, graders, loaders, wheeled bulldozers, multi-wheeled rollers, wheeled cranes, high speed cranes and other construction machinery used at civil engineering construction sites, mines and the like. These vehicles are used on a wide range of roads, from conditions, such as gravel, stone and mud, to good, paved, public roads. These machines assist with the task of digging, carrying, scraping and levelling earth.

Unlike truck, bus and passenger vehicle tyres, off-road tyres generally travel on unpaved roads covered with gravel or stones rather than on paved roads. Heavy in weight, they are also very large in size, ranging from the size of ordinary large tyres for trucks and buses to 4m or more in outer diameter and 7ton or more in weight. Since they have a wide range of usage conditions, the structure, rubber material and pattern is determined by the intended application. Tyre structures include both radial and bias; in recent years, the radial structure has increased proportionally in use due to its wear resistance, cut resistance and low heat build-up. For some higher speed applications, such as dump trucks and wheeled cranes, the radial structure has become the majority. For the tread, there is mixed use between natural rubber compounds for their superior wear resistance and heat resistance and synthetic rubber compounds for their superior cut resistance. The basic performance indicators are large tyres for travelling on poor roads and thick tyres for heat resistance [9)].

Construction vehicles, particularly those used in mines such as dump trucks, are large in size with a high loading capacity to improve their transportation efficiency. These types of tyres now have to support more than twice the load they did around 20 years ago and ten times more than they did in the 1960s [10)]. However, if the tyre were to be made larger, this would raise the vehicle's centre of gravity and compromise the stability and controllability of the vehicle; therefore, the tyres have been flattened. This increase the loading rate per air volume without increasing the external size of the tyre. However, to achieve this required other technology to maintain the heat resistance, wear resistance and cut resistance. This necessitated new structural and material technology [10)].

Development of these tyres did not simply mean taking a truck or bus tyre and making it bigger. A lot of research had to be carried out from many different angles to overcome a number of major hurdles, such as preventing deterioration in rubber quality during the longer vulcanisation time required for a thicker tyre, preventing heat build-up while travelling and preventing cuts in the tread from travelling on rough roads. (See Chapter 1, Fig. 1.2 for the external view of a construction vehicle tyre.)

7.2. Tyres for Specific Manoeuvres: Wider Friction Surface

7.2.1. Tyres for Two-Wheeled Vehicles

Two-wheeled vehicle tyres are generally categorised into public road tyres and racing/non-public road tyres.

Two-wheeled vehicle tyres differ from four-wheeled vehicle tyres while travelling in that they turn by means of the horizontal rigidity of the tyre and by means of camber thrust (horizontal force generated when the tyre tilts while travelling). Accordingly, the tread radius is smaller and the area that comes in contact with the road surface extends as far as the tyre shoulder, so the tread pattern continues as far as this area (see Fig. 7.1). The tyre structure is mainly radial, like passenger vehicles, but bias tyres are still used for some rough road tyres and in some family motorcycles.

Usage conditions differ between four-wheeled vehicles and two-wheeled vehicles in the following two ways [8)].

(i) High air pressure for a comparatively light load, meaning a smaller ground contact area. Around half the number of passenger vehicles.

(ii) High horse-power engine to generate driving power for a comparatively small ground contact area. A high driving force on the tyres for a comparatively small ground contact area, meaning the horse-power load per unit surface area ranges from low to high depending on the make. Large motorcycle tyres face driving conditions around twice as rigorous as passenger vehicle tyres and around five times that of truck tyres.

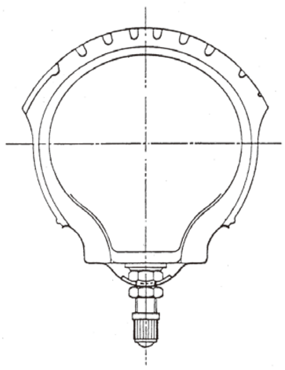


Fig. 7.1. Cross-Section Diagram of a Two-Wheeled Vehicle Tyre [11)]

Fig. 7.2. Two-Wheeled Vehicle Tyres [12)]

(1) Tyres for Public Roads

Tyres for ordinary public roads fall into two broad categories: tyres for good road conditions and tyres for both good and poor road conditions. Both are considered to be suitable for use in all weather conditions. The important factor is the arrangement of grooves in the tread.

Tyres for both good and poor road conditions use a block pattern, focusing on travelling performance on poor road conditions. The block pattern also allows for stable travel on good road conditions.

(2) Tyres for Racing/Non-Public Roads

(i) Competitive road racing tyres

There are three types of motorcycle racing: road racing, motocross and trials.

(ii) Distinguishing characteristics of road racing tyres

1. Flattened tyre used for the rear wheel to increase stability at high speed. This also prevents slipping while cornering.
2. Moderately rigid, thin tyre with a rib-type tread design to reduce rolling resistance at high speed as much as possible.
3. Special wear-resistant, age-resistant tread rubber is used to withstand high-speed travel.

The wheels must be in perfect balance for travelling at high speeds on paved roads.

Tyre pressure rapidly increases immediately once travel commences. High pressure reduces rolling resistance but also reduces road holding. Starting pressure must be adjusted with care. The appropriate pressure depends on the weather, temperature, road conditions, tyre properties, vehicle properties and other factors.

(iii) Distinguishing characteristics of motocross tyres

For races held on unpaved tracks, tyres have a block design with most of the tread protruding out a long way to bite into the ground surface while running.

To prevent skidding sideways, the front wheel tyre has a more rib-like block design. The rear wheel tyre is as thick as possible with low tyre pressure so as to grip the track surface even on soft earth (by enlarging the ground contact area).

As with other tyres mentioned above, there is a transition to radial tyres as development continues.

7.3. Improved Friction Performance on Snow and Ice

7.3.1. Studless Tyres

Studless tyres are a category of tyre developed out of conditions in northern Japan. Developed as a result of dust problems caused by spiked tyres in high-traffic snow areas, these tyres pioneered new areas of winter performance technology, particularly low-temperature rubber performance.

While spiked tyres used on cars in northern winters are popular due to their capacity to maintain high running stability on snow and ice, dust issues in the 1980s saw local authorities and other groups actively campaigning against them.

Fig. 7.3 shows the high amount of dust during winter. Prior to the prohibition on spiked tyres, the times in which spiked tyres were used coincided with the dust levels. This was due to the spikes on the tyres shaving away the road surface and spreading as dust

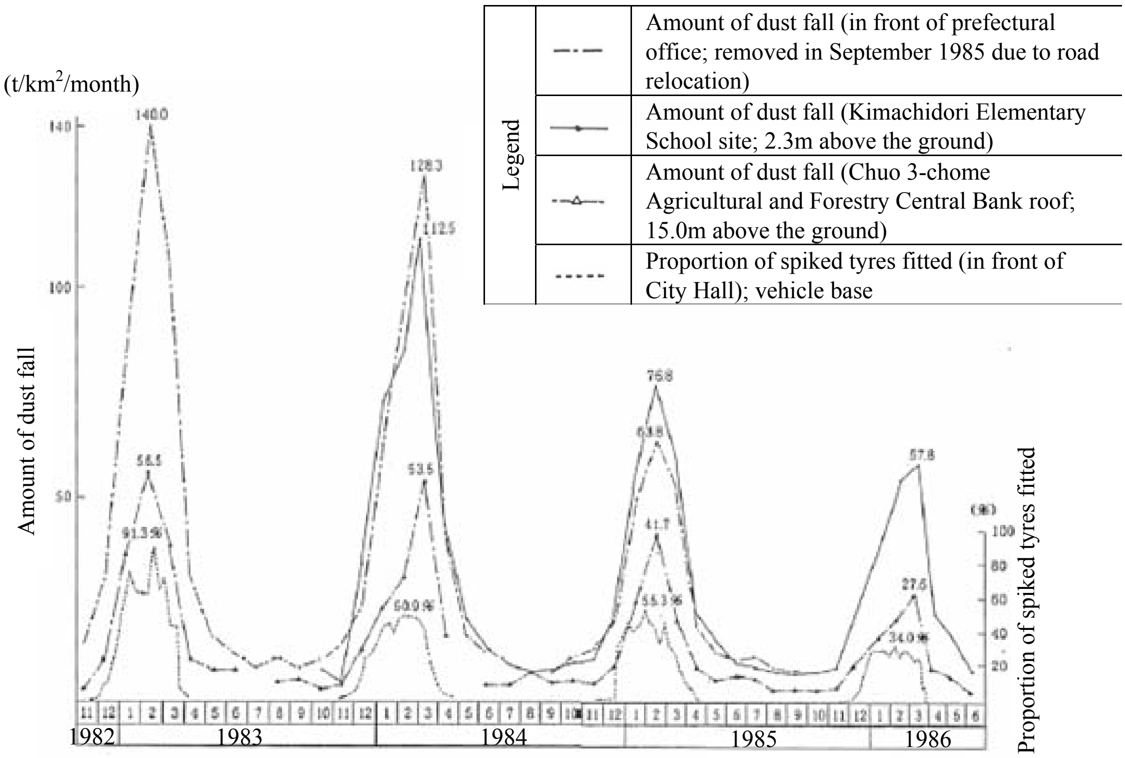


Fig. 7.3. Trends in the Amount of Dust Fall in Sendai City and Proportion of Spiked Tyres Fitted [1)]

In June 1986, arbitration was set up between residents and the tyre industry. It was decided that manufacture of spiked tyres would stop at the end of 1990, while sales would cease at the end of March 1991. Studless tyre sales volumes grew rapidly from around 1986, turning the tables on spiked tyre sales for passenger vehicles.

Use of studless tyres spread so rapidly that they accounted for 98% of passenger vehicle tyres by 1991.

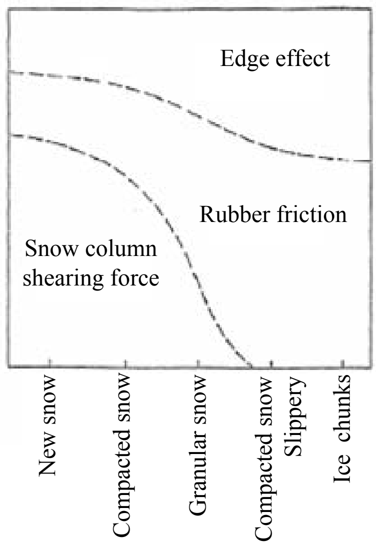


Fig. 7.4. Tyre Friction Contribution Ratios on Snow and Ice (Schematic Diagram) [2)]

(1) Friction on Ice and Snow

Studless tyre driving and braking power on snow and ice can be represented as the total of snow column shearing force F_B (the shearing force on the snow columns formed by snow pressing into the grooves on the tread pattern), rubber friction force F_C (the friction acting on the road surface and the pattern surface) and edge effect F_D (the edges of the blocks and sipes digging into the snow and ice on the road surface) in Fig. 7.4. Each of these braking-related shearing forces contributes differently on snow and ice surfaces.

The capacity of the grooves is related to the snow and ice shearing force at the point of departure, while the digging friction is strongly linked to the edge effect during rolling. If there are a fixed number of edges, the water repelling effect and digging in effect can be increased by facilitating the opening of the sipes (fine grooves on the tread).

(2) Measures to Improve Friction

(i) Adhesion / Traction Force

A method to increase adhesion and traction at molecular level, such as molecular binding between the surface of the snow or ice and the tread rubber. The tyre road contact surface is increased and special rubber is used. While making the tread rubber softer has the effect of increasing the adhesion / traction force (F_A), if it is too soft, the blocks will be lost to deformation, thereby reducing the friction force. An optimum firmness is required.

(ii) Digging Friction

Friction force caused by the edges of the blocks on the tread pattern scratching or breaking the road surface. While making the blocks smaller and greater in number increases the number of edges, this also reduces the rigidity of the blocks; if the blocks undergo significant deformation, then the ground contact area reduces in size and the friction force decreases. The optimum values are determined by the size of the tyre, the size of the blocks, the number of sipes, the rigidity of the rubber and other factors.

(iii) Drainage / Hydrophilic Friction

Sipes working effectively can use drainage to increase friction by removing the pseud-liquid layer, or water film, at -5˚C to 0˚C, thereby proving to be an effective means of improving performance over ice. However, with frequent use, the blocks deform too much, which has the opposite effect. Hydrophilia has mainly to do with the effect of the rubber.

Frozen road surfaces have a low friction coefficient and are very slippery. Frictional heat can easily turn the pseudo-liquid layer on the surface of the ice into a water film, which acts as a lubricant.

(iv) Use of Special Rubber

Multi-cell compounds are special rubber compounds with large numbers of cells. These microscopic closed cells are combined with microscopic air bubbles as shown in Fig. 7.5 to produce optimum tyre performance. These compounds have the following distinguishing characteristics.

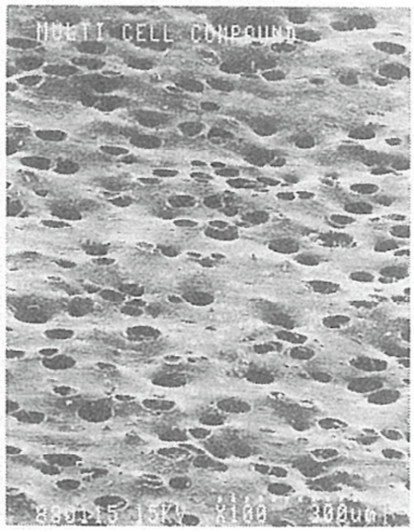


Fig. 7.5. Rubber Containing Bubbles (Multi-Cell Compound) [3)]

1) The microscopic cells produce microscopic irregularities on the surface of the tread rubber. These provide an escape for water generated through continuous slipping and also prevent microscopic water film from occurring between sipes.
2) These microscopic irregularities scratch the ice and thereby improve the digging friction F_D.
3) The microscopic bubbles reduce the rigidity of the rubber, meaning it does not lose its elasticity even at low temperatures (→ improved adhesion friction F_A due to increased ground contact surface).
4) New bubbles appear even as the tyre starts to wear, thereby enabling continuation of the aforementioned effects 1) and 2).

(v) Special Arrangements for Microscopic Drainage

While using soft rubber is good for improving traction, removing the thin water film between the rubber and the road surface is also effective. Having microscopic asperities on the surface of the rubber makes this more effective. For example, if we were to measure the friction on ice after rubbing the rubber with sandpaper, we would find that the coarser the sandpaper used, the greater the friction on the ice. This is because the microscopic protrusions penetrate the surface film on the ice, enabling direct contact with the surface of the ice. Conversely, it is also thought to remove the water.

The use of foamed rubber is one means of ensuring asperities on the surface. This has also shown to be effective in tyres.

Short fibres are added to prevent deformation of the tread blocks (see Fig. 7.7); these are placed along the blocks to reinforce them. This reinforcing phenomenon is shown in Fig. 7.6.

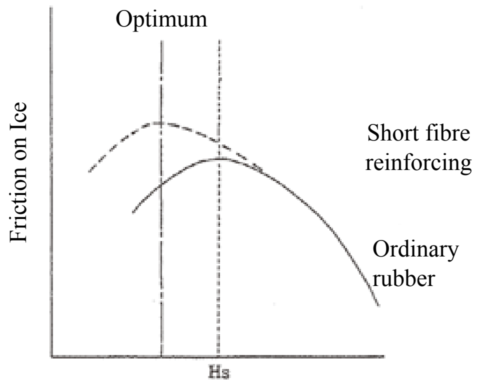


Fig. 7.6. Short Fibre Reinforcing Effect on Friction on Ice [4]

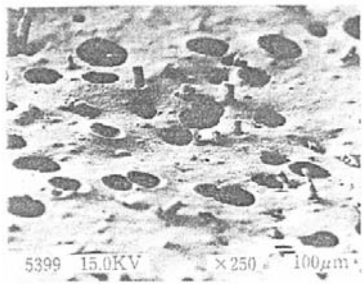


Fig. 7.7. Rubber Surface Containing Short Fibres and Bubbles [4]

While adding bubbles and short fibres creates an asperity effect that drains water, the fibres can also prevent the blocks collapsing if the rubber is too soft. This means that even relatively soft blocks can have improved friction on ice [6].

Compounds with additives such as ground walnut shells (microbit compounds) have also shown to be effective (see Fig. 7.8). In any case, surface asperities are thought to ensure drainage.

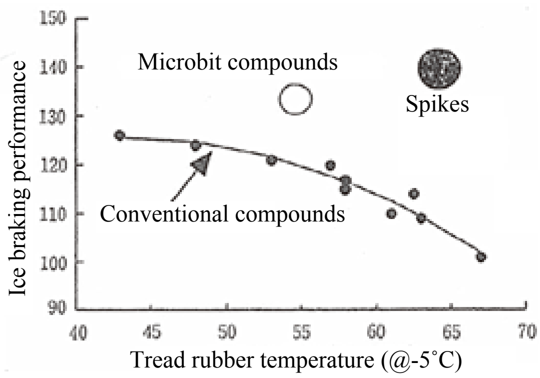


Fig. 7.8. Microbit Compound Effect [5]

The use of glass fibre is another example of using fibres in the rubber to harden it. Mixing in glass fibres, which are softer than asphalt but harder than ice, with the adhesive creates a "scratching effect", which improves the friction against the ice [7].

(vi) Rubber Properties and Adhesion Friction Force

As previously mentioned, adhesion friction force is a primary cause of molecular-level adhesion, such as molecular bonding between icy or snowy road surfaces and tread rubber. Increasing this adhesion requires the rubber to precisely follow the microscopic irregularities on the surface of the road to enable good microscopic contact between the rubber and the road surface. Accordingly, it is important that the rubber is elastic at low temperatures, such as on icy surfaces; this is usually achieved by using rubber that remains as soft as possible at low temperatures. To ensure softness at low temperatures, polymers with a low glass-transition temperature (Tg) (such as natural rubber or butadiene rubber) are used, while use of low-temperature plasticisers ensures the rubber does not harden at the temperature of use.

1) Interaction between Rubber Hardness and Tread Block Hardness

Block size, number of sipes and rubber hardness work together to create optimum values for performance on ice.

Fig. 7.9 shows the relationship between rubber properties and coefficient of friction μ on ice. For this experiment, the μ on ice taken to shift one block sideways was measured. As the figure shows, when the surface pressure on the rubber block varied, it peaked against the hardness at all levels of surface pressure. The higher the surface pressure at the peak location, the further the shift in the direction of hardness. In other words, when the block is shifted, it becomes softer than at peak position and the contact area reduces due to collapsing from contact pressure. Conversely, the harder the rubber, the better the contact and the higher the friction force. Accordingly, the softness of the rubber contributes to the total friction force. The softness of the rubber is balanced between providing friction and avoiding collapse. In other words, truck and bus tyres, which have high contact pressure, must be harder than passenger vehicle tyres, which have lower contact pressure.

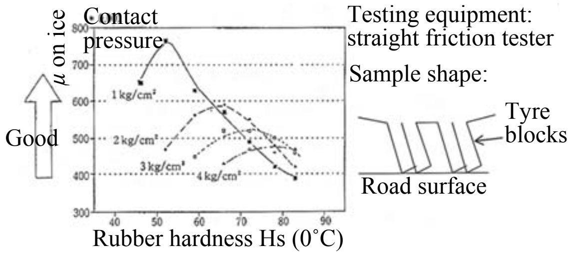


Fig. 7.9. Relationship between Tyre Block Rubber Properties and μ on Ice [4)]

(vii) Friction by Pattern

1) Removal of Water Film

Arrangements of fine grooves such as siping are another basic design method for studless tyres.

The block sipe edge effect in the pattern is effective for increasing the digging friction and breaking the water film occurring between the road surface and the tyre surface.

As shown in Fig. 7.10, the friction force increases as the number of pitches and sipes on the tyre circumference increases to create the edge effect. This is because the fewer the pitches, the longer the blocks become and the longer the area that comes into contact with the water film occurring in the road surface contact area. The same can be said of the number of sipes. However, each arrangement has a peak friction force; having too many pitches or sipes reduces the block rigidity, which results in block collapse and leads to a reduction in actual ground contact area.

While studless tyres can be said to be an item of Japanese technology born out of Japanese conditions, the main developments in Japan have been to do with developing tread rubber and tread patterns.

The following three developments in tread rubber are worth noting.

- Use of soft rubber to fit against the surface of the snow or ice
- Adding combined materials to scratch the surface of the snow or ice and improve the friction
- Arranging cavities such as bubbles to remove the water from the boundary layer occurring on the surface of the snow or ice

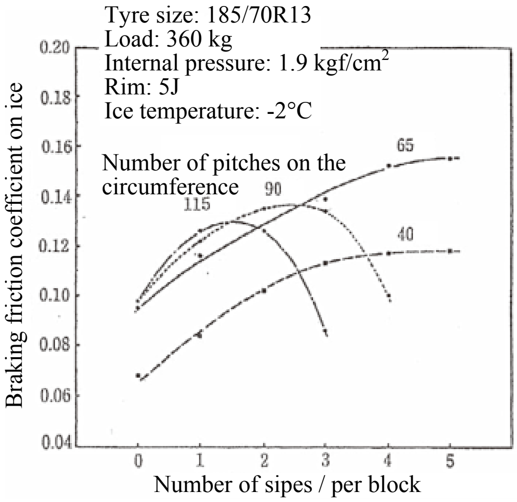


Fig. 7.10. Braking on Ice and the Edge Effect [3)]

In terms of pattern design, patterns have tended to use the scratching effect at the pattern edge and reinforce blocks that have been softened by using soft rubber.

(8) Summary

The above developments came about in response to the environmental issue of dust. These started out for the Japanese market, but have since built up a strong position and currently have a major market. As mentioned above, these are still being researched by tyre companies, with further performance improvements expected.

(See Chapter 1, Fig. 1.2 for an external view of a studless tyre.)

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1) *Supaiku Taiya Funjin Hassei Bōshi-hō [Methods to Prevent Dust from Spiked Tyres]*, Sendai Bar Association, February 1991, p. 13.

2) *Gomu Kōgyō Binran [Rubber Industry Handbook]*, fourth edition, The Society of Rubber Science and Technology, Japan, ed., January 1994, p. 754.

3) "Sutaddoresu Taiya no Kaihatsu (Jōyōsha Taiya) [Development of Studless Tyres (Passenger Vehicle Tyres)]", Sakamoto, Takao; Hirata, Yasushi: *Journal of The Society of Rubber Science and Technology, Japan*, Vol. 65, p. 713, 1992.

4) "Sutaddoresu Taiya no Kaihatsu (Torakku oyobi Basu-yō Taiya) [Development of Studless Tyres (Truck and Bus Tyres)]", Tomoda, Hajime; Ishikawa, Yasuhiro: *Journal of The Society of Rubber Science and Technology, Japan*, Vol. 65, p. 721, 1992.

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6) Ishikawa, Yasuhiro: *Journal of The Society of Rubber Science and Technology, Japan*, Vol. 70, p. 198, 1997.

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8) *Jidōsha-yō Taiya no Kenkyū [Studies on Automobile Tyres]*, Yokohama Rubber Company, ed., April 1995, p. 47.

9) *Jidōsha-yō Taiya no Kenkyū [Studies on Automobile Tyres]*, Yokohama Rubber Company, ed., April 1995, pp. 56-58.

10) Based on Fig. 2-7-3, *Jidōsha-yō Taiya no Kiso to Jissai [Foundation and Reality of Automobile Tyres]*, Bridgestone Corporation, Sankaido, 2006, p. 53.

11) *Gomu Kōgyō Binran [Rubber Industry Handbook]*, fourth edition, January 1994, p. 772.

12) *Jidōsha-yō Taiya no Kiso to Jissai [Foundation and Reality of Automobile Tyres]*, Bridgestone Corporation, Sankaido, 2006, p. 44.

8. Summary of Technology Progress

Fig. 8.1 shows the progress of the technology. Tyre technology is divided into broad categories: “seeds”, or product ideas from tyre companies to provide technology and develop products; and “needs”, or demands placed on tyre companies by society for products in response to issues that arise. Fig. 8.1 shows that while the major trends have varied for both “seeds” and “needs”, up until around the year 2000, “needs” and “seeds” products were appearing in an almost alternate progression. “Seeds” products also tended to relate to structural elements, while “needs” tended to relate to material elements; accordingly, structure and materials appeared in alternate progression.

8.1. Seeds and Needs in Tyre Development

New materials: nylon, SBR (needs / material elements)	→	Transition to radial (seeds / structural elements)	→	Wet μ/LRR (needs / material elements)	→	
	→	HPT A/S High performance Flattening (seeds / structural elements)	→	Lightweight / fuel economy (CAFE: US fuel consumption standards) Studless (needs / material elements)		

Following the post-war introduction of new materials (nylon, SBR), the transition to radial tyres began around 1970. During the oil crises, work reached a global scale on technology to avoid the trade-off between wet μ (grip on wet road surfaces) and LRR (low rolling resistance). Later, once the work on low fuel consumption as a result of the oil crises eased off, tyre manufacturers turned their attention to high tyre performance (flattening). In the 1990s, new global environmental issues arose, ushering in an age of “needs”, with very high levels of demand for ultra-low fuel consumption, ultra-lightweight tyres, studless tyres and safety.

High performance tyres (HPT, high grip tyres) and flattened tyres were recognised to be in a distinct category from fuel-efficient tyres (wet μ / LRR) in terms of grip and friction. However, there was a very high demand for technology that could avoid a trade-off, providing both high performance and ultra-low fuel consumption, as well as being lightweight.

As time progressed on from the 2000s to the present day, there came a turning point in the transition from HPT (“seeds”) to lightweight and fuel economy (major “needs”). Development issues such as uniformity, noise and driving ability, which were both “needs” and “seeds”. Fulfilling all of these criteria at once was a major hurdle. This was an era of significant additional required performances; this required technology that could integrate both materials and structure.

This age of major needs required a balance between multiple performance factors at once. The design theories that had been proposed by various Japanese tyre manufacturers from the 1980s onwards proved to be beneficial in providing a way forward.

Transitions in Tyre. "Needs" and "Seeds"

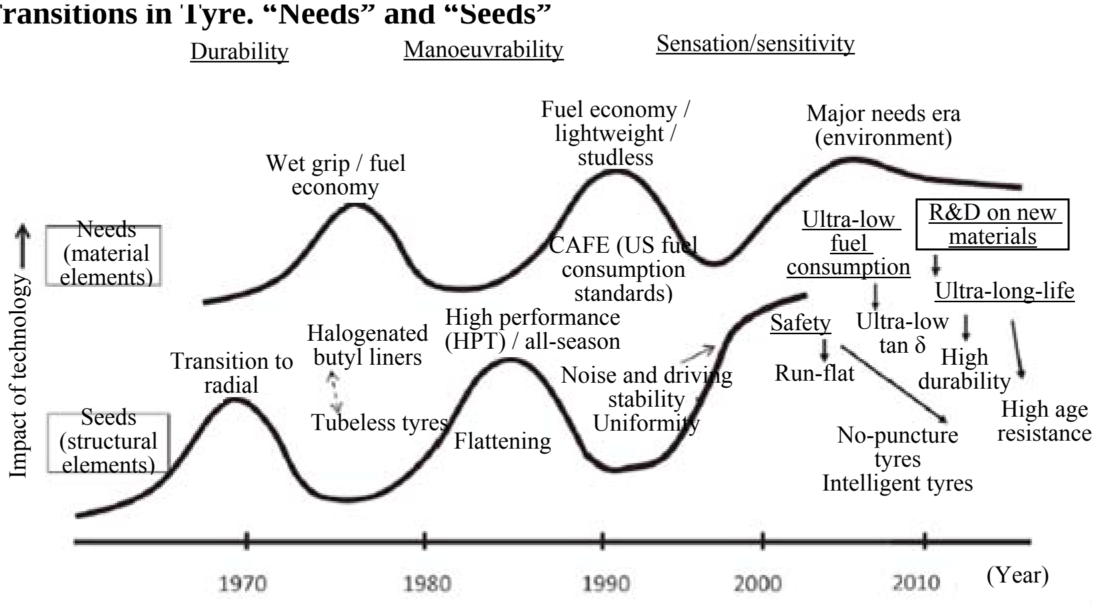

Fig. 8.1. Trends in Tyre Technology [1)]

Tyre Technology Development by Scale

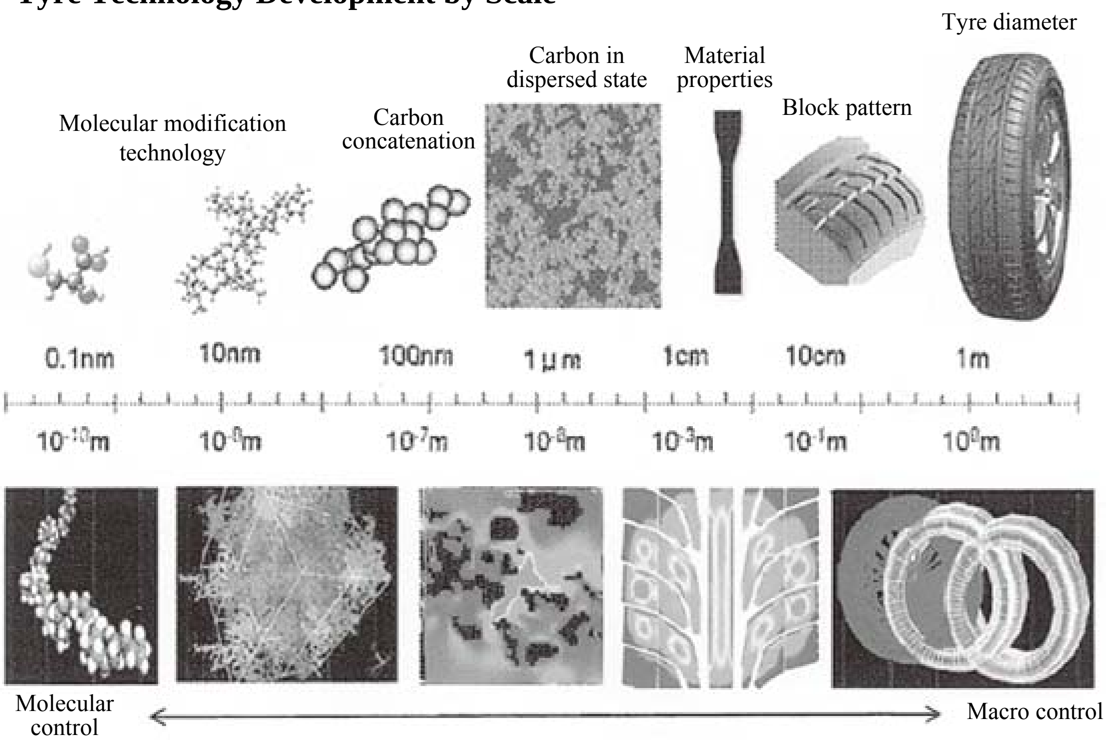

Fig. 8.2. Tyre Technology Development by Scale [2)]

8.2. Future Integration Methods

For future methods of integration, initiatives are being carried out as shown in Fig. 8.2.

This is the idea of tyre technology development by scale. From the micro perspective, tyre structure fits into the nano-world of molecular reaction control, while the world of tyre surface tread design is a world of centimetres, and the world of rolling resistance – repeated loading and non-loading due to rotation – is a world of metres. In other words, tyre performance ranges in scope from nano-order phenomena to metres. How all of these factors are controlled, from molecular order to metre-level order, affects tyre performance. The way these parameters are calculated and incorporated will become a major aspect of performance competition. Many Japanese tyre manufacturers are basing their designs on these ideas and are working effectively in the environmental age.

In this technological environment, the question remains as to how to balance the many demands placed on tyres, many of them mutually exclusive; however, progress has been made on laying a foundation. This has been made possible by the large number of automobile manufacturers in Japan, as well as the large number of tyre manufacturers. This has meant that tyre manufacturers have had to compete with each other to achieve the various improved performances demanded by many automobile manufacturers, discovering and carrying out ways to fulfil these desired performance factors. Tyre theories were one result of this adaptability.

The *Gomu / Erasutomā to Mirai no Kōtsū [Rubbers / Elastomers and Future Transportation]* Rubber Technology Forum tyre team gave the following prediction of future tyre performance, shown in Fig. 8.3. The team predicted that by 2030, both wet μ and rolling resistance will be around 40% better than they were in 1980.

Progress in Tyre Performance

T. Haraguchi Toyota at IRC 2005
2030 extrapolated from published data

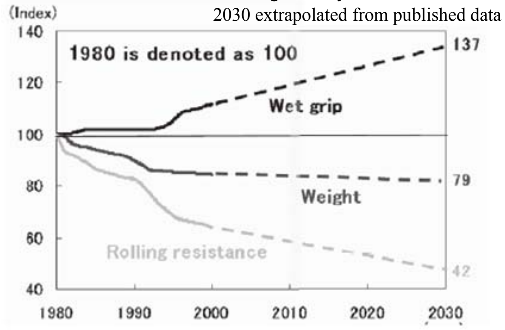

Fig. 8.3. Predicted Future Tyre Performance [3)]

There is a sense that current tyre technology has been largely established as culmination of post-war technologies.

Hardly any of the ground-breaking developments in this technology have come from Japan, although Japan has mastered and optimised technology invented overseas to an advanced level. However, Japan has certainly reached a high level of tyre technology, mastering many technologies, balancing them and taking them to new levels, for example, a very high level of advancement is evident in the tyre theories published by various tyre manufacturers.

While there is currently a sense of plateauing in technology, when we enter a new growth period, the challenge for the next generation will be how to implement uniquely-Japanese technology. While this can be seen in embryonic form, some driving force will be required to develop it.

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2) *Gomu / Erasutomā to Mirai no Kōtsū [Rubbers / Elastomers and Future Transportation]*, The Society of Rubber Science and Technology, Japan Rubber Technology Forum, March 2010, p. 75.

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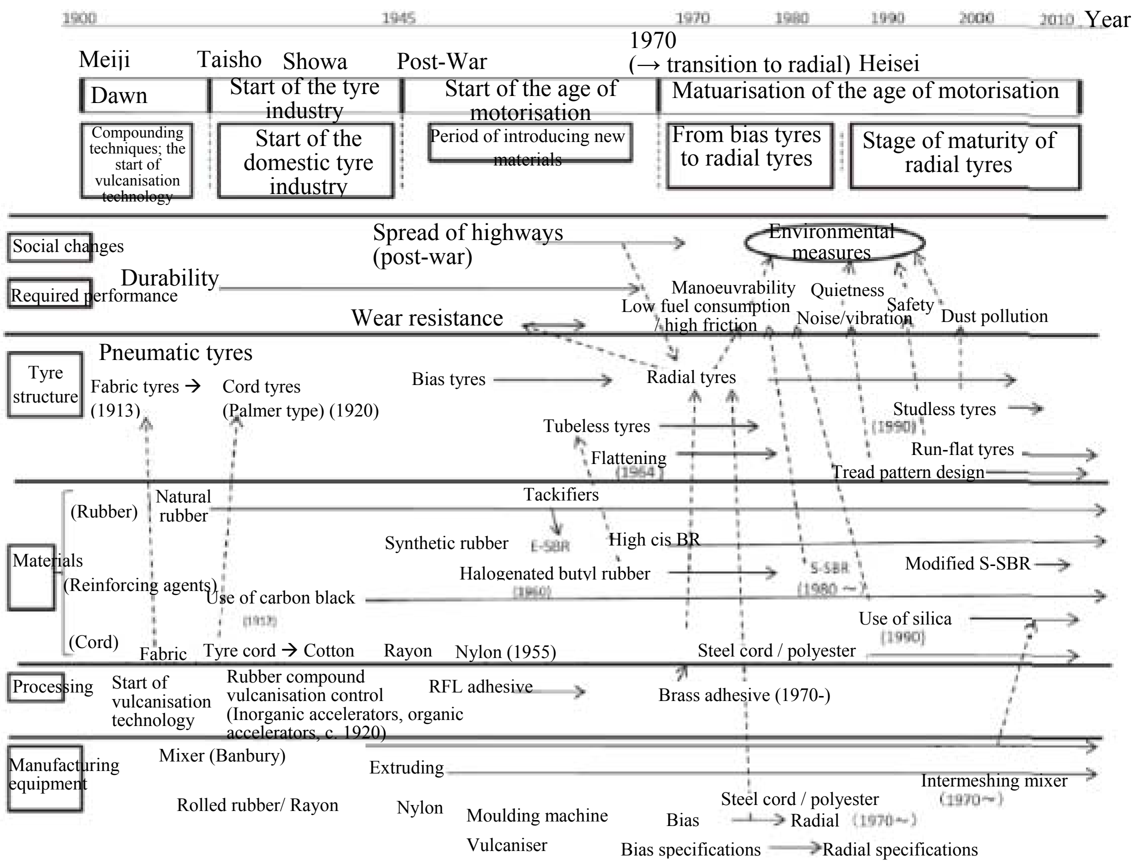

Fig. 8.4. Flow Diagram of Tyre Technology

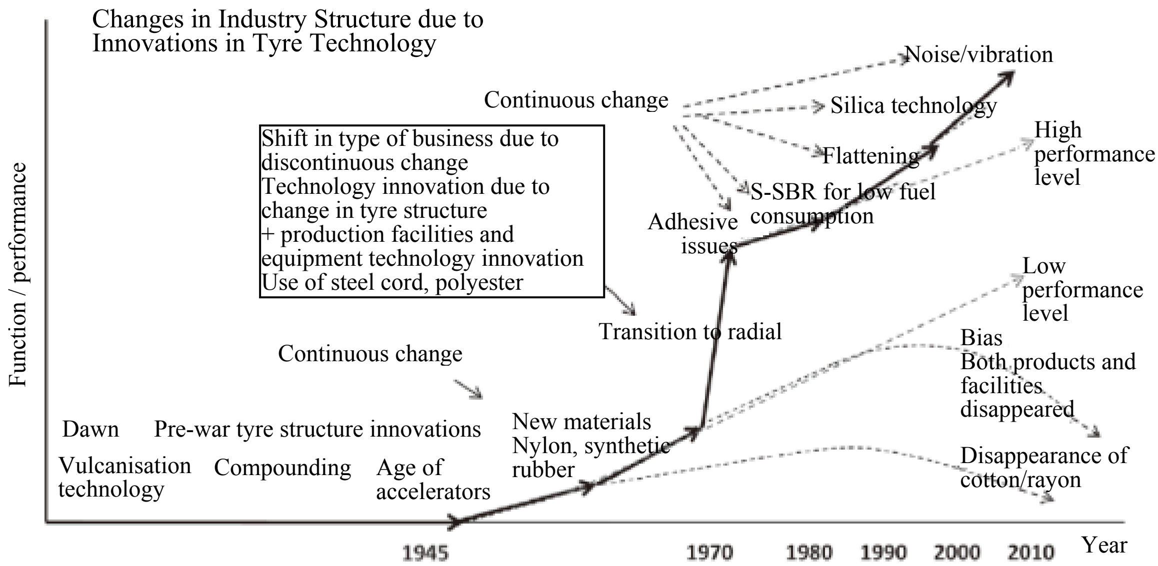

Fig. 8.5. Changes in Industry Structure due to Innovations in Tyre Technology

(Appendix) Tyre Technology Timeline

Overall trends; little epoch-making technology from Japan, implemented around 1-10 years behind the West.

Text in bold represents Japanese technology; underlined text represents epoch-making technology.

Tyre Related	Material Related
1769 Steel disc tyre used on Cugnot steam car wheel (France)	<u>1839 Goodyear discovers vulcanisation phenomenon (USA)</u>
1835 Solid tyre invented	
1842 Hancock solid tyre commercialised (UK)	1843 Hancock obtains patent for vulcanisation (UK)
<u>1845 Thomson obtains pneumatic tyre patent (UK)</u>	
1863 Michelin established (France)	
1871 Macintosh patents hollow solid tyre (UK) Continental-Gummi established (Germany)	
1872 Pirelli established (Italy)	
1886 Tsuchiya Rubber Factory established, Japan's first rubber company	
<u>1888 J.B. Dunlop obtains pneumatic tyre patent (UK)</u> Dunlop's patent commercialised (UK) Michelin clincher tyre produced (France)	
1890 Hartlet clincher tyre patented Goodrich produces the first American tyre (USA)	
1892 United States Rubber (later Uniroyal) established (USA)	
1893 Solid tyres used on Daimler automobile (Germany) B.F. Goodrich automobile tyre prototype (using tyre fabric) (USA)	
1896 Dunlop Holdings established (UK)	
1900 Firestone established (USA)	
1902 Appearance of tyres with tread pattern	

(USA) **Meiji Rubber produces Japan's first automobile tyre**	1904 Reinforcing effect of carbon black discovered
1904 Bead wire straight side tyre (USA)	<u>1905 Oenschlager (USA) discovers organic vulcanisation accelerators</u>
1908 Palmer-type tyre patented (USA)	
1909 Dunlop Rubber (Far East) established in Kobe (now Sumitomo Rubber)	
1910 Appearance of Goodrich cord-type tyre (USA)	<u>1912 Carbon black used as rubber reinforcing agent (USA)</u>
1912 B.F. Goodrich established (USA)	
1913 Dunlop (Far East) produces the first domestically-produced tyre	
<u>1915 Use of woven cord by J.F. Palmer</u>	
1917 Yokohama Rubber founded	<u>1916 First Banbury mixer prototype (USA)</u>
1918 Appearance of pneumatic truck tyres (USA)	
1920 Pirelli produces cord tyres (Italy)	1924 Discovery of anti-ageing agents
1921 Yokohama Rubber produces Japan's first cord tyre	**1926 Toyobo produces Japan's first tyre cord**
1923 Low-pressure tyre (balloon) developed (18-30psi vs 20-55psi)	
1928 Motorcycle tyres standardised in the USA	
1929 Michelin railcar tyre prototype (France)	
1930 Bridgestone produces Japan's first tyre using domestic technology (by Nihon Tabi)	
1931 Bridgestone established Michelin railcar tyre announced (France)	1930 DuPont succeeds in commercialising synthetic rubber
1932 Agricultural and construction machinery tyres standardised in the USA	
1934 Michelin commences research on the application of steel cord for truck tyres (France)	<u>1935 Synthetic rubbers Buna S and Buna N produced (Germany)</u> <u>Carothers invents Nylon 66</u>
1937 Michelin announces steel cord tyre (bias)	**1936 Japanese companies produce rayon tyre**

(France)	**prototype**
1938 Reinforced rayon tyre appears in the USA	1939 Schlank invents Nylon 6
1940 Butyl tube prototyping begins (USA)	1939 RFL adhesion discovered (USA)
1942 Military nylon tyre prototype (USA)	1940 Butyl rubber (IIR) announced (USA)
	1941 Synthetic rubber GR-S production expands
1943 Toyo Tire & Rubber established	
1944 Dai-Nippon Aircraft Tyres (later Ohtsu Tire and Rubber) established	
1946 Steel radial tyre patented and production commences (France)	
1947 Tubeless tyre invented (USA)	
1948 Michelin enters commercial radial tyre production (France)	
1949 Nitto Tyres (later Ryoto Tyres) founded	**1950 Use of SBR begins in Japan** **Use of reinforced rayon cord begins** Oil-extended SBR commercialised (USA) **Nippon Zeon founded**
1951 Pirelli releases a radial tyre (Italy) **First rayon tyre produced in Japan**	1952 Ziegler catalyst invented (Germany) 1954 IR (polyisoprene) successfully synthesised (USA)
1955 Tubeless tyres adopted on new automobiles (USA) **Tubeless tyre production starts in Japan**	1955 BR (polybutadiene) synthesis announced (USA) **First use of nylon cord**
1956 Use of snow tyres spreads in Europe	
1958 Nylon tyres produced **Snow tyres appear in Japan**	 **1957 Japan Synthetic Rubber founded**
1960 Radial tyre prototype (Japan) **Snow tyre production begins (Japan)**	**1958 Japan's first synthetic rubber successfully commercialised** 1960 Halogenated butyl rubber appears (USA)
1962 Polyester tyre cord becomes the norm (USA) **Steel cord tyre produced (Japan)**	1962 Polyester cord becomes popular (USA) **Successful polyester fibre production**
1963 First exports by Bridgestone to Malaysia and Singapore (later withdrawn)	
1964 Flattened tyre (LSH70 %) first used (USA)	

Spiked tyre produced (Japan) **Okamoto Riken enters the tyre business** Belted bias tyres appear around this time (USA)	
1966 Polyester tyres fitted to new vehicles (USA)	
1967 Polyester tyres fitted to new vehicles (Japan)	1967 Fibreglass cord first used (USA)
1968 FMVSS come into force (also related to tyres) (USA) Belted bias tyres produced (USA) **Radial tyres fitted to new vehicles (Japan)**	
1969 Belted bias tyres produced (Japan)	
1970 Steel radial tyres produced (Japan)	
1972 JATMA "Automotive Tyre Safety Standards" issued (Japan)	1972 Aramid cord used in tyres (USA)
1973 TGS (safety tyre) prototype (Japan)	
1975 ECE30 safety standards start (Europe) **Puncture sealing tyres produced (Japan)**	
1977 Obsolete tyre grinding facility completed (Japan) Japan joins ISO and starts being active	
1978 Use of obsolete tyres as fuel for cement kilns (Japan) JIS standard D4320 incorporates safety standards such as dynamic tyre testing Fuel efficient tyres (1979 energy crisis) HPT tyres	
1983 Run-flat tyres	
1986 Studless tyres increase in sales	
End of 1990 Spiked tyre production ceases; sales cease at the end of March 1991	
1980s-1990s Japanese companies publish tyre theories	
Early 1990s Michelin announced green tyres Since these contained silica, silica began to be	

used around the world, particularly in passenger vehicles; progress was also made on related processing technology.	
2000- Popularisation of run-flat tyres (side-reinforced)	

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The above table was created using references from the following sources, among others.
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Yokohama Technical Research team	

List of Candidates for Registration

No.	Name	Format	Location	Manufacturer	Year	Reason for Selection
1	The first domestically produced automobile tyre	Conserved	Sumitomo Rubber Industries Chuo-ku, Kobe	Dunlop (Far East)	1913	The Dunlop Rubber Co. (Far East), Ltd. started production of automotive tyres in 1913. At this time, 25-26 tyres were produced in Japan and were very hand-made in nature. These “fabric tyres” or “canvas tyres” were produced by overlapping cotton fabric. The first domestically produced automotive tyres are a valuable piece of technology heritage.
2	Main landing gear tyre used on a Type-0 fighter for the Imperial Japanese Navy	Conserved	Yokohama Rubber Company Hiratsuka, Kanagawa	Yokohama Rubber Company	May 1943	A Zero fighter tyre made during World War II. It was fitted to a fighter plane found in Guam in 1963. The aircraft was no longer distinguishable, but the tyre was still in useable condition. It is still preserved in that state to this day. Wartime tyre technology developed for the military and was very high performance, as can be seen. The size is 6.00-17.5.
3	‘Falcon’ fighter tyre	Conserved	Bridgestone Today Kodaira, Tokyo	Nippon Tyre Company	February 1944	Valuable as a highly durable product used on a fighter aircraft during the war. Japanese wartime tyre technology is thought to have reached quite an advanced level using only Japanese technology. This tyre was made in 1944 and was fitted to a ‘Falcon’ fighter. Even in its current state it appears to have hardly deteriorated. The size is 5.70-19.

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