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RACING CAR CHASSIS

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ABSTRAKT

Cílem této bakalářské práce je analýza současných konceptů podvozků závodních okruhových aut. V první části práce je zpracován historický vývoj, charakteristika kol a pneumatik s reprezentací dobře známých produktů. V druhé části je popsán systém odpružení, pružné média a tlumící členy. Systémy odpružení je zde rozdělen na nezávisle a polozávislé zavěšení kol a odpružení pevných náprav. Následující oddíl této práce je zaměřený na standardní kontrolní systémy, jako jsou ABS, ESC a TSC. Závěr přináší rychlé shrnutí této problematiky.

KLÍČOVÁ SLOVA

historický vývoj, kola, pneumatiky, pružné média, systémy odpružení, standardní kontrolní systémy

ABSTRACT

The aim of this bachelor thesis is to analyse contemporary concepts of circuit race car chassis. In the first part of the thesis, the historical evolution is described and then wheels and tires characteristic within some well-known brand products are represented. The second important part includes the suspension systems, springing medium and damping members. The suspension systems are further divided to independent and semi-independent solutions and rigid axle suspensions. The end of this thesis deals with the standard braking control systems, such as ABS, ESC and TCS. The conclusion brings the quick summary of this subject.

KEYWORDS

historical evolution, wheels, tires, springing medium, suspension systems, standard control systems

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Prohlašuji, že tato práce je mým původním dílem, zpracoval jsem ji samostatně pod vedením prof. Ing. Václava Píštěka, DrSc a s použitím literatury uvedené v seznamu.

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INTRODUCTION

Motorsport is a group of sport which primary involve the use of motorized vehicles for racing competition. A great deal of success is largely connected with technology innovation and the driver’s skills, eventually with less desirably technical failures, which is the part of this kind of sport. A various sorts of motorsport can be differentiated, such as Formula racing (F1, IndyCar series), Touring car racing (WTCC-World Touring Car Championship, V8 supercars), Sport cars racing (24 Hours of Le Mans, FIA GT1 World championship), rallying (WRC-World rally championship), drag racing, targa racing, off-road racing and so on.

This bachelor thesis deals with analysis of racing car chassis in terms of specific requirement imposed upon them. That analyze is related to contemporary concepts of circuit race car chassis. The thesis provides only descriptions of contemporary suspensions in terms of the function principle, because there is a huge diversity in design and construction. Any technical innovations of rally or off-road vehicles are not going to be concerned.

1 HISTORICAL EVOLUTION

Road vehicle design and manufacturing evolution are over one hundred years in progress. The tradition led us recognize rarely chassis, as visible subsystem ladder framework, to current sophisticated powertrain system. Ladder framework chassis was assembled separately from the rest of the car, due to present chassis components, which are assembled directly to the body. The situation was completely different in the past. In the first cars, the chassis was designed as a real self-moving subassembly, which was composed of:

- A structure, usually known as 'ladder' framework, able to carry on all the remaining components of vehicle like body.
- The suspensions used for mechanical linkage of wheel with framework. Independent mechanical linkage was not present in the far past.
- The wheel and their tires.
- The steering system for changing wheel angle (a toe angle) to the vehicle direction.
- The braking system for the acceleration or deceleration of the vehicle.
- The transmission for applying engine torque to the driving wheels.

When this group of components within engine assembly was attached together, whole part was able to autonomously move from the shop of the car maker to that of the body maker. This contemporary particular architecture and function can be found in industrial vehicles.

In almost every car the chassis structure cannot be separated from the body, because it is being floor (platform). Too many car models of single brand are released on the identical platform. To understand the significance of platforms, one must appreciate that manufacturers spend a fortune developing platforms and the production lines that build them. As a result, automakers only have so many platforms available to them, and building multiple models from a single platform yields economies of scale. This is why you can say, the Volkswagen Beetle is built on the Golf platform.

1.1 RIGID AXLE MECHANICAL LINKAGES

Rigid axle mechanical linkages are so-called dependend systems or mechanical linkages. It is the simpliest system of wheel's suspension mounting, which is physically linked. It is basically a solid bar under the car, kept in place by leaf springs and shock absorbers. They haven't been used on mainstream vehicles for years, because for these three reasons:

- Primary deformation - The wheel wobble (shimmy) is the main disadvantage, because wheels are physically linked. The bean can be set into oscillation, if one wheel hits a bump and other doesn't. It sets up a gyroscopic torque about the steering axis, which starts to turn the axle left-to-right [1].

- Secondary deformation - The weight is more likely unsprung weight. Solid axles weigh a lot and either needs sturdy, heavy leaf springs or heavy suspension linkage to keep their wheels on the road. The unsprung weight (or the unsprung mass) is the mass of the suspension, wheels, wheel bearings, wheel hubs, tires and a part of the weight of driveshaft, springs, shock absorbers, and suspension links and other components directly connected to them [3]. The mass of the body and other vital components supported by the suspension is the sprung mass. Even if the vehicle's brakes are mounted outboard, their weight is still considered part of the unsprung weight. The next figure demonstrates why unsprung weight is so important.

Fig.1 Un-sprung weight [3]

- Alignment of wheels cannot be performed on the rigid axis. From the factory, there are perfectly set, but if the beam gets even slightly distorted, you can't adjust the wheel to compensate.

The primary deformations were caused by breaking (S-deformation) or by vehicle roll, which means different elongations of the two suspensions of the same axle. The first motion could cause resonances of entire driveline, while starting up or braking. The roll motion of body, due to centrifugal force in a turn, forced the rigid axle to steer, while the vehicle is turning. The scheme at the top of figure 2 demonstrates this behavior of Rolls-Royce rear suspension, which can provide a self aligning steering action, while driving on asymmetric obstacle. The lower part explains shimmy effect, mentioned before. The last figure 3 of this subchapter gives an example of mechanical solution. This solution is adding two rods with double function of avoiding the S deformation and of giving the axle an understeering behavior [1].

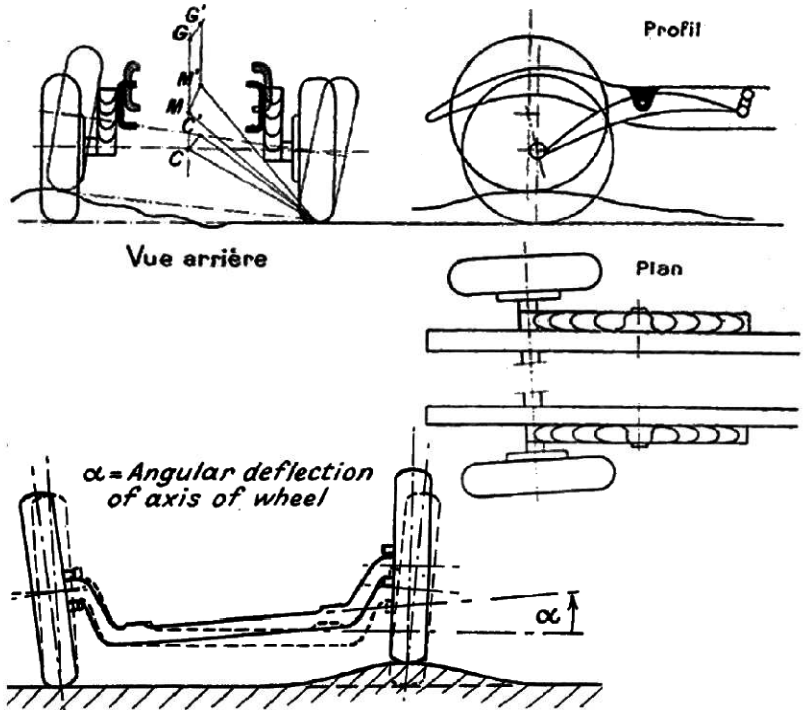

Fig.2 Upper scheme – Rolls-Royce rear axle, Lower scheme – shimmy phenomenon [1]

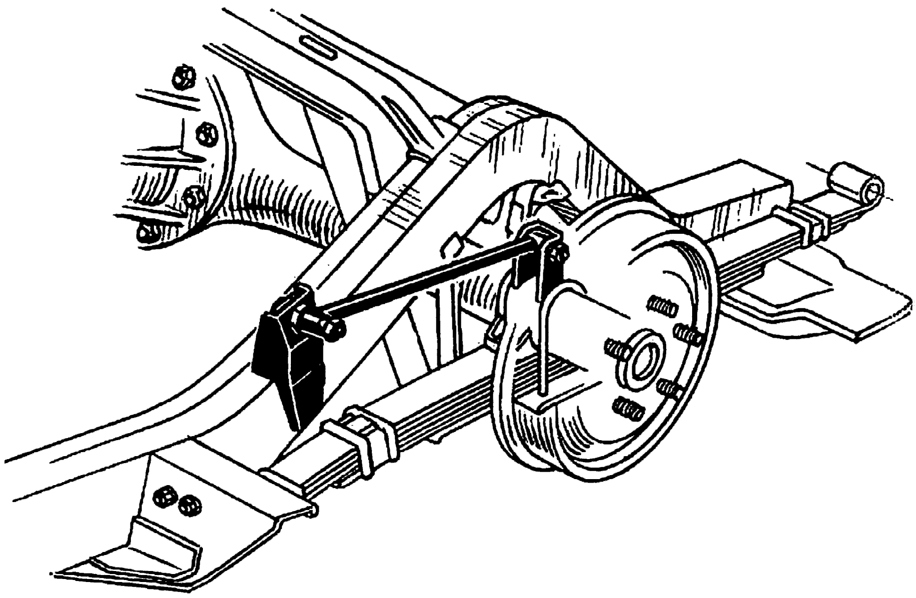

Fig.3 Rigid axle with leaf spring – avoiding S deformation [1]

1.2 THE INDEPENDENT SUSPENSION MECHANICAL LINKAGES

FRONT AXLE SUSPENSION

Rigid axle mechanical linkages with leaf springs controlled the marked for a long time. But technical innovation has been vital for furthermore suspension system concept. The innovation consisted in the advantaged obtainable for the entire vehicle architecture. The front rigid axle could not be set too close to the ground and engine had to be positioned at exact height over the ground. The front part of the body begun just behind the front axle. The independent suspension should not copy this layout. The engine could be set down and forwards. Reduction of the height of the centre of gravity improved speed, because the use of streamlined aerodynamic shapes.

The independent suspension replaced older rigid axle suspension in the 1930s. However, we can find many applications of independent suspensions before mentioned date.

Let’s consider steering suspension, which first dated to 1898. Function is based on wheel hubs guided by vertical tubes. Front wheels are attached and guided by telescopic steering fork reminding bicycle fork. They are strengthened by a transversal leaf spring fit in the middle of the body. The solution was first designed and produced by Lancia. Regarding to simplicity of the whole mechanism, there is no need to analyze driving behavior.

The predecessor of the first racing cars was Lancia Lambda launched in 1922. The independent suspension was designed by Falchetto, who was under the guidance of Vincenzo Lancia. The most important feature was a huge problem of efficient lubrication of the sliding tubes. When coil springs came on scene, there was the new introduction of the independent suspension system. It was presented by Cottin-Degouttes on the car showed in the figure 4 and introduced in 1927. The tubes are slightly inclined to the centre of the car, because of circular path of the spring tip. Elastic medium is again a cross leaf spring. Kinematic properties can resemble a double wishbone suspension.

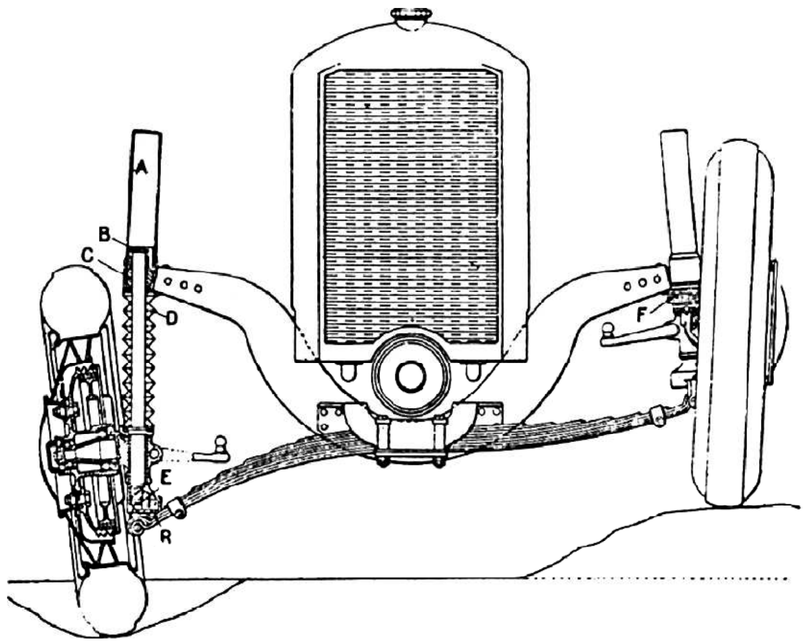

Fig.4 Front suspension presented by Cottin-Degouttes [1]

A different solution of the independent suspension is attributed to Dubonnet, an important car designer, who diffused his work to Fiat and other car manufacturers. Fiat applied this solution into production in 1935. The suspension consists of sealed bearing element (cartridge), which integrates helical spring in the same oil as the shock absorber. The construction is explained in the figure 5. The cartridge is firmly attached to a cross member of the chassis structure. The suspension arm can swing but not steer. The steering system is provided by a knuckle between the wheel strut and the oscillating arm.

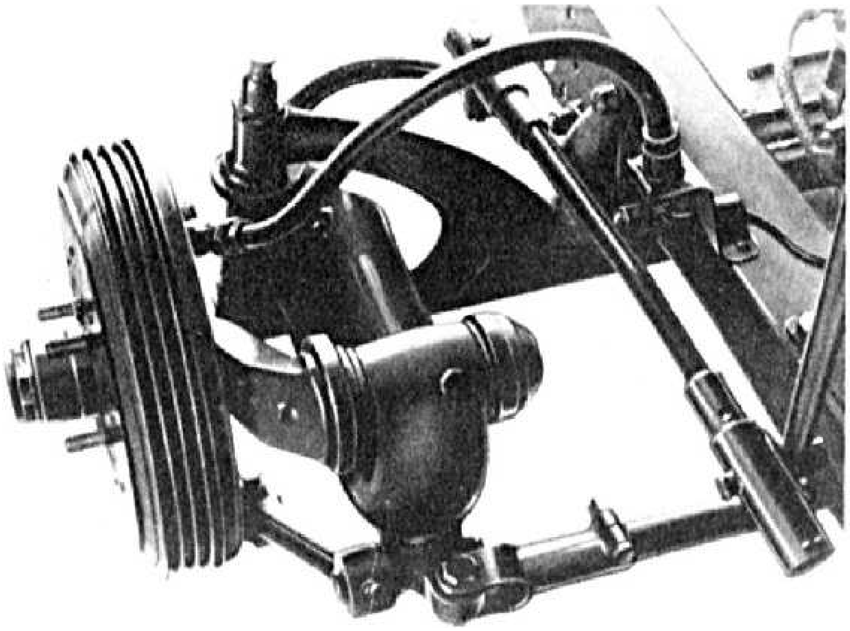

Fig.5 Fiat independent suspension designed by Dubonnet [1]

Following innovations of the front independent suspension are very similar to those nowadays. That's why they are going to be discussed in the chapter 3. A suspension very similar to double trailing arms is attributed to Porsche. It was developed in 1931 and until 1970s on the Volkswagen Beetle and others cars from this company. While they reduced shimmy effect, later it became real trouble feature: In turns within centrifugal forces vehicle body started to tilt. The roll angle was equal to a camber angle. The camber angle characterizes scale of the wheel tilt among the ground [1].

To improve this undesirable situation, double wishbone suspension were right choice. One of this example was introduced by Studebaker in 1939 and followed or improved by many car manufacturers until the present. This kind of suspension is shown in the figure 6. I would like to remake on an elastic element, which is still the transversal leaf spring. Reliability and the function of two elements (the arms and the spring) were the only reason not to keen of abandon manufacturing.

Double wishbone suspension with unequal length arms spread rapidly in the following years. This type became almost common in front axles during the 1960s. The construction of the double wishbone suspension with fairly good elastokinematic behavior was very similar to present racing cars. This kind of the suspension with stamped steel low thickness steel arm and coil springs was launched by Fiat in 1950 on the 1400 models.

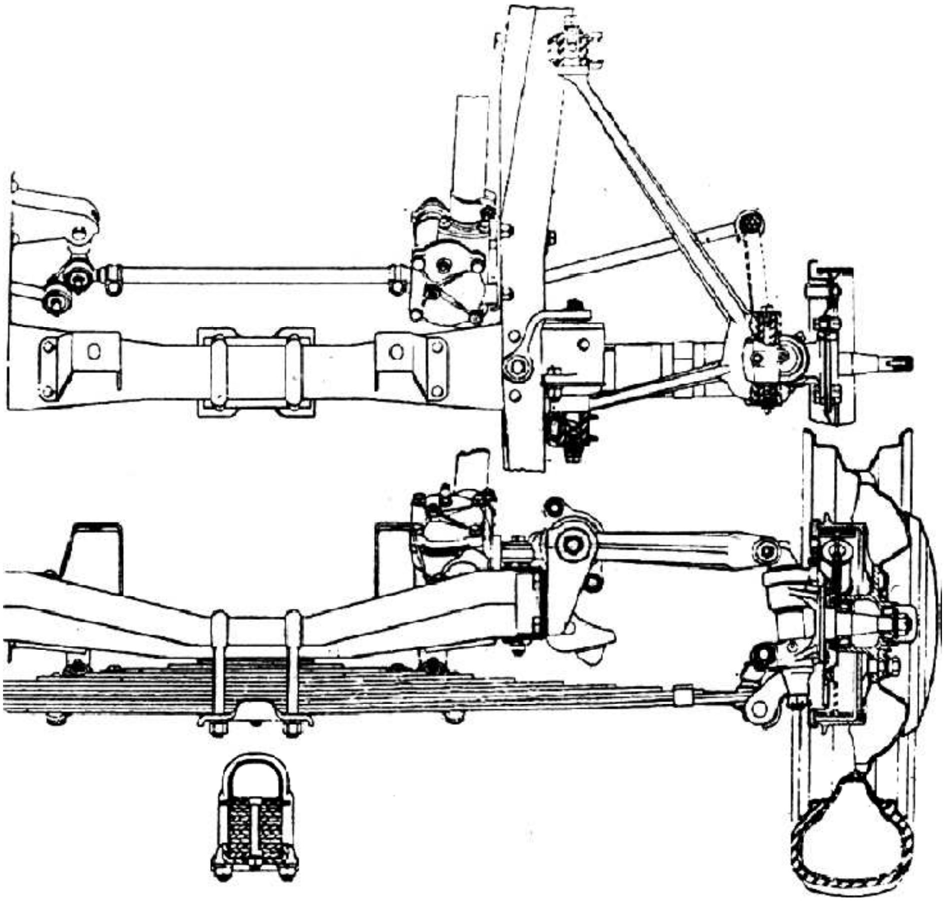

Fig.6 Front suspension made by Studebaker in 1939 [1]

McPherson, a design engineer of Ford in the U.S., introduced to the world his front independent suspension system in 1947 and it was also named after him. It can be considered as a double wishbone with different length arms. The length of the upper arm is infinite. This lack of material cannot by connected to the cost reduction or conserving material. On the other side, it contributed to the diffusion of modern front wheel driven cars. The lack of upper arm helped to make necessary space for a transversal engine installation. The reduction kinematic movement in comparison to the double wishbone solution is not very relevant and this solution is also applied to contemporary sport cars.

The final innovation of the double wishbone suspension came in 1980s by Honda developers. It conceived a bent wheel strut. The descendants of the McPherson and Honda suspension with tiny details today share the market.

REAR AXLE SUSPENSION

Rear suspension history is in certain way much more complicated. It should not be forgotten that rigid axle, enriched with elastic member more sophisticated like leaf spring, had long life both front and rear driven cars. Rear rigid axle, obtained with coil springs and more complicated linkages, can be found on older sport or luxury cars. They had quite good kinematic behavior.

One of this application was presented by Alfa Romeo on different cars starting in the 1970s. Figure 7 shows the design. The Rigid axle is formed to a triangular structure, which is linked to a spherical joint in the front. Suspension stroke and body roll (the roll angle) do not effect axle steering achieved by guidance. The guidance is given by a Watt mechanism in the back. The Watt mechanism (Watt’s linkage) intends to prevent relative sideways movement between the axle and body of the car [1].

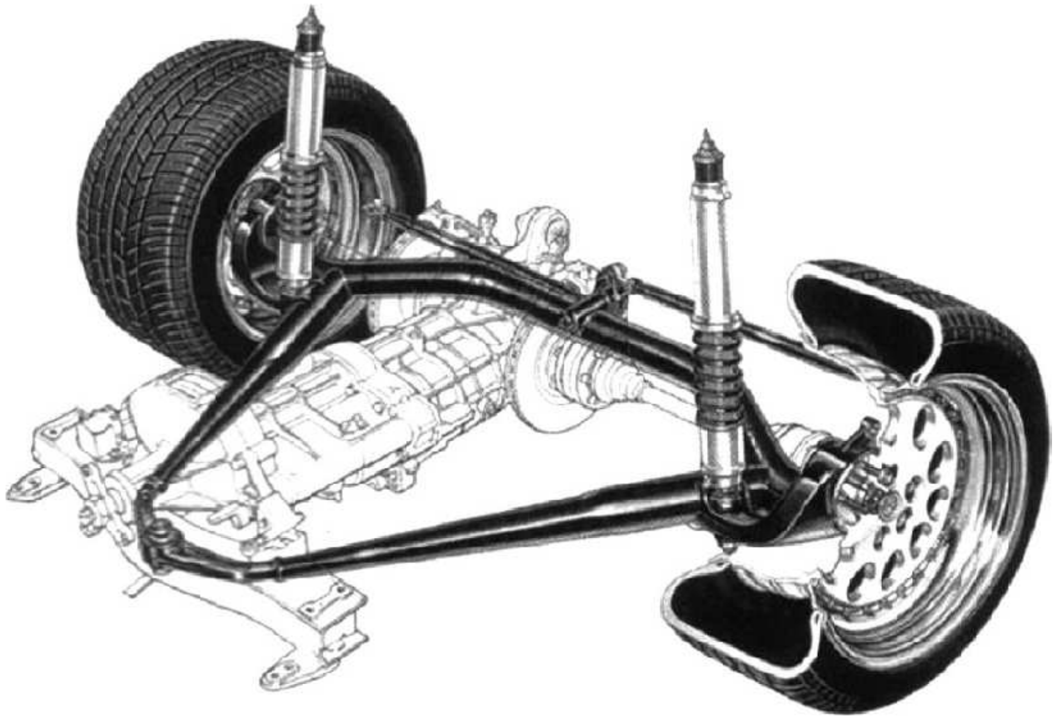

Fig.7 Alfa Romeo rigid rear axle [1]

A well shaped and spacious trunk required better solution than the rear rigid axle. One of this solution was eventually conceived by Volkswagen in 1969. A new rear suspension was quite suitable to front wheel driven cars. This so called semirigrid axle or twist axle spread to the most architectures. On twist axle the structure that bears the wheels is characterized by a steel bar with open cross section. By using this feature the structure was flexible to differential suspension strokes and also stiff to side forces.

In conclusion of this historic overview of car suspension, it should not be forgotten a multilink architecture. It represents the top of suspension evolution. Mercedes was first who introduced it during the 1960s on competition and sport cars. But the first mass production started in 1982 and it is shown in figure 8. We can apply maximum of five linkages to reduce the six degrees of freedom of a free body in the space [1]. The multilink is conceived of 5 linkages to obtain the maximum number of adjustable parameter reaching the ideal behavior. The multilink minimizes camber variation. We can also optimize steering behavior and longitudinal flexibility. The multilink suspension group is very wide. It can be found in almost every contemporary rear wheel driven race car with front engine (Nissan GTR R35).

This subchapter summarized the last 60 years of automotive history, but evolution has not stopped.

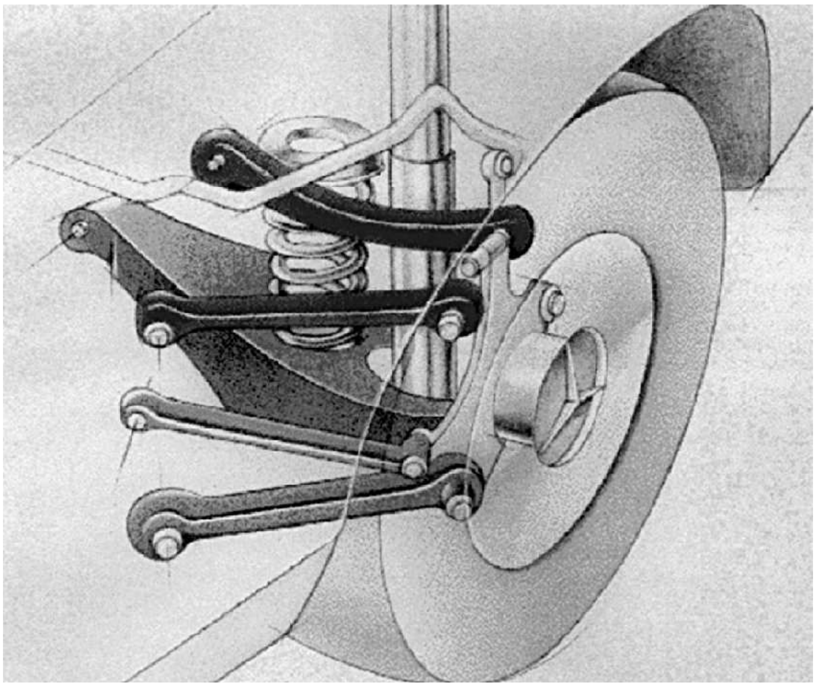

Fig.8 Multilink rear suspensions by Mercedes [1]

2 WHEELS AND TIRES

A Wheel rims, as it might sounds strangle, are not really part of suspension, except as tire carriers. Wheels, as a unit, have got two vital functions. The first function support the weight of the vehicle by exchanging vertical forces, caused by acceleration of gravity, with ground surface. And the second function allow to exchange with road surface longitudinal and side forces. This provides vehicle movement and path control.

2.1 RIM CHARACTERISTIC

A rim of a wheel is outer circular shaped metal on which the inside edge of tire is mounted on. A unique characteristic of the rim is that it allows fast and simple replacement of the tire. The wheel is made of a disk and of a flange, which are usually integral. Figure 9 describes parameters for simplification.

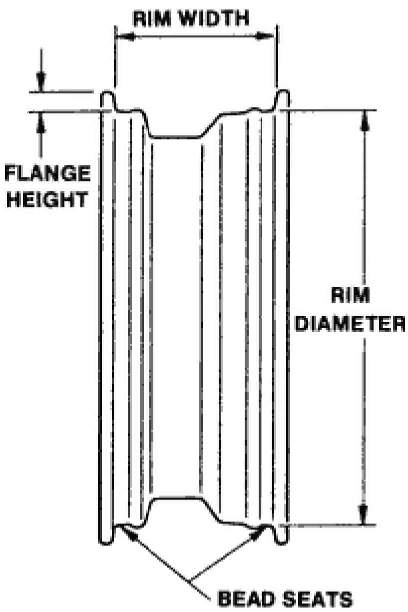

Fig.9 The wheel parameters [4]

The wheel size measurement is interpreted in the following example [1]:

$$8\frac{1}{2}\,J\;x\;18,$$

to show the rim width dimension (in inches) of 8,5” (215,9 mm) and the rim diameter dimension of 18” (457,2 mm). The letter J represents the most common type of the rim profile.

Rims can be made of stamped and welded steel or cast aluminum or magnesium. This last option is the most preferred in race cars, otherwise it can be found in classic mainstream vehicles. For better overview of the wheel construction I am going to specify modern BBS racing wheels. Most of the BBS racing wheels consist of 3 pieces – a centre section made of magnesium and rims made of high quality aluminum. The centre section height is vital for clearance of a caliper mounting. The offset of the wheel and another technical specification are clarified in figure 10. BBC racing wheels are available in 4 and 5 bold-circles and also in centre-lock systems, which allow mechanists to replace wheel very quickly during the race. Normally they are mounted on the car with flathead nuts with sleeve and washer, but they are also available for roundhead or taperhead systems. BBC provides two types of a wheel profile – *flatbase wheel* or *drop-centre wheel*. The flatbase wheels are conceived of the centre section and rims in the same diameter. Because of the equal diameter of the flatbase wheels shape, it is impossible to mount or remount a tire. The wheel has to be disassembled for tire changing and then reassembled on the tire. Otherwise damage is caused. A wheel with rims in bigger diameter than the centre section calls the drop-centre wheel. Because of the smaller diameter in the middle of the drop-centre wheels shape a tire that can be mounted in the same way as on a road wheel [5].

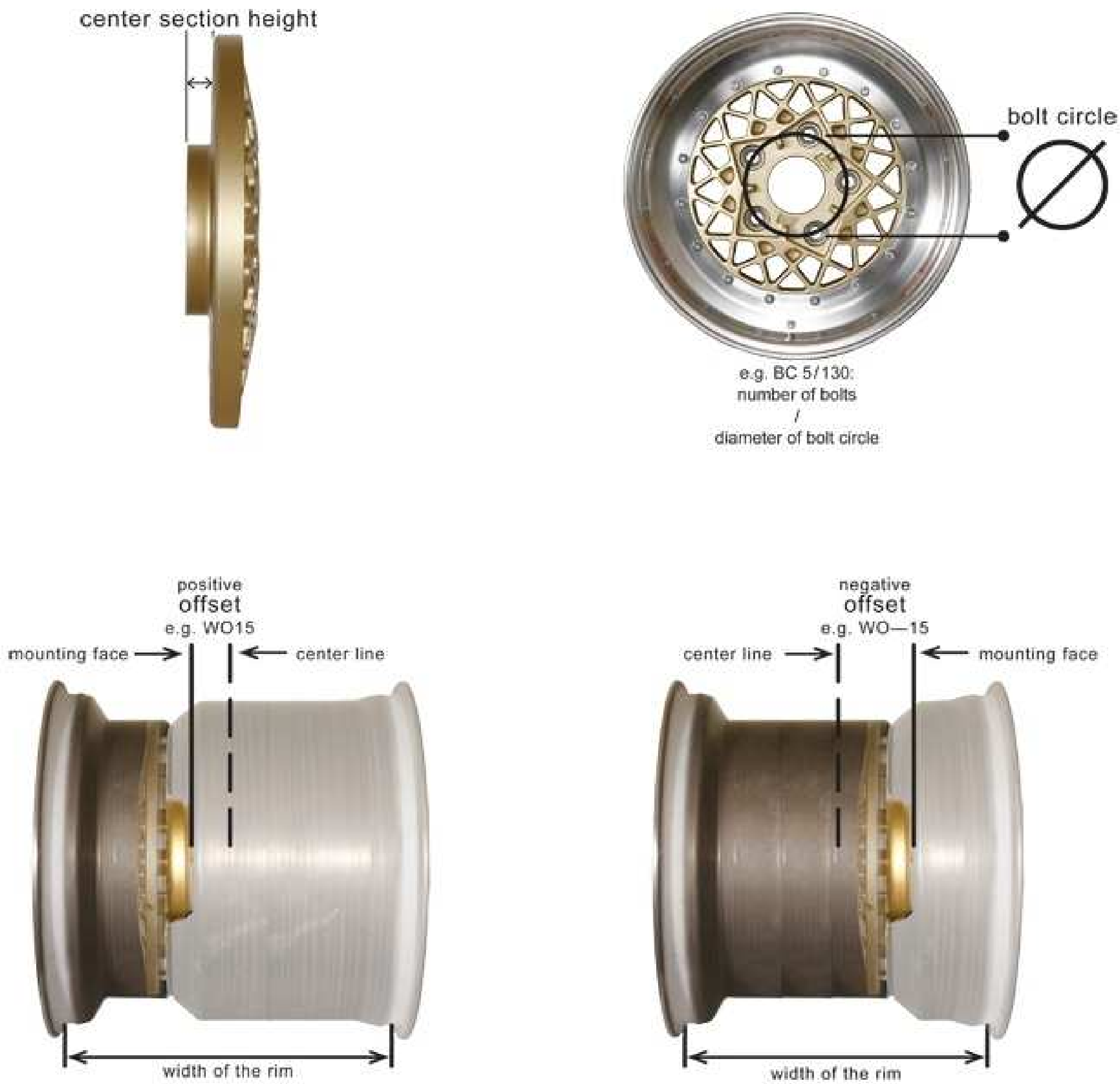

Fig.10 BBS racing wheel – the centre section, offset and bolt circle [5]

2.2 TIRE CHARACTERISTIC

The rigid structure of the wheel (the disc) is surrounded by a flexible element, which consists of the tire and its tube. They are supposed to maintain inflation pressure. Tubeless tires, the most preferred today, are hermetically fitted to the wheel and they provide improved safety because of slower loose of pressure. The tire is made of many layers of rubberized fabric (plies) with reinforcement cords. The unique mechanical characteristic is distinguishable by the orientation of the warp or profile and cords. That orientation is characterized by the angle between the direction of the cords with respect to the circle direction of the tire. This angle is called the *crown angle [1]*. Better handling characteristic is obtained by plies with a low value of crown angle; otherwise plies with a high value, up to 90 degrees, of crown angle enhance ride comfort.

Each tire can be classified by the following example [1]:

225/50 R16 92W.

- The first figure (225) determines the width of the tire measured in millimeters. An undeformed situation with correct inflation pressure and no load applied should not be omitted.
- The second figure (50) refers to the aspect ratio, which gives us the ratio H/W – ratio between the radial height and the width. In this example H is 50% of W. A standardized value of 80% should be assumed, when this figure is omitted.
- The following letter characterizes the type of the tire plies; R means the radial.
- The third figure refers to the rim diameter in inches.
- The fourth figure is the load factor, which specifies the allowed vertical load at a rationed inflation pressure. This figure has no physical meaning.
- The last letter specifies the maximum speed allowed for the tire.

Regarding the tire carcass, the organization of plies can be sorted to two categories: *cross* or *conventional ply* and *radial ply*. On cross ply tires reinforcement cords have a crown angle of 35÷45 degrees. The radial tires have some plies running perpendicular to the circle direction and they are surrounded by other plies (belt plies) with an angle in range of 15 degrees. Plies on the cross ply tires expand from bead to the other bead, while on radial tires belt plies are terminated to the place, which come into contact with the ground. And radial carcass plies hold the sides of the tire into form. The conventional ply tires are less vulnerable in the flanks and more flexible in the belt region in comparison to the radial ply tires, which have opposite properties. Because of cornering stiffness and comfort the radial tires are the most common type. Otherwise they have a penalty in flank vulnerability. The conventional tires are used in more demanding application such as off-road driving.

The tread of the tire features tire shapes in different designs and is made of vulcanized filled rubber. It’s essential to tire behavior. The contact surface determines friction at the tire-ground interface. Circumferential and transversal grooves provide better water drain from interface when the road is wet. Such grooves would be unnecessary on well paved roads or on racing tracks. The *slick tires* are that solution.

For better focus on race slick tires it's vital to describe real reputable racing tire by Yokohama. Yokohama Advan AO48 tire combines design, construction and compounding to provide a new level of performance. This allows more precise in high lateral transition, a better footprint under braking and predictable grip. This radial tire is based on two steel belts covered by jointless nylon belt and edge. It is shown in figure 11. *The single block design* provides continuous tread, which increase stiffness, enhance cornering and optimizes power transitions during acceleration and braking. This continuous design ensures constant contact with road and responsive steering. *The rounded casting design* enabling predictable handling. The tire is available in 2 compounds: M-compound (short-track competition) and MH-compound (endurance competition). They are also divided into soft, medium and hard compound [6].

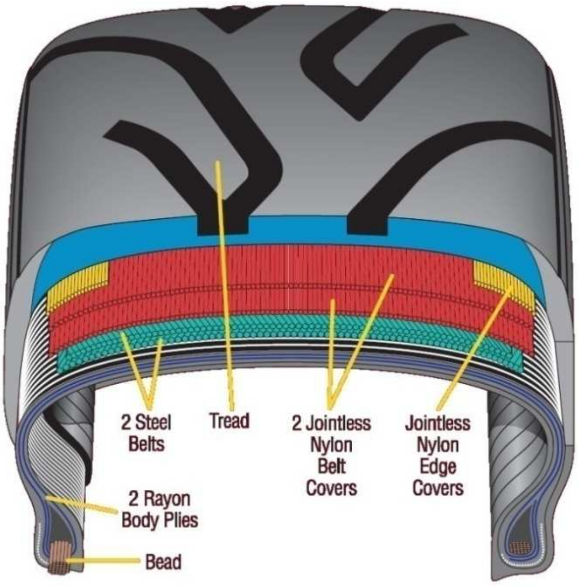

Fig.11 Yokohama Advan tire structure [6]

2.3 TIRE OPERATION

Explanation of tire operation is focused on prepared ground, when the tire is in contact with paved or concrete surfaces. Ground deformation is not considered on dry paved roads. Two different aspects are going to be discussed:

- The *adhesion* between tire rubber and ground allows tires to exchange the ground forces contained in the contact plane.
- The *elasticity* of the tire structure gives to the tire certain absorption capabilities, when it comes to contact with irregularities.

We define adhesion as the result of physical phenomena that allow a specimen of rubber set on the ground and pressed with a certain vertical force to withstand forces contained in the ground plane, without any relative motion [1].

Adhesion is caused by two aspects, *physical adhesion* and *local deformation*, which have similar results.

Let's study the physical adhesion phenomena focusing on a sample of rubber pressed onto a completely smooth and rigid ground. From micro view rubber and ground molecules apply certain attraction forces in the pores of material and irregularities. This forces refer to distances in the range between 0,001÷0,01 µm. It is evident that, if we are applying a lateral force to the rubber sample, we will see that it is balanced by the adhesion force. This force is maintained until a certain distance is reached, but after distance increases the adhesion force is destroyed and it is attended by the dissipated energy. The adhesion is controlled by priorities like surface energy of contacting materials, damping properties of those materials and deformation of contacting surfaces. Damping properties play important role in rubber and they are connected with temperatures and relative speed.

On the other hand, local deformations are caused by road irregularities. Mechanical work dissipated by damping creates forces along the contact surface.

Wet surfaces can radically affect these mentioned phenomena. From one point of view, water layer thickness is too strong enough to behave as permanent lubricated layer. In this case adhesion and local deformations cannot take place (aquaplaning). From the other point of view, water layer thickness cannot create permanent lubrication, but it can establish adhesion forces. This allows building up some handling. It is vital to obtain means of tire grooves and water draining.

Friction coefficient µ can be defined as the ratio between tangential and vertical pressures [1].

Elastic behavior can be explained on a simplified model of a tire for better overview of the tire behavior under a longitudinal force F_x in driving direction (middle illustration of Fig. 12) and braking direction (right illustration of Fig.12). The tire is reduced to certain number of springs, featuring lateral, vertical and longitudinal flexibility and bound specimen of rubber on their tips. Springs are fitted on a rigid rim with a uniform angular displacement ξ. The wheel, affected by a driving force, should roll faster than when rolling free of force. If the wheel is braking, it should roll slower that when it is rolling free. *Longitudinal slip speed* is a speed variation, which should be proportional to applied longitudinal speed [1].

When a centrifugal force is applied to the vehicle in a turn, the tire undergoes a vertical and lateral force. Because of deformation proportional to the force, the wheel hub is expected to deviate by an angle alpha, proportional to lateral force. This angle is called *sideslip angle [1]*.

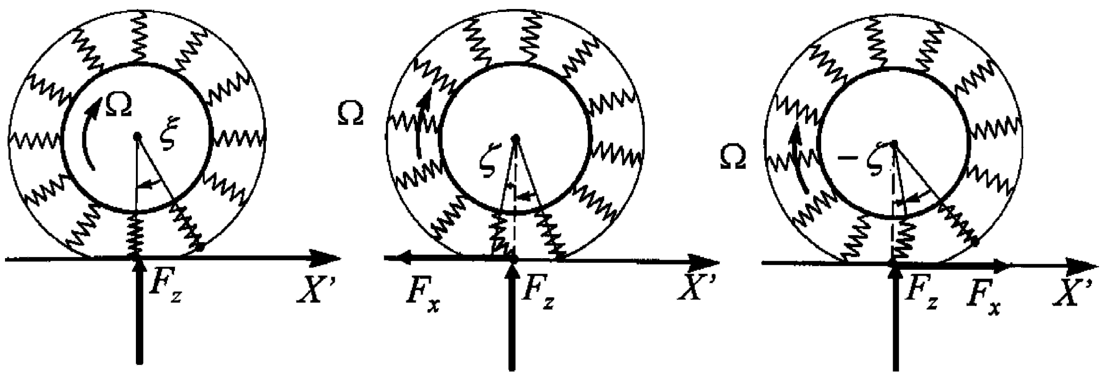

Fig.12 The simplified model of the tire [1]

3 SUSPENSION

Vehicle suspension is meant to be a mechanism that links the wheel directly to the body or by attached frame. To accomplish the task of handling and comfort characteristic of vehicle, suspension must allow a distribution of forces, exchanged by the wheels with the road. Vehicle *trim* has to be also observed. Vehicle trim represents the three angles of the body reference system. Suitable damping system is also vital to absorb shocks that are received by the wheel from the road and transmitted to the body.

Suspensions are divided into three classes: *independent, dependent* and *semi-dependent* suspensions. Another important characteristic separates steering from non-steering suspensions. Independent suspensions can be designed to become steering suspension, while depended suspensions are no longer used to steering axles, except of industrial vehicles. Independent steering suspension based on mechanical system was first introduced by Honda in 1985 on Prelude model. Mechanical system was replaced by electro-magnetic and electro-hydraulic system. This innovation was first applied in Renault Laguna GT in 2008 in cooperation with Renault and Renault Sport Technologies [13].

Next articles will concern about suspension systems used in the racing vehicles, but some of this applications can also appear in contemporary mainstream vehicles.

3.1 THE SPRINGING MEDIUM AND DAMPING MEMBERS

The springing medium is divided into two categories: primary elastic members and secondary elastic members.

PRIMARY ELASTIC MEMBERS

These include coil, leaf and bar springs (torsion bar springs), then anti-roll bars, strut braces and stop springs. Spring members are used to connect the wheel to a caste elastically and store/subsequent the energy produced by the road irregularities. They also determine body position as a function of payload.

We can distinguish between *normally wound coil springs* and *progressively wound springs*. Normally wound springs are characterized by regular coil pitch all the way up the spring. Progressively wound springs have the coil pitch tighter the closer to the top of the spring you get. This gives the effect of giving the spring more resistance, the more it is compressed. The spring stiffness is given by:

$$k = \frac{G \cdot D^4}{64 \cdot n \cdot R^3} \ , \qquad (1)$$

where G is an elastic material property, D the wire diameter, n the number of coils in the spring and R stands for the radius of the spring.

By increasing the number of coils decreases the stiffness of the spring. The effect of the progressively wound spring is to reduce the suspension travel at the top end resulting in less body roll and better handling properties. They are also ensured by powder-coat, which means they have been treated with a good anti-corrosion system and then covered in powdered paint. After baking the paint seals and sticks and brings out its elastic properties.

Torsion bars (torsion rods) are type of springs, which can substitute coil or leaf springs. A torsion bar is a solid bar of steel restrained to the car chassis at the one end and free to move on the other end. This 'free moved' end is connected to the suspension frame. They can be installed across the car (transverse) like rear suspension on Peugeot 205 or along the car (longitudinal) like the front suspension on Chrysler's vehicles. Vertical motion of the wheel causes the steel bar to twist around its axis and this springing is provided by bar's resistance. The interaction between the torsion bar and the chassis or the suspension parts is provided by splined ends. This mechanical connection allows to raise or lower car by twisting round a few splines and then re-inserted. The figure 13 shows an example of the longitudinal torsion bar. As the suspension at the front moves upwards, the bar twists along its length providing the springing motion. An absorber assembly is out of the rendering for clarity.

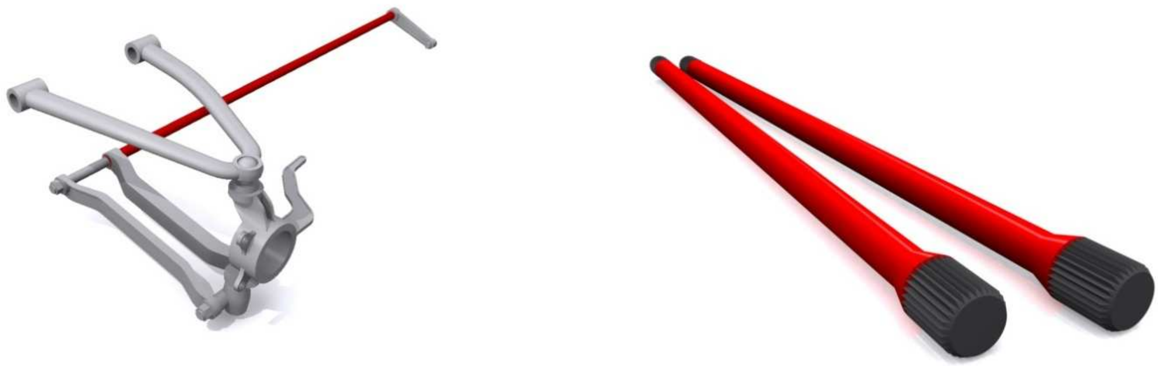

Fig.13 The longitudinal torsion bar and its mounting [7]

Anti-roll bars (sway bars/stabilizers) connect opposite wheels together through short lever arms connected to the front lower edge of the bottom suspension joints. It also passes through two pivot points under the chassis, usually on the subframe. This provides increased suspension's roll stiffness, which means resistance to roll in turns. Almost every car is equipped with this as standard part. From the factory they are conceived to become more comfortable, but stiffer aftermarket anti-roll bars enhance the handling against reduced comfort. Some explanation of how the anti-roll bar works is shown in the figure 14.

Strut braces (strut bars) are mostly aftermarket car suspension accessory used in the connection with McPherson strut to provide extra stiffness between the strut towers. The whole chassis is twisting slightly in the cornering. It means that the front suspension pillars will be moving relative to each other, because there is no physical link between them. That connection is obtained via the car body, which can flex a bit. The strut brace mounts across a top of the engine right to the tops of the two suspension bearing posts and makes totally direct physical connection. The result enhances rigidity and handling of suspension relative movement.

Leaf springs were mentioned before as well. It is one of the oldest forms of springing, dating back to medieval times. The only advantage of a leaf spring over a helical spring (coil springs) is that the end of the leaf spring may be guided along a path. A damping action is provided by the interleaf friction. Sometimes the leaf spring was transverse, trapped in the middle (Cooper Formula One, Austin Seven) sometimes it was quarter elliptic, trapped at the end while the other one flexes (Austin Seven rear) [2]. All applications would be irrelevant in racing terms nowadays.

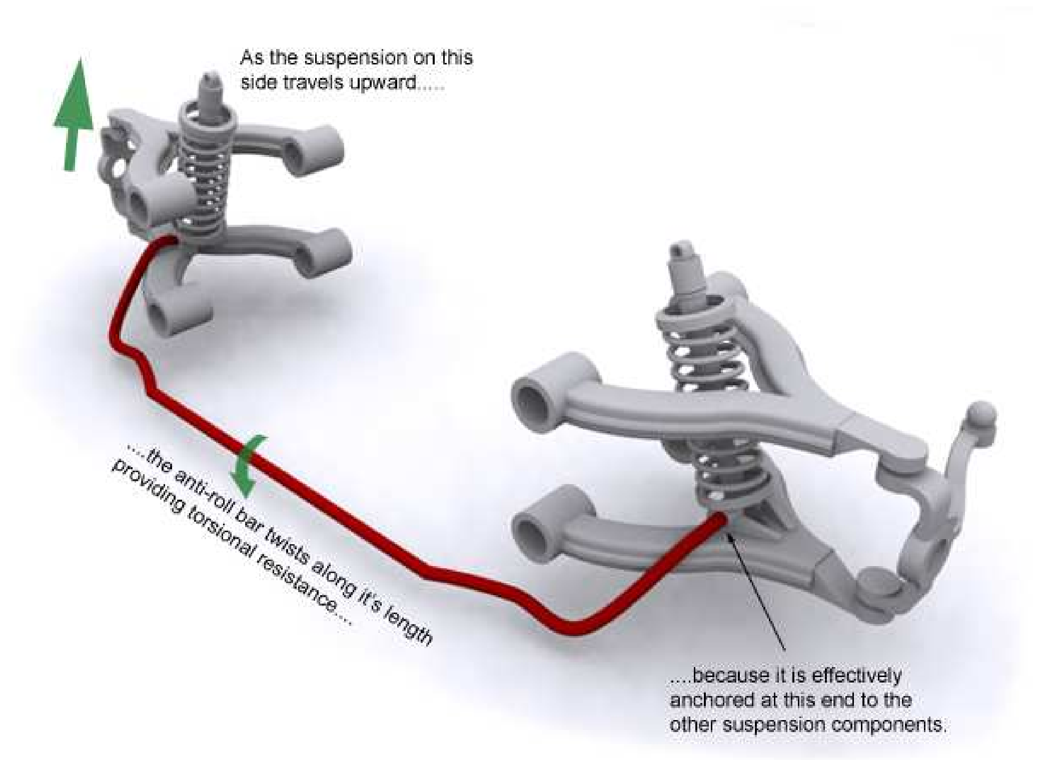

Fig.14 The explanation of how the anti-roll bar works [7]

SECONDARY ELASTIC MEMBERS

Elastic bushings on linkage joints are considered to be secondary elastic members. They are manufacturing with a difference in certain elastic flexibility. This attribute was seen as a drawback to avoiding joint lubrication. At the present, it was understood that it could improve the design of the elasto-kinematic behavior of the suspension. They play an important role in determining vehicle handling.

DAMPING MEMBERS

A damping member consists of dashpot and spring with some cushions. The dashpot is a fluid-filled piston combination, where piston is able to slide inside. Whole mechanism as a unit is called a *shock absorber* or *damper*. They are designed to smooth out impulse and dissipate kinetic energy. Compression damping is provided by the spring itself and rebound damping ensures the dashpot. In the case of rebound damping, this is the damping that the dashpot provides as it returns from its compressed state to its steady state. When the wheel and the other unsprung mass is too light, the wheel moves very quickly and you reach control under the car. Otherwise, when it is too heavy, the shock absorber cannot return quickly enough. This results in minimized traction and control of the vehicle. There is an importance about energy conversion. Energy is converted to heat inside the viscous fluid placed in the dashpot. In hydraulic cylinders the hydraulic fluid heats up, while in air cylinders the hot air is usually exhausted to the atmosphere. Another most recent dashpot is an electromagnetic dashpot, in which the dissipated energy can be stored and used later. Figure 15 shows the shock absorber to clarity.

The most high-tech shock absorbers have control for both compression and rebound damping. Compression damping setting is represented by a knob either on the side or on the remote control and rebound damping is typically represented by a screwdriver slot at the top of the shock absorber. Ultra high-tech shock absorbers have got a separate control for high (high speed compression and rebound) and slow (low speed compression and rebound) speed damping. Low-speed damping can make the shock absorber behave differently over small bumps, in comparison to what it does over the large bumps by the high-speed damping. Another beneficial setting is a spring preload, which can alter pre-tension [7].

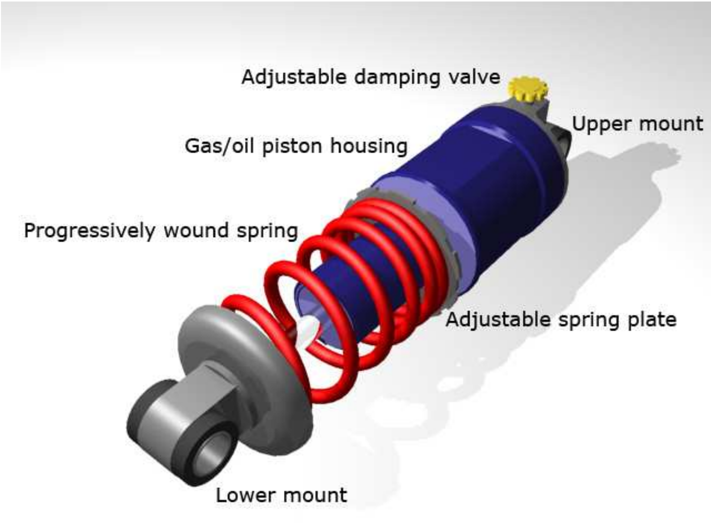

Fig.15 The shock absorber structure [7]

3.2 INDEPENDENT SOLUTIONS

Independent suspensions are so-named, because of wheel's independence of each other in exception, where they could be joined by the anti-roll bar. They came on scene around 1930 and have been in use in same or other shape pretty much ever since then. If the wheels are suspended independently, linkages have to constrain five out of the six degrees of freedom of the wheel. This unconstrained motion allows wheel to move in a direction perpendicular to the ground. This translation movement is provided by a construction of system made up of five bars with spherical hinges at the end. This layout refers to multilink suspensions. From five bar multilink suspension almost all configurations can be obtained by bounding these bars in different way. In following subchapters will be described suspensions like McPherson strut, Double wishbone suspensions, Trailing arm, Multilink suspensions and other applications of these.

3.2.1 McPherson suspension

McPherson suspension (McPherson strut) is, without doubt, the most widely used front suspension system in cars today. This kind of suspension is obtained by replacing the upper triangle by a prismatic guide. It is simplicity itself, which it leaves considerable free space for engine installation. This suspension system is common for automotive front axles in small and medium size cars. This solution was also adopted on large cars and sometimes sport cars as touring sport cars (BMW M3 E92 GTR).

In the beginning, the wheel linkages will be observed first. The wheel linkages are guided, copying vertical motion, by a lower arm and sliding guidance, integral to the shock absorber equipped with a spring installation. An upper pivot attaches it to the body. The lower arm 2 is connected to the body trough an auxiliary frame, also known as subframe 1. The lower arm is attached to the strut through a spherical joint and subframe connection is provided by two different points through elastic bushings. The strut is the element, where the hub from outside and roll bearing from inside are installed. The hub is flanged to the disc brake and wheel and it is fixed to the drive shaft through homokinetic joint, which allows the transmission of torque from differential to the wheel by spline. There are also two flanges on the strut to fix the brake caliper. Shock absorber base consists of two brackets welded and then bolded to the strut in a rigid way. The spring remains on two seats, where a lower seat is fixed to the shock absorber and an upper seat to a needle bearing. The upper ring of the bearing rests on an elastic mount, fixed to the body, in the wheel case. The rack and pinion steering box is also shown in the figure 16. This mechanism is bolted to the subframe and its steering tie rod is articulated to the rack through two spherical joints. When you steer, the steering box twists the strut, shock absorber housing and consequently the spring. The anti-roll bar is fixed to the subframe, but it is free to rotate. Connection to the shock absorber is provided by rod called a pendulum bar.

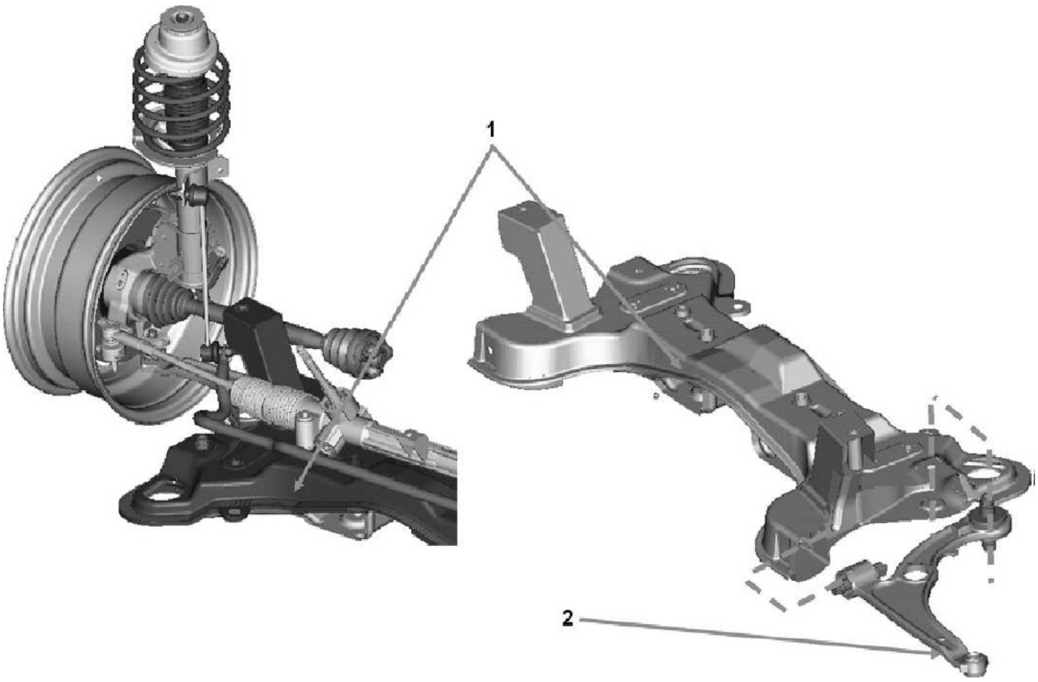

Fig.16 McPherson suspension for the front axle used in FIAT [1]

ADVANTAGES

- The most importance is in design simplicity and reduced cost. This suspension system based on production version is used in huge spectrum of touring sport cars, but there is a considerable difference in wheel setting. Wheel caster angle is increased, enhanced wheel camber and enlarged track width. Caster angle is the angle between the pivot line and vertical line, where the pivot line is an imaginary line through the center of the upper ball joint to the center of the lower ball joint. Stock shock absorbers are replaced by new five-way adjustable shock absorbers with progressive springs. There are also some modifications in tubular anti-roll bar [2].

- Forces exerted on the body are low in comparison to other suspension systems.

- Higher suspension stroke, because of non-limitation on upper arm length.

- Suspension system is beneficial for transversal engine installation, because of the absence of the upper arm.

- Freedom in designing elasto-kinematic properties.

DISADVANTAGES

- Shock absorber piston rod deformation can raise friction and hysteresis.

- A position for the upper pivot interface with the body is usually far-away from the stiffest parts of the body. This is significant problem that causes vibration and noise from the road.

- Lower performance in camber recovery. The camber recovery means camber angle variation as a function of suspension stroke [1].

- Too high shock absorber and spring setting degrades the vehicle's aerodynamic shape.

McPherson suspensions can also be applied to rear axles, but construction has to be compatible with the installation of fuel tank, spare wheel, exhaust pipe and so on. It should allow a suspension stroke longer than for the front axle, because rear load variations are bigger. This rear axle suspension is also suitable for driving axles, providing enough space for differential and transmission shaft. It has got good potential for proper toe angle variation by cornering forces. Disadvantages are the same as for front axle suspension. The shock absorber unit reduces the cargo compartment width. Medium complexity and cost are also drawbacks. McPherson rear suspension systems are used in medium size luxury cars or on sport cars (Alfa Romeo rear suspensions).

3.2.2 DOUBLE WISHBONE SUSPENSION

Double wishbone suspensions are used in the most luxury sedans and sport cars as well. They provide very good elasto-kinematic behavior, which offers optimum compromise between handling and comfort. The acronym SLA suspensions refers to short and long arm suspensions, because the upper arm is in general shorter than the lower arm. There can be recognized two different kinds of double wishbone suspension, what is illustrated in the figure 17. The first on left is suitable for front wheel drive cars with transversal engine installation and the second on the right can be applied to longitudinal engine installation. Suspensions of this type are classified as high (on the left) or low (on the right) according to the upper arm position with respect to the wheel. Low double wishbone suspensions featuring excellent elasto-kinematic behavior, but they interfere into the engine compartment and are generally applied to luxury touring cars (Aston Martin). This kind of suspension system is also used in the rear axles. Aston Martin DBR9 Le Mans racing edition uses double wishbone suspension same front and rear axle.

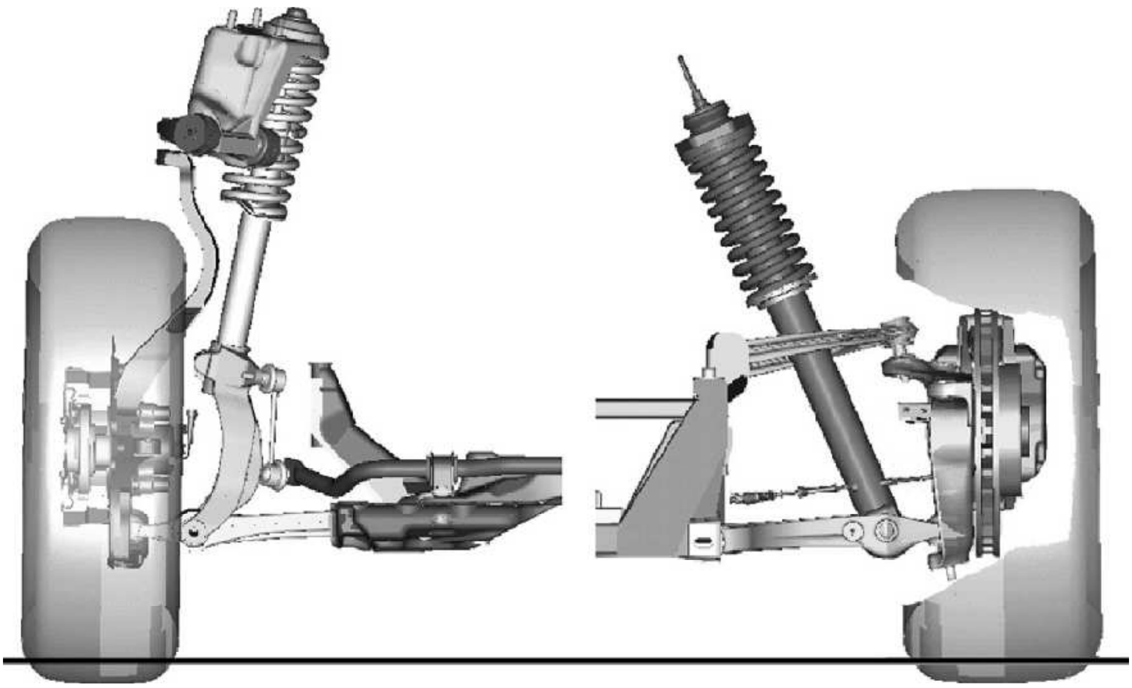

Fig.17 High and low type of double wishbone suspension [1]

The upper and lower arms are linked to the body through elastic bushings, as used in the McPherson. The lower arm carries most of the load. These arms are connected to the strut by spherical joints, which allow the steering motion of the strut. It means that the steering rotation involves the wheel strut only. And that is why there is no need to bearing installation on the upper seat of the shock absorber. The line connecting the two spherical joints is called the king-pin axis [1]. The shock absorber and the coil spring are unitized, as in the McPherson suspension. This assembly is connected to the lower arm through the elastic bushings and has a shape like a fork to make required space for the driveshaft. Other application can have a different shape with bushings and bearings connected directly to the body. The lower arm is linked to the subframe and the anti-roll bar is connected to the shock absorber thorough the pendulum bar. The rack and pinion steering box is connected to the subframe as well.

ADVANTAGES

- Excellent elasto-kinematic properties, particularly as far as camber recovery is concerned.
- Comfort is obtained because of hysteresis reduction. Shock absorbers have no more structural function.

DISADVANTAGES

- Production cost gets higher because of increased bushings and upper arm attachment parts, as compared with the McPherson suspension.
- Transversal engines demand the higher type. This type is equipped with the reduced length of the upper arm, which compromises possibility of reaching the maximum elasto-kinematic properties.
- Wheel angles (toe angle, camber angle) are affected by increased number of joints and bearings. These connections have a permanent deformation in the bushing rubber in negative consequence on tire wear.

Different alternative positions for the coil spring and the shock absorber for low double wishbone suspension should be recognized. The First solution is characterized by upper position of the shock absorber and the coil spring. This transfers the load-bearing capability of the suspension almost entirely to the upper arm. The second solution uses the torsion bar instead of the soil spring. This solution introduces limited values of stress operating in the upper body parts. These two solutions of system are not so popular as it takes up a lot of space.

Virtual centres suspensions are slight modification of double wishbone suspensions. This modification consists of replacing one or two arms by a doubled number of linkages, each with its spherical joint. From that point of view, we recognize single or double virtual center links [1]. As it was mentioned to this point, the strut is linked to two spherical points, which identify king-pin axis. The king-pin axis in virtual centres suspensions is no longer identified by the physical position of joint, but by a virtual point. The virtual point is given by intersection of two lines connection the articulation points of linkage. For example, single lower virtual centre has the king-pin axis characterized by the intersecting the two planes through the lines connection the four articulation points of the arms and the upper physical center (Mercedes). Some manufacturers in high end cars use this kind of design for improvement vehicle stability during braking.

3.2.3 TRAILING ARM SUSPENSION

Trailing arm suspension or more improved guided trailing arm suspension, where more linkages have been added, is less often connected with racing car rear suspension. Some manufacturers use this solution in particularly low end market cars, so due to this fact they will be described only superficially.

The guided trailing arm suspension has got two or three additional arms linked to the trailing arm to improve elasto-kinematic performance of the suspension. This longitudinal trailing arm, made from an iron casting, is guided by two mentioned cross arms, which identify an axis through the two elastic bushings. Under the action of the cornering force and braking force this axis is designed to create a toe angle variation. The elastic bushing, providing longitudinal motions with undesirable steering rotation of the wheel, is placed at the end of the trailing arm. This position creates a given longitudinal flexibility and enhances comfort. Suitable camber recovery is considered as another advantage of this suspension system. But many adjustment points for correct assembly on the subframe and higher cost complexity are considered to be the drawbacks.

The guided trailing arm suspension with three additional arms, known as Control Blade suspension, is provided by Ford used on medium model cars [7].

A less widely used and obsolete trailing arm suspension fits into semi-independent suspension, known as the semi-trailing arm suspension.

A twin-trailing arm suspension is other less used generation of the trailing arm suspension, which is represented by the pairs of arms. This system works on exactly the same principle as the double wishbone suspension where two arms move parallel to the chassis.

3.2.4 MULTILINK SUSPENSION

This kind of suspension is applied on most large, luxury or race car rear axles (Audi A8, A4), for both front and rear wheel drive with penalty on weight and cost. As mentioned earlier, in multilink suspension the strut is linked to the body through five linkages. These five are conceived to subtract the degrees of freedom, leaving only the suspension stroke motion. This suspension can also be consider as double wishbone suspension with lower and upper steering virtual points. The additional linkage, also called *false steering linkage*, is used to control the wheel steering motion. In considering a rear driving axle, the toe angle variation depends on the traction force, in addition to the cornering and braking forces. This fact has to be taken into account while designing and creating rubber bushings. There are a lot of variations on this theme appearing at the moment, with huge differences in the numbers and complexity of the parts, but they are all fundamentally the same.

There is a phenomenon, called *torque steering*, which is usually connected with rear wheel driven cars. Torque steering is directly related to differences in the forces in the contact patches of the left and right drive wheels. This phenomenon reflects in pulling the steering to one side during heavy acceleration [1]. In the following case, multilink suspension of a large front wheel drive sedan (figure 18), torque steering is not to be taken into account. This suspension solution is characterized by the spring separation from the shock absorber. The triangular arm 1, a cross beam 2, a false steering linkage 3, a linkage 5 and the remaining linkage 4 are other cognitive parts. The linkage 4 connects the triangle to the suspension strut and increases wheelbase variations during the compression stroke. Alfa Romeo uses this particular kind of suspension for front wheel driven cars in large model spectrum. The Alfa Romeo 156 was as well vested in motorsport as its predecessor, the 155. It ran in the British

Touring Car Championship as well as various European championships, most notably the WTCC and formerly the ETCC, where it was especially successful. Alfa Romeo 156 super 2000 was the latest touring version.

ADVANTAGES

- Camber recovery
- Wheelbase increase during the compression stroke
- Stabilizing toe angle variations as a function of cornering and breaking forces

DISADVANTAGES

- High mechanical complexity
- High volume and weight effect the unsprung mass
- Expensive production cost
- High sensitivity to variation in the elastic behavior of rubber bushings

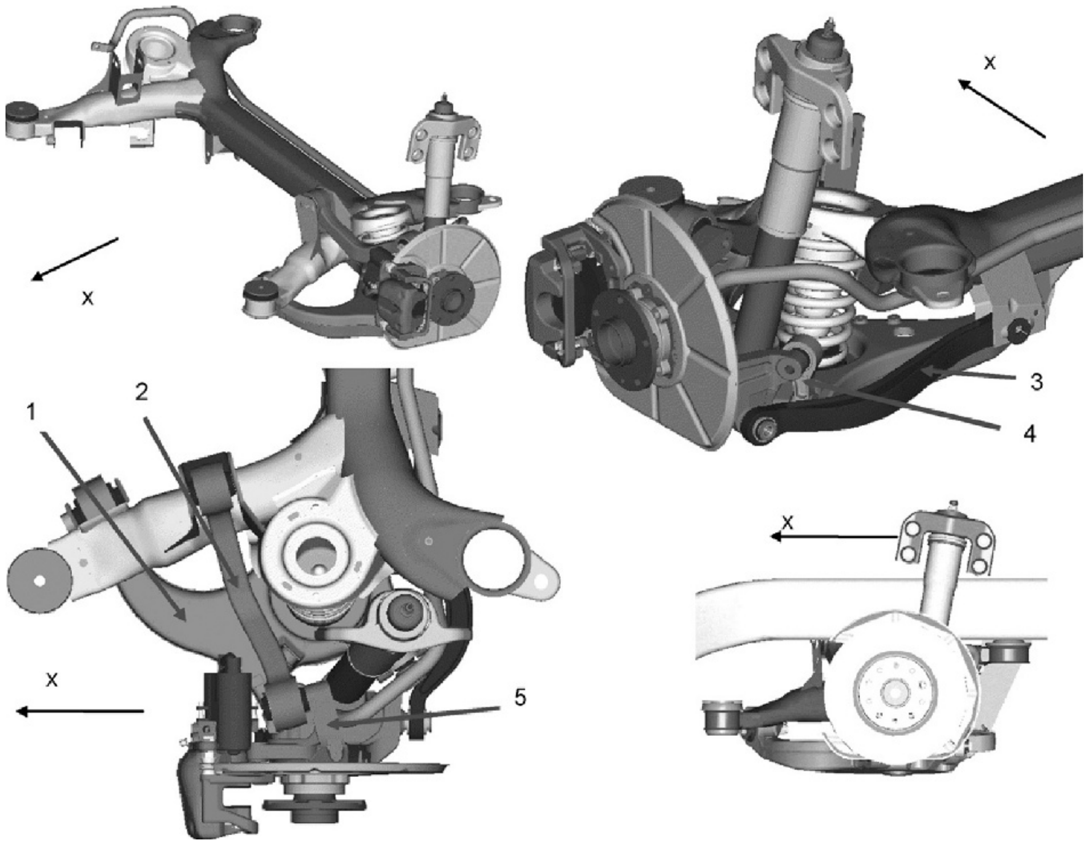

Fig.18 Alfa Romeo multilink suspension for front wheel driven cars [1]

3.3 SEMI-INDEPENDENT SOLUTION

This kind of suspension falls into a group between independent and non-independent solution. That means the two wheels can move relative to each other, but their motion is still somehow inter-linked, to a greater extent than in a true independent rear suspension.

TWIST BEAM SUSPENSION

The twist beam suspension, shown in the figure 19, can be imagined as two trailing arms 4, attached to the body with elastic bushings 2. A cross beam 3 holds the two trailing arms together, and provides roll stiffness of the suspension, by twisting as the two trailing arms move vertically, relative to each other. The arm is made from two stamped and welded steel shells. The plate 1, welded onto the arm, is used for strut attachment. The spring seat is shaped on stamped shell and the lower shock absorber mount 7 will be screwed to a tube, also welded onto the shell 5. The cross beam intersection may take the form as H, U or V shaped member. The cross beam 3 has the U shaped cross section and is welded to the arms at its ends. The anti-roll bar is also welded to the arms. Different arrangement for coil springs and shock absorbers can be established. The optimum position for shock absorber is perpendicular to the arm as far as possible from articulation point to the body.

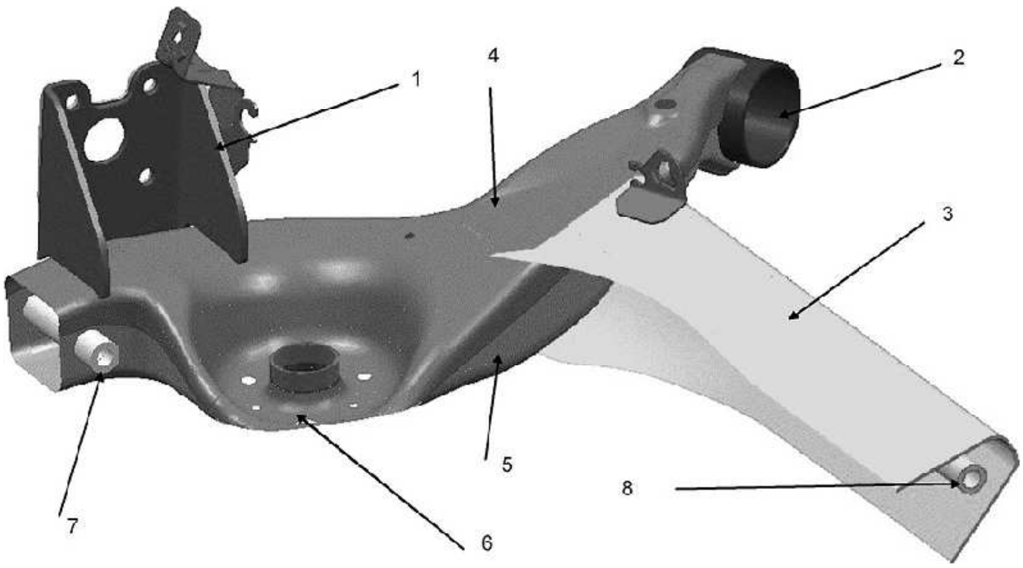

Fig.19 Pre-installation scheme for a rear axle twist beam suspension (FIAT) [1]

ADVANTAGES

- Assembly and design simplicity
- Fairly light weight and durability
- Unsprung mass is smaller compared to a rigid axle

- Almost total camber recovery by asymmetric strokes

DISADVANTAGES

- High wheel case because of expected camber variation
- Highly stressed parts especially twist beam and its welds
- Unsuitable in driving axles
- Observably different behavior in empty vs. full load condition (toe angle variation)

Twist beam axles are commonly used on a wide variety of front wheel drive small and medium cars. It was probably introduced on the Audi 50 in 1974. As regards contemporary touring race cars, the twist beam suspension can be found in European superminis like Volkswagen Polo Mk5 or Citroen C3.

3.4 RIGID AXLE SUSPENSIONS

This solution does not only appear in commercial and industrial vehicles, but it can be found in many off road vehicles and some American and Australian V8 touring race cars. Because of that fact, we will consider two different design alternatives: so called ‘live’ axles, where the kinematic function is performed by guidance and more sophisticated De Dion suspension. Leaf springs as the springing medium will not be further in consideration.

3.4.1 SOLID LIVE AXLE

This kind of suspension is equipped with separate coils and shock absorbers or combos rather than unused leaf springs. Applied to driving axles the suspension cross structure (axle) can integrate final drive, differential and driving shafts. In this case whole driving unit increases unsprung mass weight. From kinematic point of view, this solution features no track variation by roll and parallel springing motion. Improved transversal and longitudinal guidance of the axle and better elasto-kinematic behavior is obtained by adding more suitable linkages. The first linkage is so called panhard rod (panhard bar), where the reaction to cornering forces is assigned to [7]. Figure 20 shows solid live axle suspension and their panhard connection, linked to the car body at one end and to the axle on the other. Panhard rods can reduce the oversteering behavior by setting limits to lateral spring elasticity. The second linkage is known as *Watt’s linkage* (figure 21), used in the rear axle of some car suspensions as an improvement over the Panhard rod. Both methods intend to prevent relative sideways motion between the axle and body of the car. Watt’s linkage approximates a vertical straight line motion more closely than Panhard rod. It consists of two horizontal rods of equal length mounted at each side of the chassis. In between these two rods, a short vertical bar is connected. The center of this short vertical rod is mounted to the center of the axle. All pivoting points are free to rotate in a vertical plane [7]. The linkage can be inverted, in which case the centre is attached to the body, and the two rods mount to the axle. This reduces the unsprung mass and changes the kinematics slightly. This is used on Australian V8 Supercars (Ford Falcon, Vauxhall Commodore).

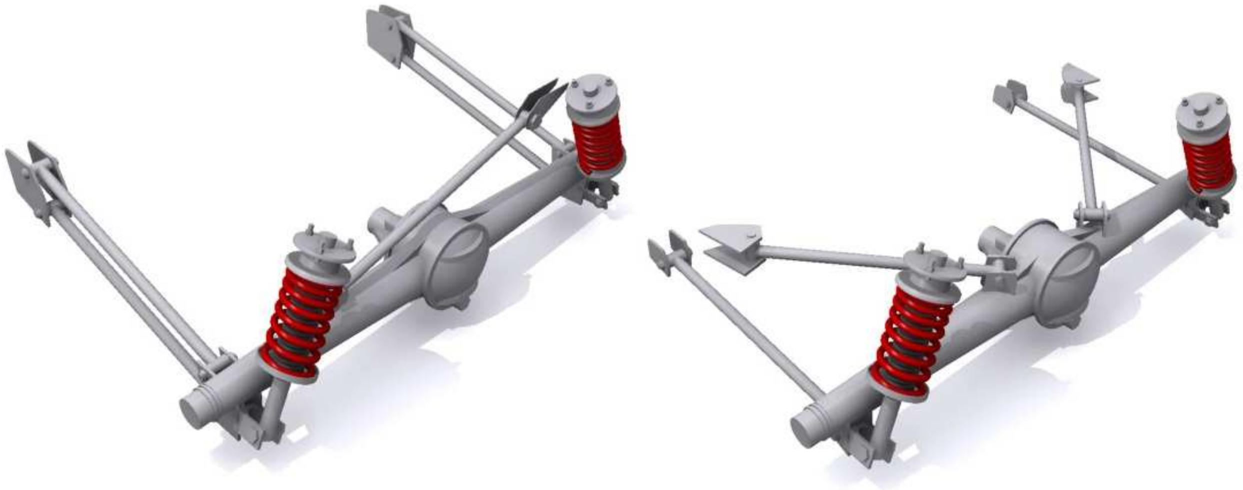

Fig.20 Right scheme – 4-bar triangulated suspension, Left scheme – 4-bar parallel suspension with panhard rod [7]

4-bar suspension, also shown in the figure 20, is the solid axle with certain bar connection to the chassis. This 4-bar solution is divided into two categories. Triangulated one, shown on the right side, and parallel, shown on the left side. The parallel design of the 4-bar is such, that the rear end housing is always parallel to the ground. The design is equipped with panhard rod to maintain lateral stability. The triangulated design operates on the same mentioned principle, except of the top two bars inclined inwards and attached to the rear end housing much closer to the centre. This setup is more compact without panhard rod.

Fig.21 Watt's linkage as handling improvement in Mustang GT or Shelby GT500 [8]

3.4.2 DE DION SUSPENSION

A de Dion suspension (figure 22), also known as a de Dion tube, is considered to non-independent suspension more sophisticated than older swing axle suspension. This kind of suspension was originally conceived to combat the unsprung weight and poor ride quality in the solid live axle suspensions. In suspension geometry it is something between the trailing arm suspension and solid axle suspension. This is something special, because it is neither one, but at the same time it is both. The wheels are interconnected through solid tubular beam to hold the opposite wheels in parallel. The tubular beam is not connected directly to chassis. This setup allows the wheel rebound with no camber change, which contributes to traction. The de Dion suspension uses CV joints at the both wheel hubs and differential. CV joints (constant-velocity joints or homokinetic joints) allow drive shaft to transmit power through variable angle, at constant rotational speed, without any increase in friction. The brakes are usually mounted inboard with the brake calipers attached to the transfer case, which means to dismantle entire suspension system to change a brake disc. With coil spring arrangement it needs extra lateral location links, such as the panhard rod or watt’s linkage, wishbones or trailing links.

Most recently de Dion suspension has got a quite renaissance in the specialist sports car and kit car market such as those from Caterham 7 (a development of the Lotus 7 after Lotus sold the design rights to Caterham cars), Westfield and Dax. These all uniformly now use outboard brake setups for simple maintenance or repairs, and de Dion tube, usually with trailing links and an A-bar for lateral location (rather than a Watts linkage or Panhard rod) [7].

ADVANTAGES

- Reduced unsprung mass since the differential is connected to the chassis.
- Unlike a fully independent suspension there are no camber changes on the wheel rebound. Fixing the camber of both wheels at 0° contributes in obtaining good traction from wide tires and also tends to reduce wheel hop under high power operations.

DISADVANTAGES

- A pair of CV joints is required for each wheel, adding complexity and weight.
- If coil springs are used then a lateral location link (usually either a Panhard rod or Watt's linkage), plus additional torque links on each side (five link suspension) or a combination of lower trailing links and an upper transverse wishbone are required.
- Compared to a fully independent rear suspension the ability to refine the dynamic response of the vehicle is somewhat limited.
- Camber changes are present in a single-wheel suspension, which can be more critical for rough road.

Fig.22 de Dion tube suspension with trailing and upper leading arms [7]

4 STANDARD CONTROL SYSTEMS

Control systems improve the vehicle's dynamics and safety – the most appreciated. These systems are working on the steering mechanism, the brakes and the elastic and damping elements of suspensions in common mainstream vehicles. Otherwise, this chapter is dedicated to control systems working on the brakes, which are most commonly used in the racing terminology. Almost all of these systems, in general, are addressed to improving vehicle dynamics behavior via a suitable control of the forces exchanged between tires and track. In the braking case, this control action can be the result of the breakdown of braking forces through the brakes of each wheel. It is very important to realize, that longitudinal forces, generated by the breaking system, can affect not only longitudinal, but also lateral dynamics. Brake is thus actuator not only for reducing velocity of the wheels, but also for controlling its path and traction capacity.

4.1 ANTI-LOCK BRAKING SYSTEM

An anti-lock braking system (ABS), first introduced by Bosch in 1978, is one of the active safety systems that allows the wheels to continue interacting with the road surface be traction. Its function is to prevent the wheels from locking up and therefore avoid from skidding. This system generally offers better vehicle control and decreased stopping distances on dry and slippery surfaces. But on the other hand ABS can significantly increase braking distance on loose surfaces like gravel or snow, although still improve vehicle control. This system can be found in racing vehicles, but it can be easily deactivated inboard according to some strict regulations.

There are four main components to the ABS: induction speed sensors, valves, a pump and a controller. In a typical ABS system a central electronic control unit (ECU) cooperates with four wheel speed sensors and at least two hydraulic valves within the brake hydraulics. The ECU invariably detects the rotation speed of each wheel via speed sensors, where an induced field is created by a rotary motion of sensor ring, figure 23. If the control unit detects a wheel rotating considerably slower that the others, a condition indicative the wheel locking up, it actuates the valves to reduce hydraulic pressure to the brake at the affected wheel. It reduces the braking force and the wheel turns faster. On the contrary, if the ECU detects the wheel rotation quite a bit faster than the others, brake hydraulic pressure to the wheel is increased and this allows to slow down the wheel. This process is repeated continuously and it can be detected by the driver via brake pedal pulsation. The most developed anti-lock systems are able to release or apply braking pressure 16 times per second [13].

The modern ABS is offered as standard on the most vehicles today and it is foundation for ECS and TCS systems, which are rapidly increasing popularity due to vehicle electronic improvement.

Anti-lock brakes are differenced by the number of channels and the number of speed sensors. The number of channel means how many valves are individually controlled [14].

- Four-channel, four-sensor ABS: This best solution is shown in the figure 23, where all of four wheels are equipped with a speed sensor. There is a separate valve for all four wheels. This configuration monitors each wheel individually to make sure it is achieving maximum braking force.

- Three-channel, three-sensor ABS: This scheme has a speed sensor and a valve for each of the front wheels, with one valve and one sensor for both rear wheels. This speed sensor is mounted on the rear axle. Therefore, the rear wheels are controlled together, so they both have to start to lock up before the ABS will activate on the rear. This can be commonly found on pickups trucks.

- One-channel, one-sensor ABS: It has one valve, which controls both rear wheels, and one speed sensor, located in the rear axle. This system operates the same as the rear end of a three-channel system. The rear wheels are monitored together and they both have to start to lock up before the ABS kicks in. This can also be found on pickups trucks.

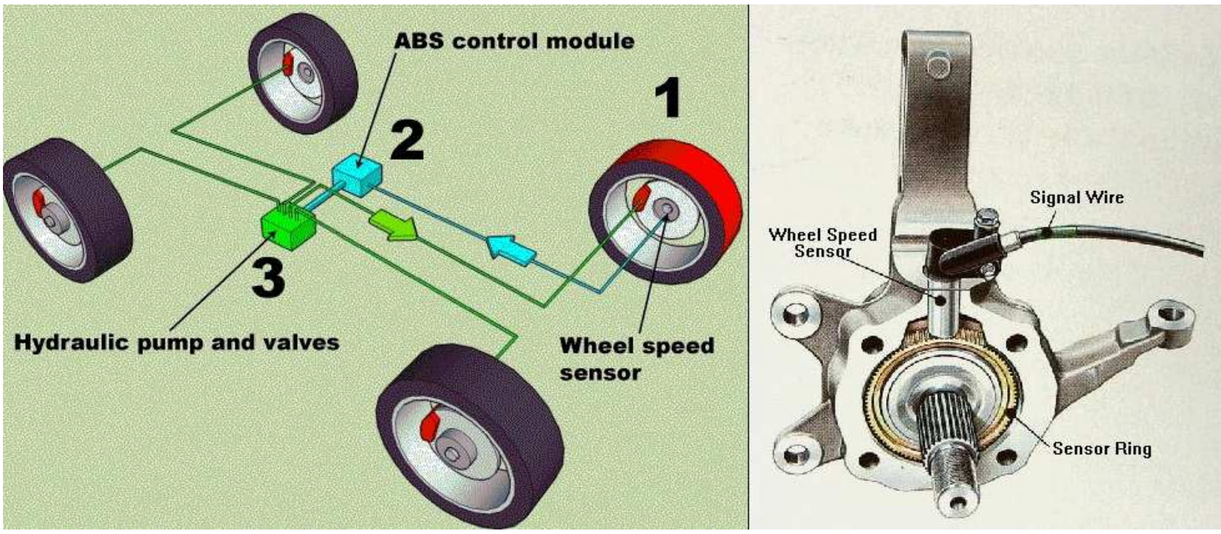

Fig.23 Left scheme –ABS simplified scheme, Right scheme – Induction speed sensor mounting [9]

4.2 ELECTRONIC STABILITY CONTROL

Electronic stability control (ESC) is also known through different acronyms, such as VDC (Vehicle Dynamics Control) or VSC (Vehicle stability control). The objective of this computerized technology is to improve safety and vehicle's stability by detecting and minimizing skids. Electronic stability control essentially makes ABS a full-time expert, that's continuously monitors how the vehicle is responding to the driver and road conditions. This includes braking, which is automatically applied to wheel individually. Some ESC systems also reduce engine power by backing off the throttle and/or retarding spark timing. ESC does not improve a vehicle's cornering performance; instead, it helps to minimize the loss of control.

ESC compares the driver's intended direction to the vehicle's actual direction. This system intervenes only when it detects loss of steering control, for example, when skidding during emergency evasive swerves, oversteer, understeer or hydroplaning. If a vehicle begins to oversteer in a turn and the rear end starts to come around (which would cause the car to spin out), the speed difference between the left and right front wheels increases. If the vehicle understeers (loses front traction and goes wider in a turn), the speed difference between the left and right front wheels decreases. ESC estimates the direction of the skid, and then applies the brakes to individual wheels asymmetrically in order to create torque about the vehicle's vertical axis, opposing the skid and bringing the vehicle back in line with the driver's commanded direction. ESC systems typically inform the driver when they intervene, so that the driver knows that the vehicle's handling limits have been approached [13].

The sensors used for ESC have to send data at all times in order to detect possible defects as soon as possible. They have to be resistant to possible forms of interference (rain, holes in the road, etc.). The most important sensors are:

- Steering wheel angle sensor: determines the driver’s intended rotation.
- Yaw rate sensor: measures the rotation rate of the car; i.e. how much the car is actually turning. The data from the yaw sensor is compared with the data from the steering wheel angle sensor to determine regulating action. It is measured in degrees per second or radians per second.
- Lateral acceleration sensor: measures lateral acceleration of the vehicle.
- Wheel speed sensor: measures the wheel speed and it is the basic sensor for ABS.

Other sensors can include longitudinal acceleration or roll rate sensor. Components necessary to ESC are same as for ABS, i.e. ESP provides some kind of upgrade to the vehicle’s stability and safety.

Many ESC systems have an "off" override switch so the driver can disable ESC. Some systems also offer an additional mode with raised thresholds so that a driver can utilize the limits of adhesion with less electronic intervention.

4.3 TRACTION CONTROL SYSTEM

A traction control system (TCS), also known as ASR (Anti-slip Regulation), is typically a second function of anti-lock braking system on production or race vehicles. This system is designed to prevent loss of traction of the driven wheels, and therefore obtain the control of the vehicle when excessive throttle is applied and condition of road is unable to cope with this torque. The intervention can be obtained by one or more of the following:

- Brake one or more wheels.
- Reduce fuel supply to one or more cylinders.
- Reduce or suppress the spark to one or more cylinders.
- Reduce boost and therefore engine power in turbo-charged vehicles.

Traction control is used as a performance enhancement in race cars, allowing maximum traction under acceleration without wheel spin. When accelerating out of turn, it keeps the tires at the optimum slip ratio. Very effective small units are available to remove the traction control system after an event if desired [12]. In Formula One every car must have a standard (but custom mappable) ECU, issued by FIA, which is relatively basic and does not have TC capabilities.

CONCLUSION

The main aim of this thesis was to evaluate racing car chassis. The first chapter offered the description of some historical milestones from rigid axles mechanical linkages to the ancestor of the first independent solutions designed by Cottin-Degouttes or Dubonnet. Then tire and rim characteristic within famous Yokohama tire and BBS rim from the racing terminology were described. The third chapter relates to the most used suspension systems found so as in any productions car as well as from touring to sport racing car. The representatives of independent solutions are well known McPherson, double wishbone, multilink and less often used trailing arm suspension. Semi-independent solutions or rigid axles, which are common rear suspensions in V8 supercars, are the rest of this chapter. And the last chapter dealt with some standard braking controls like anti-lock braking system, electronic stabilization control and traction control system. This mentioned control systems should be adjustable or removable according to some regulations.

Development of a new chassis from sketches to production is associated with creating the right geometry and dynamics as well as stress analysis of the arms with an appropriate selection and positioning of springing medium and damping members. This can be done by a variety of programs such as Suspension analyzer [10] for geometry and dynamics or Ansys [11] for stress analysis.

Both tires and rims include the unsprung mass and therefore the right choice to achieve even improves driving performance. Magnesium alloy rims, lighter than aluminium, are produced exclusively for racing, which are renowned for its extreme lightness, high resistance to impact and vibration.

The total mechanism of racing car chassis is immensely complex system where even the smallest details, such as wheel angles, can mean degradation in adhesion and even the tire wear. And this may reflect the lap times and telemetry data from several sensors.

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LIST OF SYMBOLS

G	[MPa]	elastic material property
D	[mm]	wire diameter
n	[-]	numbers of coils in the spring
R	[mm]	radius of the spring
k	[$N.m^{-1}$]	spring stiffness