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Balanced Suspension

Erik Zapletal

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Erik Zapletal

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ABSTRACT

Modern racecars have very stiff suspensions. When travelling over uneven ground, these racecars lose grip, and lose time.

Balanced Suspension is a clean sheet approach to suspension design. It allows a suspension to be very supple, so that it can absorb bumps and undulations, thus giving a smooth ride and high levels of grip. At the same time the suspension can be very stiff, giving flat handling and minimal ride height changes.

INTRODUCTION

A vehicle's suspension has two major functions. Firstly, it has to support the vertical loads of the vehicle's body. It should do this in a way that provides the vehicle's body with as smooth a "ride" as is possible, regardless of any unevenness of the supporting ground surface.

Secondly, the suspension has to transmit the horizontal forces between the ground and the vehicle that are necessary to accelerate the vehicle forwards, backwards and sideways. It is a fairly accurate generalization to say that a car can maximize these horizontal forces if it keeps all of its wheels in firm contact with the ground, all of the time.

Modern motor racing is won by maximizing the horizontal accelerations. When we watch modern racecars, we see that they often lift one or more wheels off the track. When the wheels of a car are off the road they cannot exert the horizontal forces that are necessary to accelerate the car. The car loses its "grip" of the road. Furthermore, the lifting of the wheels can upset the "handling balance" of the car, making it difficult for the driver to extract the maximum performance from the car.

This paper examines a seldom-used conceptual approach to the design of vehicle suspension systems. This approach allows a suspension system to have both the supple, and the stiff, characteristics, which are necessary for good ride, grip, and handling.

A practical embodiment of this conceptual approach is presented. This is a simple mechanical arrangement that supports a vehicle's body above four or more wheels. It is suitable for use on all multi-wheeled vehicles, including trucks, buses, passenger cars, and on-road, and off-road, racecars. To the author's knowledge, this system has not yet been implemented on a racecar. However, there are many vehicles that take advantage of the most beneficial feature of this system. Some of these are listed in the Appendix.

BACKGROUND

SCOPE OF THIS PAPER - The subject of vehicle suspensions is broad, so we will clarify here, what we are, and are not, considering.

We are mainly concerned with what is happening at the four "wheelprints" - that is, at the "tyre contact patches". We are considering the essentially vertical motion of the wheelprints relative to the vehicle's body. We are not considering the other wheelprint motions of lateral and longitudinal displacement, rotation, steering and camber change.

The non-vertical movements of the wheelprints can significantly affect suspension behaviour. For instance, the lateral and longitudinal movements affect the height of the notional "roll and pitch centres". Since these factors affect the roll and pitch moments, and the "jacking" forces, that act on the vehicle's body, they should be considered in conjunction with the concepts presented in this paper.

We are not considering the control methods, such as beam axles, wishbones, trailing arms, and so on, that attach a wheel to the vehicle's body. These control arms are directly responsible for transmitting the horizontal forces between the ground and the vehicle. However, they have little influence in supporting the vertical loads of the body, nor in ensuring that the wheelprints stay in firm contact with the ground so that the horizontal forces can be developed in the first place.

This paper is mainly about that behaviour of a suspension that is controlled by its various springs and dampers.

THE EVOLUTION OF RACECAR SUSPENSIONS - The modern racing suspension is derived from the "independent" systems fitted to some 1930s luxury passenger cars. These "double-wishbone" systems were introduced to improve ride comfort over that possible with beam axles, and to this end they were fitted with soft springs. However, the independent suspensions with soft springs had a low resistance to body roll forces, and thus allowed the body to lean outwards whenever the car travelled rapidly around a corner. So sporting versions of these cars were fitted with stiffer springs, and "anti-roll-bars" were added to further restrict body roll.

The introduction of wide tyres required even tighter control of body roll. If a wide tyre is allowed to lean outwards during cornering, then it will lift its inner edge off the road, and thus lose grip. To get the most grip from the wider tyres, the springs and anti-roll-bars were made even stiffer. When the racing community discovered the benefits of aerodynamic download, the springs became stiffer again. Likewise, the increased cornering forces that were available required even stiffer anti-roll-bars.

The end result of this incremental evolution of a passenger car suspension, is that there is almost no movement left in the modern racecar suspension. The modern racecar's four wheelprints are held, almost rigidly, in a flat plane.

SUSPENSION MODELS

We can think more clearly about the behaviour of a particular suspension, if we use a simplified conceptual "model", to describe that particular suspension.

Each wheelprint of a vehicle's suspension has one degree-of-freedom in its vertical motion relative to the vehicle's body. For a car with four wheels, there are four degrees-of-freedom for the vertical motions of the four wheelprints. We shall refer to each of the time varying degrees-of-freedom as a "mode" of the suspension movement. The four degrees-of-freedom, or modes, taken together, will constitute a "suspension model".

It is important to realize that we have a lot of freedom in how we define each of the four modes. We have, in fact, four infinities of choices. Any choice of four modes that we use will describe a particular suspension movement, with a particular set of four numbers, for each point in time. Another choice of modes will result in a different set of numbers. That is, we have four infinities of different descriptions available to us, for the same particular suspension movement. Each of these descriptions is equally valid, but some are more illuminating than others.

THE "SINGLE-WHEEL-MODEL" - The most obvious way to specify the modes, is to have one of the modes corresponding to the vertical motion of one of the wheelprints - say, "left-front-bounce" - and so on for the other three modes and wheelprints. Conventional suspensions follow this obvious way, and use a separate spring-damper to control the vertical motion of each individual wheelprint. In this case, each mode is controlled by its associated spring-damper, and thus each mode has an associated spring-rate curve.

THE "AXLE-MODEL" - An alternative approach to the above, is one in which each mode involves the simultaneous movement of two wheels.

Here, two modes define the movement of the front pair of wheels, and another two modes define the movement of the rear pair of wheels. Each axle has one mode in which the pair of wheels move in a "similar" manner (that is, both moving up, or both moving down), which we call the "axle-bounce-mode". In the second mode the wheels move in an "opposite" manner (one moving up, while the other moves down), which we call the "axle-roll-mode" – see Figure 1.

The so-called "monoshock" suspension is a direct implementation of the axle-model. A single spring-damper - the "monoshock" - controls the bounce motion of the two wheels at one end of the car. A second spring-damper controls the roll motion of the two wheels. Thus each mode has a spring rate that is uniquely determined by the mode's associated spring-damper.

We can use the axle-model to describe the simple "spring-at-each-corner" suspension. Since both the axle-bounce-mode, and the axle-roll-mode, involve equal amounts of movement of the left and right wheelprints, and if we assume that the wheelprint rates are linear, then it follows that the stiffness of both modes will be equal to the sum of the two wheelprint rates. That is, when viewed in terms of the axle-model, the spring-at-each-corner suspension has equal stiffness in its axle-bounce, and axle-roll-modes.

CHOOSING THE RIGHT MODEL - Many racecars have four springs controlling each axle. These suspensions are an evolution of the single-wheel model. They have gained the axle-bounce-spring (the "monoshock", aka

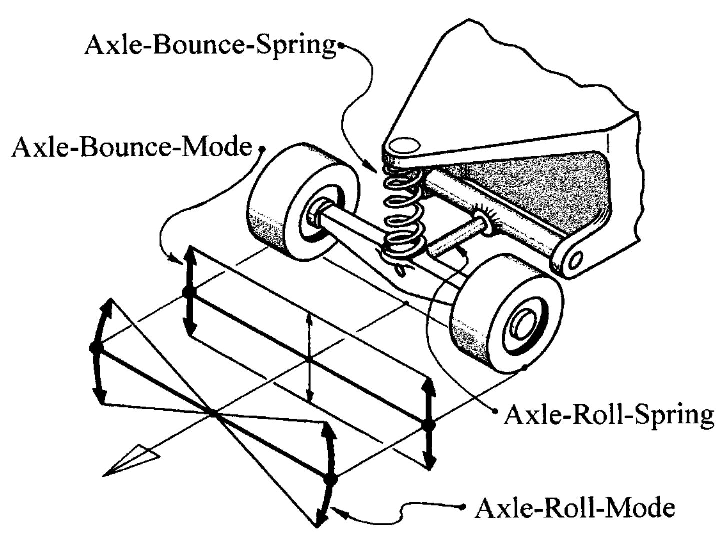

Figure 1. The "Axle-Model"

the “third spring”) and the axle-roll-spring (the “anti-roll-bar”), but they have not yet lost the vestigial single-wheel springs. These suspensions have moved towards the axle-model because it is better at withstanding large differences in aerodynamic download, whilst leaving the handling balance – controlled by the axle-roll-mode – relatively unaffected.

Since these suspensions have more springs than is necessary, neither the single-wheel-model, nor the axle-model, is ideally suited to describing their behaviour. Either model can be used, but care should be taken with the effects of the redundant springs.

THE “SIDE-PAIR-MODEL” - This model has its modes based on the similar, and opposite, movements of the pairs of wheelprints on each side of the car. If Figure 1 had the wheels turned sideways, then it would depict the side-pair-model. We could call the modes “left-side-bounce”, “left-side-pitch”, “right-side-bounce” and “right-side-pitch”.

Not many vehicles have suspensions that match this model. The Citroen 2CV, developed in the late-1930s, and to a lesser extent the Austin-Morris “float-on-fluid” cars, developed in the 1950s, had suspensions of the side-pair type.

THE “ALL-WHEEL-MODEL” - Here, each of the four modes (for a four-wheeled vehicle), involves the simultaneous movement of all four wheels. An example of four such modes is shown in Figure 2. In the “bounce-mode”, all the wheels move in a similar manner (that is, all moving up, or all moving down). In the “pitch-mode”, the front pair of wheels moves up, while the rear pair moves down, or vice versa. In the “roll-mode”, one side pair moves up, while the other side pair moves down.

Very importantly, these three modes have been chosen because they can be directly related to the similarly

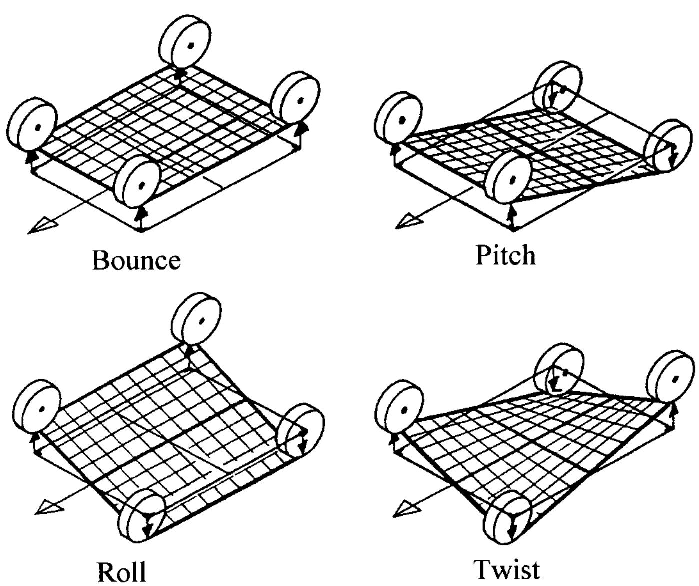

Figure 2. Four "All-Wheel-Modes"

named motions of the vehicle’s body relative to the ground. That is, we have a direct connection between our thinking of the motion of the vehicle’s body relative to the ground, and our thinking of the motion of the four wheelprints relative to the vehicle’s body.

If all four wheelprints are initially in a “flat” plane, then any combination of modal bounce, pitch and roll, will always keep those wheelprints coplanar. However any stretch of road, even if it appears relatively smooth, will soon depart from a flat plane. The fourth mode shown in Figure 2, is “twist”, and it is the only one of the four modes that allows all four wheelprints to stay in contact with non-flat ground. In the twist-mode, one diagonally opposite pair of wheels move up, while the other diagonally opposite pair move down.

We could have chosen as the fourth mode, a movement of any single wheelprint out of the plane defined by the other three wheelprints. The twist-mode shown in Figure 2, is just more symmetrical, and neater. The lateral axis of the pitch and twist-modes in Figure 2, passes through the centre of the wheelbase. An alternative definition of the modes might have this axis passing through the centre of gravity of the vehicle, which may be closer to the front axle, or to the rear axle.

When we use the all-wheel-model to describe the spring-at-each-corner suspension, we see that the stiffness of each mode is determined by the same four wheelsprings. That is, all the modes have the same stiffness. The bounce-mode has the same stiffness as the pitch, roll and twist-modes.

Using the all-wheel-model to describe the monoshock-at-each-axle suspension, we see that the bounce and pitch-modes are determined by the front and rear axle-bounce-springs. Likewise, the roll and twist-modes are determined by the front and rear axle-roll-springs. A monoshock suspension has its bounce-mode as stiff as its pitch-mode, and its roll-mode is as stiff as its twist-mode.

A similar inspection shows that a “side-pair” suspension has equally stiff bounce and roll-modes, and equally stiff pitch and twist-modes.

BOUNCE, PITCH, ROLL AND TWIST MODES

There are many advantages to be gained by having independent control of the bounce, pitch, roll and twist-modes. Before we look at how we can do this in practice, we will consider what sort of modal behaviour would be desirable.

REQUIREMENTS OF THE MODES - We want a suspension that is stiff enough to resist changes to ride height, when subject to varying aerodynamic loads. We also want the suspension to resist changes to pitch and roll attitude, when subject to accelerating, braking and cornering forces.

At the same time, we want the suspension to be compliant, so that it can soak up any bumps and undulations of the ground surface, thus giving a smooth ride. And we want the suspension to keep all four wheelprints in firm contact with the ground, so that it can deliver the maximum available grip from those four wheelprints.

The diagrams in Figure 2 give an indication of the type of “bumps” that the different modes can absorb. The bounce-mode is suited to long wavelength humps and depressions. The pitch-mode is better suited to short wavelength corrugations. The roll-mode is only suited to bumps that affect the two wheels on one side of the car at the same time - a rare occurrence. The twist-mode is suited to single wheel bumps and potholes, corrugations that are crossed at an angle, and any general unevenness of the ground surface.

Figure 3 depicts the modal spring rates that might be suitable for a racecar. The horizontal axes indicate wheelprint movement, as shown in Figure 2. The left and right sides of each curve indicate the end-stops for that mode of movement. The vertical axes indicate the resisting force.

THE BOUNCE-MODE - The bounce-mode has to carry all the downloads that act on the vehicle - the static weight, the vertical inertial loads, and the aerodynamic downloads. For almost all types of vehicle, the bounce-mode should have a rising rate, as shown by the solid line in Figure 3. This gives the vehicle a spring rate that rises in proportion to the load on the vehicle. When the vehicle is lightly loaded, it has a soft bounce-mode. When it is heavily loaded, the bounce-mode is much stiffer, and the vehicle is less likely to “bottom-out”.

For racecars with ride-height sensitive aerodynamics, the bounce-mode curve can have an even more rapidly rising rate - as shown by the broken line in Figure 3. This curve can be produced by a relatively soft spring that is fully compressed by the static weight of the car. The car thus spends most of the time sitting on its bounce-mode “bump-stop” and the aerodynamic loads cannot compress the suspension further, but the wheels can still droop downwards as the car flies over a depression in the road.

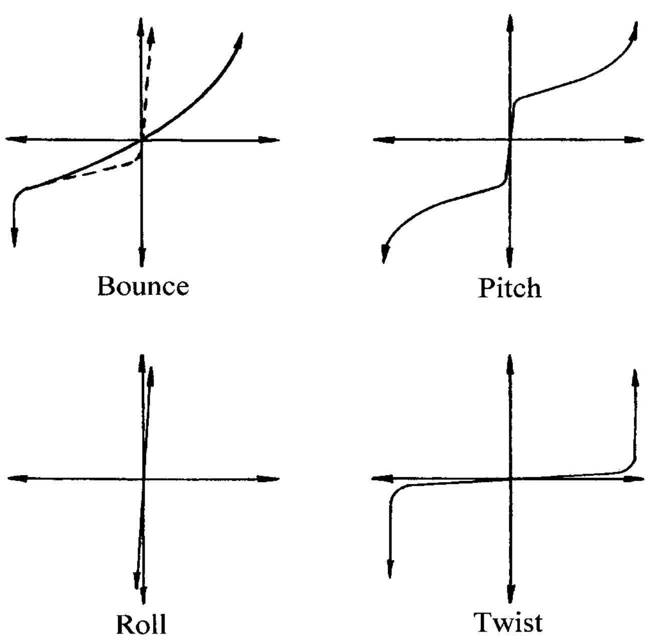

Figure 3. Modal Spring Rate Curves

THE PITCH-MODE - The pitch-mode is well suited to absorbing bumps. The pitch-mode is also required to resist changes in pitch attitude, during accelerating and braking. Therefore, for a road racer a pitch-mode spring rate that is highly non-linear is suitable. The pitch rate should be stiff up until the loading experienced during maximum longitudinal acceleration, then the pitch rate curve should “break away” to a softer rate that can absorb the harsher bumps. This type of curve can be produced by a coil spring that is pre-loaded between end-stops. The pitch-mode then compresses the spring from either end.

THE ROLL-MODE - There are not many types of bumps that can be absorbed by the roll-mode alone. A soft roll-mode will give a lot of body roll during cornering, which is in itself uncomfortable, and can reduce grip and handling balance via camber change and roll-steer effects. For passenger cars, or desert racers, a degree of compliance in the roll-mode can help to smooth the ride. For road racers, the roll-mode is best left very stiff, for flat cornering, and minimal camber change.

THE TWIST-MODE - When we consider the twist-mode's interaction with the vehicle's body, we see that the only forces that the twist-mode can exert on the body, are torsional forces. The twist-mode has no influence on the bounce, pitch or roll motions of the vehicle's body relative to the ground. All we can expect from a stiff twist-mode, is that by stressing the body in torsion, it will try to iron out any bumps in the road.

When a rigidly suspended car passes over a single-wheel bump, then the centre of the car will rise one half of the height of that bump. When a car with a soft twist-mode, and rigid bounce, pitch, and roll-modes, passes over the same bump, then the centre of the car rises only one quarter of the height of the bump. The ride of the soft twist-mode car will be, quite obviously, smoother than that of the stiff twist-mode car.

When a car with a stiff twist-mode is parked on uneven ground, then the pair of diagonally opposite wheels that are on the high ground will carry most of the weight of the car, while the other pair of wheels will carry less weight. A soft twist-mode allows the four wheelprints to accommodate to any unevenness of the ground, and thus share the vertical loads that act on the car. Even when stationary, a stiff twist-mode will make a car lose its grip on the road.

The above “static” disadvantage of a stiff twist-mode applies equally well at 200+mph. A stretch of road can have a constant, non-zero, value of twist over a certain distance. For example, a “cambered” road surface will introduce a constant amount of twist into a vehicle’s suspension, when that stretch of road is traversed diagonally (such as when the vehicle travels from one side of the road, across the centre line, towards the other side of the road). This is typical of an approach to a corner, and although none of the suspension modes might be moving, the non-zero level of twist will reduce the grip of the car.

For the above reasons concerning ride and grip, and also because of its affects on handling balance (explained later), the twist-mode should be as free as possible.

THE TWIST-MODES OF CONVENTIONAL SUSPENSIONS - The spring-at-each-corner suspension has all modes equally stiff. Adding anti-roll-bars makes the roll and twist-modes the stiffest. Monoshock suspensions have the roll and twist-modes as the stiffest at low downloads (at high downloads, the axle-bounce-springs may bottom-out, making the bounce and pitch-modes almost rigid).

Conventional racing suspensions have the twist-mode much stiffer than is necessary. The inadequacies of these suspensions can be traced to the simple fact that their twist-modes are very stiff, when they should be completely soft.

The side-pair suspension has equal pitch and twist-mode stiffnesses. Since a vehicle's wheelbase is usually greater than its track, its pitch-mode can usually be made softer than its roll-mode. Any roll motions of a wheel assembly (that is, “camber” changes), especially with wide tyres, usually reduce wheelprint area, and thus reduce grip. Any pitch motions of the wheel assembly do not reduce wheelprint area, or grip, in this way. Thus, the side-pair suspension can have stiff bounce and roll-modes, for good load carrying capacity and flat cornering. The pitch and twist-modes can be somewhat softer, for a smooth ride, and good levels of grip.

A completely soft twist-mode would be better, but between the single-wheel-model, axle-model, or side-pair-model, it is the side-pair-model that has the best pairing of modal stiffnesses. Since the side-pair-model has been in use for over 50 years, it is surprising that the motorsports community has not embraced its advantages.

ADDING MODAL DEPENDENCIES - There are some situations where an interdependence of the modes can be beneficial.

One such situation involves the pitch curve breakpoint. A racecar with aerodynamic download might be able to generate, say, 1G braking deceleration at low speeds, and perhaps 4G deceleration at high speeds. If the breakpoint is set high enough to prevent the nose from dipping during high speed braking, then the breakpoint will be four times higher than necessary for low speed braking. This, in turn, will restrict the pitch-mode's ability to absorb low speed bumps. Therefore, a useful refinement would be to link the pitch-mode breakpoint to the bounce-mode, so that the breakpoint increases as download increases.

Another dependency would have the vehicle's pitch attitude change, as the aerodynamic download, acting on the bounce-mode, increases. This could provide more downforce at low speeds, and less drag at high speeds.

However, if we wish to implement any specific dependencies between the modes, it is easiest if we start with independent modes.

BALANCED SUSPENSION

“Balanced Suspension” is the author's approach to implementing a vehicle suspension that has independent control of the bounce, pitch, roll and twist-modes. Figures 4 and 5 are from the author's patent application for this system. Some other approaches to the same problem are listed in References 1, 2, 3 and 4.

THE CONCEPT - Figure 4 illustrates the basic principles of the Balanced Suspension system.

Since each mode that we are trying to control involves the movement of all four wheels, and since we would like each mode to be controlled by a single spring-damper, it follows that we will need some sort of “linkage” to connect all four wheels, to each mode controlling spring-damper. As we shall see later, this linkage can use mechanical or hydraulic elements, or both. In Figure 4, the connecting linkage starts with the four vertical pushrods connected to each wheel hub.

The next, and conceptually most important, elements in the linkage are the various balance beams. These balance beams - which give the system its name - work in the same way as does a “balance scale”, or the “brake balance bar” often fitted to racecars. The most important characteristic of the balance beams, is that the magnitudes of the forces acting on the two end joints, and on the central “fulcrum” joint, will always be in a ratio that is determined solely by the geometry of the balance beam.

For example, if all three joints lie on a straight line, and the fulcrum is midway between the two end joints, then any vertical forces that act on the end joints, will each be 50% of the vertical force that acts on the fulcrum. Most importantly, they will remain at that 50% even if the balance beam is tilted at an angle to the horizontal.

Let us now consider the bounce-mode. A study of Figure 4 shows that any nett vertical force that acts between the body (31) and the four wheelprints, must pass through link (32). Any downwards force acting on this link is distributed, in the appropriate ratios, by the three balance beams (33), (34) and (35), and is thence transmitted to the four wheelprints. We can thus replace link (32) with a vertical spring-damper, and this will be our bounce-mode-spring.

We note that the distribution of the vertical force by the balance beams (33, 34 and 35) is unaffected by the relative vertical positions of the four wheelprints. That is, the measured “cornerweights” of this vehicle will be unaffected by any unevenness of the supporting ground surface.

In a similar way, any pitch moments acting on the body must pass through, and can only be resisted by, the U-bar (48) - which is the pitch-mode-spring. The body-pitch moments cause an upwards force at the end of one arm of the U-bar, and an equal, but downwards force, at the end of the other arm. These upwards and downwards forces act on the fulcrums of two more lateral balance beams, which in turn distribute the forces to the wheelprints.

In Figure 4, the pitch-mode balance beams are shown as (34) and (35) - that is, the same beams that the bounce-mode uses. It is important to note that the pitch-mode beams, and the bounce-mode beams, are conceptually distinct. That is, beams (34) and (35) should be thought of as four beams, two for the bounce-mode, and two for the pitch-mode. The position of the fulcrums of each of these four, conceptual balance beams, can all be varied independently.

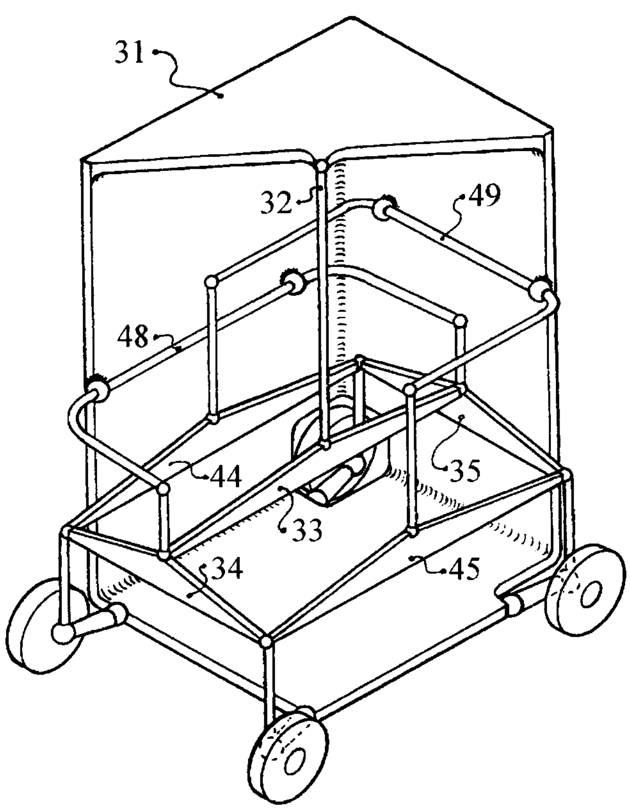

Figure 4. Conceptual Balanced Suspension System

The roll-mode is controlled in a similar way to the pitch-mode. The U-bar (49) is the roll-mode-spring, and it distributes any body-roll moments to the four wheelprints via balance beams (44) and (45). As before, the longitudinal position of the fulcrums of these balance beams, can be varied independently of any of the other balance beams.

Finally, we could add two more balance beams between the diagonally opposite pairs of wheelprints. If a spring was fitted between the fulcrums of these diagonal balance beams, then that spring would control the twist-mode. The only function that this system could perform, would be to resist any movement of the four wheelprints out of a flat plane. Since there are only a few benefits to be gained from such a system, and many disadvantages, it is not shown.

A PRACTICAL EXAMPLE - The system of Figure 4, as shown, is a little unwieldy for a practical racecar. Some streamlining would help. Figure 5 depicts a system that is intended for a passenger car. It illustrates some considerable simplifications to the system of Figure 4.

The interconnecting linkage of Figure 5 uses hydraulic links to connect the front wheels to the main “balance mechanism” at the rear of the car. Each hydraulic link consists of two single acting hydraulic rams connected to each other with hydraulic tubing. These hydraulic links work in a similar way to those of hydraulic brake systems. Damper valving could be fitted to these links to damp the flow of oil between the rams.

The rear wheels are directly linked to the balance mechanism by ball joints on the rear trailing arms. For a racecar application, the rear corners of the balance mechanism would act on the ends of the usual suspension pushrods. Alternatively, if hydraulic links are used at the rear, as they are at the front, then the balance mechanism becomes a self-contained “black-box”, that can be mounted anywhere on the car. This can be useful for adjusting mass distribution.

The most notable difference of the system in Figure 5, from that in Figure 4, is that the links connecting the front wheels to the balance mechanism are “crossed over”. That is, the right-front-wheel, is connected to the left-front-corner of the balance mechanism, and vice versa.

The above “crossover” effectively rotates the balance beam (34), in Figure 4, end for end. This results in the two roll-mode balance beams, (44) and (45), crossing over at their approximate midpoints. The whole assembly of balance beams (33), (34), (35), (44), (45), the roll mode U-bar (49), and the various joints of Figure 4, thus becomes the unitary, X-shaped, “balance-plate” (75), of Figure 5. When considering the function of the balance-plate, it is worth remembering that, conceptually, it is doing the job of seven balance beams and one spring.

The balance-plate (75) is controlled in its motion, relative to the chassis, by a coilspring (91), and a U-bar (90). These two are analogous to the link (32), and the U-bar (48), of Figure 4. They are thus, respectively, the bounce-mode-spring, and the pitch-mode-spring.

As stated above, the roll-mode U-bar (49), of Figure 4, is incorporated into the balance-plate (75), of Figure 5. Considering Figure 5, it is seen that a pure roll motion of the four wheelprints (shown with arrows) causes one diagonally opposite pair of corners of the balance-plate (75) to move upwards, while the other diagonally opposite pair of corners move downwards. Thus, it is the torsional stiffness of the balance-plate (75), which acts as the roll-mode-spring.

Conversely, we see that a pure twist motion of the four wheelprints causes the balance-plate to undergo a roll motion. There is nothing in the system that can resist this roll motion, therefore the wheelprint twist-mode will be very soft.

DAMPING

There is not the space here, to cover all aspects of suspension damping. We will make only the following brief comments.

The dampers of conventional suspensions have three distinct functions to perform. Firstly, they must damp oscillations of the vehicle's body (the "sprung-mass") relative to the ground (at about 1Hz). Secondly, they must damp oscillations of the wheel-hub assemblies (the "unsprung-masses") relative to the vehicle's body (at about 10Hz). Thirdly, they have an important influence on the vehicle's handling balance (this is discussed later, under "Handling Balance").

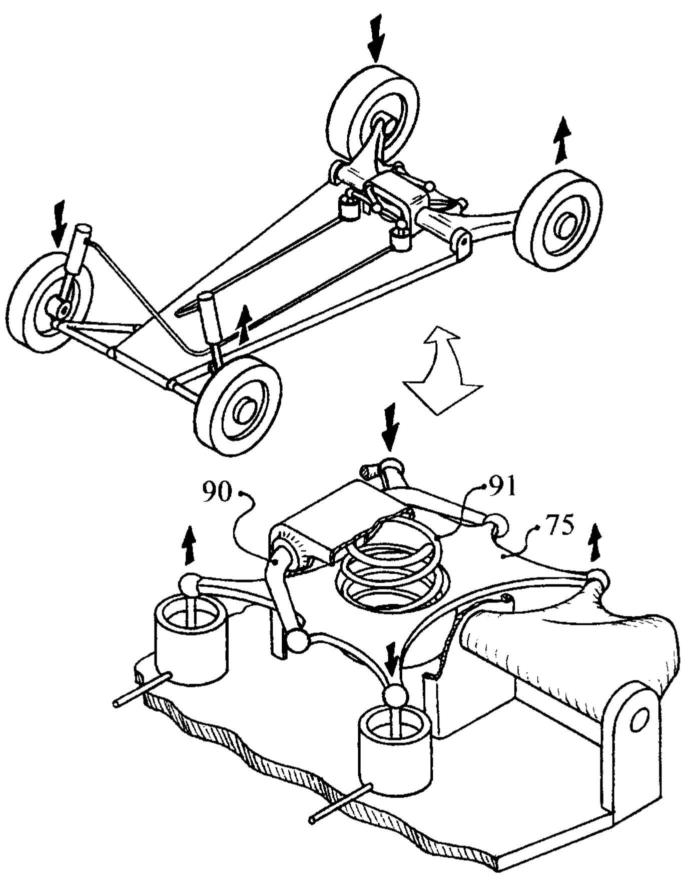

Figure 5. Practical Balanced Suspension System

Since the above three functions have distinctly different damping requirements, and since the same set of four dampers is expected to perform all three functions, the damping performance of conventional suspensions is inevitably compromised.

With a Balanced Suspension system, the damping of the sprung-mass is performed in a manner similar to that of the springing. That is, a damper that acts only in the bounce-mode is used to control the bounce motions of the sprung-mass. In Figure 5, this damper could be fitted co-axially with the bounce-mode-spring (91). Similarly, the pitch and roll-mode-springs would have associated pitch and roll-mode-dampers. Each damper would be tuned to best control its associated spring-mass system.

The unsprung-mass oscillations, often called "wheel-tramp", involve the wheel-hub assembly oscillating between the spring in the tyre below, and the weight of the vehicle above. Minimizing the mass of the wheel-hub assembly can reduce tramp. Dampers that act between the wheel-hub and the vehicle's body can be used to control tramp. The hydraulic links shown in Figure 5 could be used for this function. Alternatively, inertial dampers that are tuned to the characteristic tramp frequency can be attached directly to each wheel hub. In either case, these dampers only have to control the wheel tramp – their performance is not compromised by other demands.

HANDLING BALANCE

It is often said that a racecar's handling balance is more important than its absolute levels of grip. If the driver doesn't have the confidence in the car that good handling balance brings, then the driver cannot extract the maximum performance from the car.

The largest influences on handling balance are the vehicle mass distribution, the tyres (their size, compound, camber, and so on), and if present, any aerodynamic downloads. Generally, if the mass, tyre sizes, and aerodynamic loads are distributed in the same ratios, then the car will be well balanced.

For practical reasons, the above distributions are not always ideal. In these cases, the handling balance can be fine-tuned by utilizing the non-linear behaviour of a tyre's grip. Although it is not strictly correct to refer to the following behaviour as "friction", we can say, loosely, that as the vertical loads on a tyre increase, its "coefficient of friction" will decrease. Looking at it another way, if two tyres carry equal shares of a vertical load, then they can, together, resist a greater horizontal load than can a single tyre that is carrying all of the load. (It is for this reason that a soft twist-mode is so beneficial - it allows all four wheelprints to share the load.)

The conventional approach to the fine-tuning of handling balance involves adjustments to the wheelspring and anti-roll-bar rates, and damper stiffnesses. For this method to work reliably, the stiffness of the chassis has to be significantly greater than the stiffnesses of the various springs and dampers. As the suspension stiffness of modern racecars has increased, the torsional rigidity of the chassis has also had to increase, to stay in front of the spring and damper rates.

The conventional approach relies on the vehicle's body rolling outwards during cornering. For a given amount of body roll, the end of the car that has the stiffest axle-roll-mode will have the greatest difference in loads between its inner and outer wheelprints. The stiffest end of the car will thus have the greatest reduction in grip - due to the non-linear tyre behaviour described above. The idea is to reduce the grip at one end of the car, to bring it into balance with the maximum available, but lower grip, at the other end of the car. The ratio of the front and rear axle-roll stiffness is often referred to as the “roll-moment-distribution”.

At the initial “turn-in” to the corner the various springs have not yet deflected significantly, so they cannot balance the car by the above method. During this transient phase the dampers are used to adjust the balance. The same principles apply. Stiffer dampers at one end of the car will cause a greater difference in inner and outer wheelprint loads, and a consequent reduction of grip.

One problem with the conventional approach to handling balance, is that it only works on flat roads. An undulating section of road will very quickly overwhelm the subtle changes in wheelprint loads that are being expected from the small angles of body-roll.

As an example, assume a car is cornering to the left, thus decreasing the left wheelprint loads, and increasing the right wheelprint loads. Assume that there is a twist in the road, similar to that in Figure 2, which causes the right-front and left-rear wheelprints to gain load, at the expense of the other two wheelprints. The twist in the road is equalizing the rear wheelprint loads, and increasing the difference between the front wheelprint loads. This reduces the front axle's cornering power and leads to understeer. If the road twisted in the opposite sense then the rear axle would have the lesser available cornering force and the car would oversteer. That is, the handling balance of a stiff twist-mode car is dictated by the twist in the road. Conversely, the handling balance of a very soft twist-mode car is independent of any twist in the road.

There are other problems with the conventional approach. If the wheelprint rates are non-constant (for example, they have a “rising-rate”), then increases in download can change the relative roll stiffnesses of the front and rear axles, and alter the handling balance. That is, the handling balance is bounce-mode sensitive. It will also be pitch-mode, and roll-mode sensitive, for similar reasons. Furthermore, it is not just the spring and damper rates that affect the balance, but also the spring rate of the air in the tyre. With modern, stiffly sprung racecars, the tyres provide about half of the total wheelprint rate. Therefore, any changes to the tyre rates, such as when they get hot, and their pressures rise, can affect the handling balance.

A Balanced Suspension vehicle can fine-tune its handling balance by adjustments to the roll-moment-distribution, as described above. Considering Figure 4, the roll-moment-distribution is determined by the positions of the fulcrums of the roll-mode balance beams (44) and (45). Moving these fulcrums towards the rear axle will make the rear wheelprints carry more of the roll moment, which will reduce their maximum available grip, and lead to oversteer. Moving the fulcrums forward, will give less oversteer, or more understeer. We can make similar changes to the pitch-mode balance beams, to alter the pitch-moment-distribution, and thus alter the longitudinal balance of the car during accelerating or braking.

In Figure 5, the roll-mode balance beams have been crossed over to make the unitary balance-plate (75). The fulcrums of the conceptual roll-mode balance beams are now at the intersection of the diagonals of the balance-plate. Therefore, to move the fulcrums towards the rear axles, we have to reduce the lateral spacing between the rear corners of the balance-plate. In general, to move the handling balance towards oversteer, we reduce the separation of the rear corners of the balance-plate, or we increase the separation of the front corners of the balance-plate. For more understeer, we do the opposite.

With Balanced Suspension, the soft twist-mode absorbs any unevenness of the road that moves the four wheelprints away from a flat plane. The springs and dampers of the bounce, pitch and roll-modes serve only to absorb the high speed bumps that would excessively accelerate the vehicle’s body in bounce, pitch and roll.

With Balanced Suspension the handling balance is fine-tuned by altering the roll and pitch-moment-distributions. But unlike conventional suspensions, these distributions are independent of the chassis, spring, damper, and tyre stiffnesses. They are independent of twist-mode motion, which makes them independent of undulations in the road. They are independent of bounce, pitch and roll motions, so aerodynamic, accelerating, braking or cornering loads do not effect them. They take effect whenever there are roll or pitch moments acting on the car body - there is no difference between the transient, and the steady state, phases.

The roll and pitch-moment-distributions are dependent only on the geometry of the balance beams. They can be fine-tuned, in much the same way that a racecar's brake balance is fine-tuned - by simple adjustments to the balance beams.

CONCLUSION

This paper has presented several different conceptual models of a vehicle's suspension. Viewing a particular suspension in the light of these different models can make clear aspects of the suspension's behaviour that would otherwise go unnoticed.

When we view a vehicle's body motions relative to the ground in the light of the all-wheel-model, we see that only the bounce, pitch and roll motions will cause movement of the suspension. Any travel, sideslip or yaw motions of the vehicle are in the horizontal plane, and do not directly affect the suspension. Thus, regardless of how many wheels a vehicle has, it needs only three spring-dampers in its suspension to control its three body motions relative to the ground. Any other modes of its suspension can be left free.

For historic reasons, and possibly unconsciously, many suspension designers think in terms of the axle-model. Since this model only considers the interaction of pairs of wheels, aspects such as twist-mode stiffness have been overlooked. When viewed in terms of the all-wheel-model, it is seen that a side-pair-model suspension has benefits over the more common axle-model suspension. However, an all-wheel-model suspension seems to offer even more benefits.

To conclude, we will summarize the perceived benefits and difficulties of the all-wheel-model suspension presented in this paper. The comparison will be with the currently fashionable racecar suspension (based mainly on the axle-model) that consists of double-wishbones, pushrod, rocker, and spring-damper at each corner, two anti-roll-bars, and optionally, two third-springs. The listing is roughly in order of importance.

ADVANTAGES

1. By far the greatest advantage of the all-wheel-model is that it allows us to think in terms of independent control of the bounce, pitch, roll and twist modes.

1a. The greatest advantage of being able to independently control these modes, is that the twist-mode can be freed. For racecars, any twist-mode stiffness is redundant. It has no beneficial effects on the car's ride, grip or handling.

A free twist-mode allows the wheelprint loads to be independent of any twisting of the ground surface. This gives high levels of grip, and a predictability of lateral and longitudinal handling balance. The tyres share the loads more evenly, so they last longer. Wheelspin, or brake lockups, are less likely. Horizontal forces on the front wheels are more equal, so steering is lighter - power steering may not be necessary. The ride is smoother, which may help the driver, and the car, to finish the race.

1b. Conventional suspensions require movement in the roll-mode so that they can fine-tune their handling balance via their spring rate dependent roll-moment-distributions. The use of balance beams to effect the roll-moment-distribution allows the handling balance to be easily adjusted regardless of the stiffness of the roll-mode. This allows the roll-mode to be very stiff, for flat cornering with little camber change of the wheels during cornering. This in turn reduces the compromise between the optimum camber angle for braking or for cornering.

1c. Conventional suspensions have the pitch-mode controlled by the load carrying axle-bounce springs. As a result, the pitch-mode of such suspensions is too stiff. When there is separate control of the modes, the pitch-mode can be made stiff enough to prevent squat during acceleration, or nose-dive during braking, but it also can be soft enough to absorb the harsher bumps.

1d. Independent control of the bounce-mode allows it to be stiff enough to take large aerodynamic downloads, with no change in ride height. But unlike conventional suspensions, this bounce stiffness has no detrimental effects on any of the other modes.

1e. Conventional suspensions ask too much of their dampers. Independent control of the all-wheel-modes allows the bounce, pitch and roll motions of the vehicle's body to be optimally damped. Likewise, dampers that are optimized for the control of wheel tramp can be used without compromising the sprung-mass dampers. The use of balance beams to fine-tune handling balance means that the dampers have a much smaller effect on the overall performance of the racecar.

2. The system of Figure 5 is, arguably, simpler than a conventional suspension (see also Disadvantages - 2.).

Figure 5 has two spring-dampers (for bounce and pitch) + one balance plate (for roll control) + four connections to the wheels.

Conventional suspensions have four spring-dampers (for the wheels) + two anti-roll-bars + four (short) connections to the wheels + (optionally, two more third-springs (actually seventh and eighth springs)).

DISADVANTAGES

1. Inertia. The greatest difficulty with the all-wheel-model is the conservatism of many race teams - there is a lot of mental inertia that must be overcome. Racecar designers who adopt any of the concepts described in this paper, will have to dump a lot of hard-won knowledge, and learn some new tricks.

2. Perceived complexity. For a suspension to have independent control of its all-wheel modes, it must

interconnect all of its wheels. Conventional suspensions already connect the left and right wheels, via the anti-roll-bars, so there is no extra complexity there. However, the front-to-rear connection is further than the side-to-side connection.

The Citroen 2CV has mechanical front-to-rear connections, and it is generally regarded as the cheapest car to manufacture of the past 50 years. The Austin-Morris "float-on-fluid" models have hydraulic front-to-rear connections, and were also modestly priced. Obviously, front-to-rear connections are possible, and at a reasonable cost.

3. A racecar that has significant droop travel in its bounce-mode will require a modified tyre-change procedure. The chassis will either have to be lifted high enough to overcome the droop, or else the car can be lifted at the outer ends of its suspension control arms.

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CONTACT

The author can be contacted at:

Erik Zapletal, PO Box 231, Glenorie 2157, AUSTRALIA

Email: zap@hawknet.com.au

APPENDIX

A SURVEY OF TWIST-MODES - Presumably, the more advantages that a soft twist-mode has, then the more examples there will be of soft twist-mode vehicles. Below is a brief survey of vehicles with respect to the softness, or stiffness, of their twist-modes.

Passenger cars have a moderate twist-mode. The softer their springs, then the softer the twist-mode. Sports cars have stiff wheelsprings, and stiff anti-roll-bars, which give them a stiff twist-mode. As noted in the body of this paper, modern racecars have almost rigid twist-modes.

Trucks usually have very stiff springs, to cope with the large variations in load. However, many countries have laws regulating maximum permissible wheel loads. As a consequence almost all trucks built today - and in fact, ever - have a flexible ladder frame chassis. The flexible chassis gives the truck a soft twist-mode.

Trucks with dual rear axles have these axles connected via some sort of “load sharing” mechanism. This might be a pair of longitudinal balance beams connecting each side-pair of the four rear wheels, with the fulcrums of the balance beams connected to the chassis by stiff leaf springs. This gives the four rear wheels, as a group, stiff bounce and roll-modes, and very soft (effectively zero) pitch and twist-modes. The longitudinal separation between the front axle, and the fulcrums of the rear balance beams, will control the pitch motion of the whole vehicle. As with the four-wheeled truck, the flexible chassis will give a soft twist-mode between the front wheels, and the “averaged” rear wheels.

Trains are often supported by a four-wheeled bogie under each end of their carriages. These bogies act in a manner very similar to that of the dual-axles of trucks. That is, they have moderate bounce and roll-modes, and very soft pitch and twist-modes.

There are many types of vehicle that have no form of sprung suspension at all. Almost all of these are built to have a zero stiffness twist-mode. We can start with all the four-wheeled wooden carts that have ever been built. These typically had a loosely fitted front-axle that pivoted to provide both steering, and a soft twist-mode. Many modern four-wheeled trailers use the same design.

The very first self-propelled four-wheeled vehicles were the “steam traction engines”. These had an articulated front-axle, just like the wooden carts, which allowed the driven rear wheels to sit firmly on the ground at all times, and thus develop maximum traction. Many vehicles still use this same principle. Farm tractors, and earthmoving tip trucks, have an articulated front-axle. So do the cheapest ride-on lawn mowers. Four-wheeled loaders and forklift trucks, which carry most of the load at the front, have an articulated rear-axle.

Road graders have six wheels in a similar layout to the dual-rear-axle trucks. The graders have a longitudinal pivot at the centre of the front-axle, and a lateral pivot at the centre of each of two longitudinal balance beams that connect each of the rear-side-pairs of wheels. This arrangement gives a very clear example of how to reduce a system with six degrees of constraint (the six wheels), to a system with just the three degrees of constraint (the pivots), that are necessary for static stability. Graders have a rigid chassis, and rigid bounce, pitch and roll-modes. But the ride is relatively smooth, because the bounce, pitch and roll-modes are determined by the averaged heights of the six wheels. And the traction is excellent, since all of the wheels are always in firm contact with the ground.

Many tracked bulldozers are also built with a soft twist-mode. The track support beams are allowed to pivot about the rear sprocket axes. A lateral balance beam at the front of the vehicle controls the pitch-mode in a manner similar to that of the front-axle of farm tractors. Given the large loads and forces involved, articulating the tracks in this way can be expensive. However, the users of these dozers, and the users of the other machines discussed above, are prepared to pay the extra price. They pay, because the soft twist-mode pays. A soft twist-mode gives a smoother ride, and more traction, than a rigid twist-mode.

The earliest racecars, pre WW1, had stiff leaf-sprung beam axles, a ladder frame chassis, a large engine, a seat for the driver and mechanic, and little else. These racecars were derived from production passenger cars that had a fairly rigid chassis, enhanced by a solidly bolted four-point engine mounting. When converted for racing, crossmembers were removed from the chassis, and the engine was mounted at only three points so that the chassis could twist. The roll-moment-distribution was determined in much the same way as with Figure 4. The two engine bellhousing mounts, and the seat mounts, would lean on the central section of the chassis side rails, much as the roll-mode member (49) of Figure 4, leans on the fulcrums of the roll-mode balance beams (44) and (45). The softening of the twist-mode gave a smoother ride, more grip, and more consistent handling, than the originally stiff twist-mode.

Go-karts are the cheapest form of modern racecar. With no springs, their bounce, pitch and roll-modes are very stiff. Their chassis could be built with high torsional rigidity, to give a stiff twist-mode, but instead they are deliberately built to have a moderately soft twist-mode. The driver’s seat, which carries the greatest proportion of the car's mass, is mounted in a similar way to the engine and seat of the pre WW1 racecars. The benefits of this approach are, as before, better ride, grip and handling.

So let's tally up the numbers. In the middle, with moderate twist-modes, are the countless millions of cars and trucks that have been built during the last one hundred years. Also, the earliest racecars, and go-karts.

With zero stiffness twist-modes we have - wooden carts, trains, tractors, trailers, earthmoving trucks, loaders, graders, dozers, forklift trucks, ride-on mowers, and many more. Each of these has been built in the millions. Some of them are very fast – high-speed trains. Most of them depend on lots of traction - the earthmovers. They all benefit from a smoother ride. They include the first four-wheeled vehicles - wooden carts - and the first self-propelled vehicles - steam trains and tractors. From these first vehicles to the present day, the zero stiffness twist-mode has proved to be a winner.

That leaves the rigid twist-mode vehicles - a few thousand modern racecars. And shopping trolleys, they also have a stiff twist-mode.

Modern racecars are in a stiff twist-mode minority. They share their stiff twist-modes with vehicles that are built down to a price, rather than up to a standard. After all, has the reader ever tried to push a fully loaded shopping trolley down a bumpy footpath?