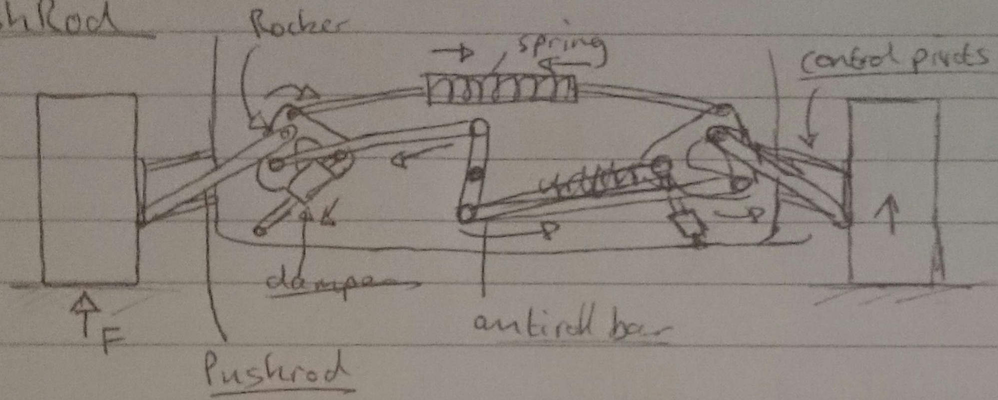
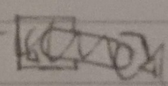
Formula Student

Suspension System

Push Rod



- Double Wishbone connections (Control Points)
- ~~Antiroll bar = Torsion Bar~~

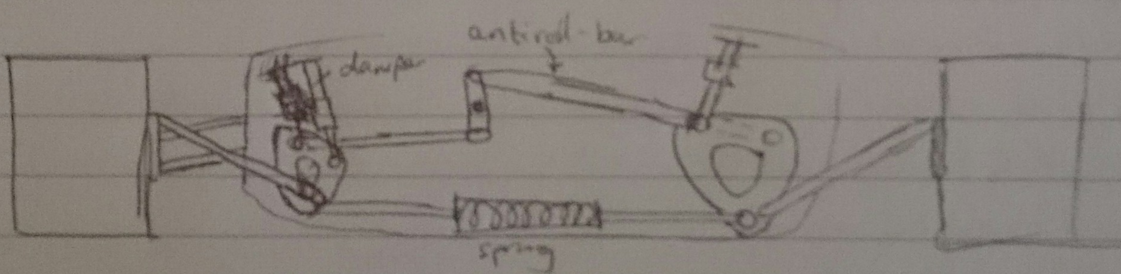


- ~~Antiroll Bar~~

Adv compared with normal suspension system

- Restrictive Wheel Movement (stiff)
  - keeps the car at same road level (ride height)
- components are internal instead of outside.
  - reduces drag

Pull rod Suspension - Pushrod suspension upside down



Compared with Pushrod

Adv

- Lower Centre of Gravity
  - better handling characteristics

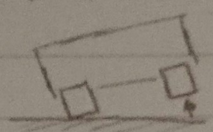
D-Adv

- Control Arms (double wishbones) needs to be stronger as Pull rod don't support weight/forces, unlike a Pushrod.
- Rarely used.

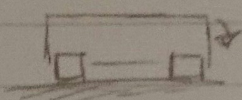
- Car can only perform when tyres are connected to the floor. Car Suspensions make sure tyres stays on the ground.

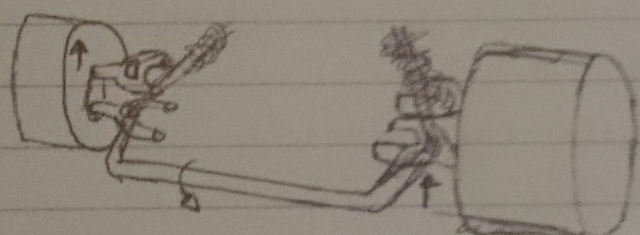
Anti-Roll Bars / Anti-sway bar

- Reduces body roll when cornering by distributing lateral forces more evenly across both tyres.
- Can Change Understeer/Oversteer.
  - Car Turning sharp Left w/o Antiroll bar



  - Car Turning Sharp Left with Antiroll bar





- Double Wishbone arms connects (wheels) tyres & Car Frame
- Antiroll bar connects (independent) suspension components together

- Antiroll bar transfers Torque from one tyre to the other.

- Forces Transfered from heavily loaded axle to the connected ends via a bushing, to the torsion bar via a flexible joint, to the connected ends of the opposite side of the vehicle and finally to the opposite axle.

<u>Reduce Understeer</u>

- Increase stiffness in rear AR bar
- OR reduce stiffness in front AR bar

<u>Reduce Oversteer</u>

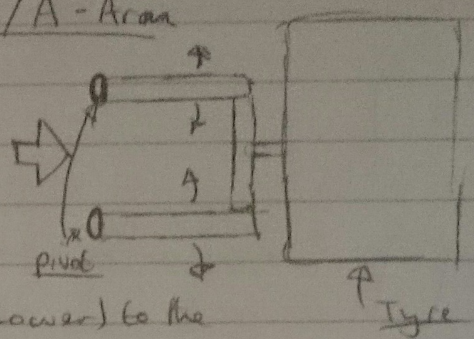
- <u>Vice Versa</u> to Reducing oversteer

- Another way to reduce roll is to increase suspension stiffness.

Drawbacks

- Driving on broken road may produce jarring side-to-side motion (waddling movement), which increases in severity with diameter and stiffness of sway bars.
- too much roll bar stiffness will make car fully lean on 1 side.

Double Wishbone / A-Arm

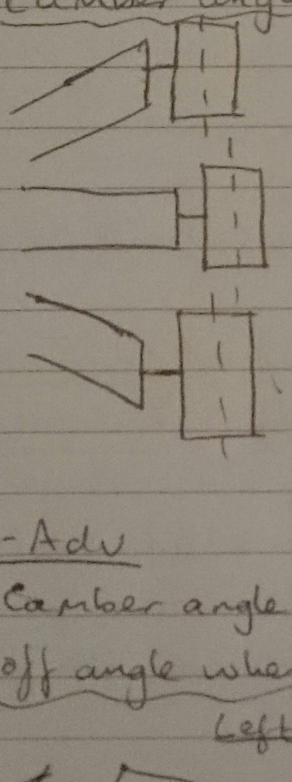


- Spring connected to 1 of the wishbone (Lower) to the frame of the car (fixed).

- 2 Control Arms (Wishbones)

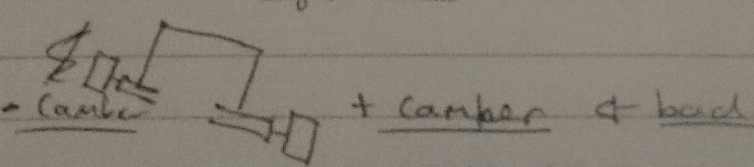
If 2 control arms (wishbones) are at equal length:

- Adv
  - as the wheel travels up & down relative to the chassis, Camber angle stays the same



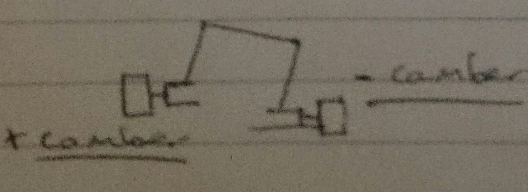
- D-Adv
  - Camber angle changes when cornering (as the chassis is at an off angle when the car rolls).

Left Corner

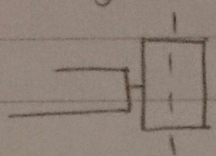


~~If the upper control a~~

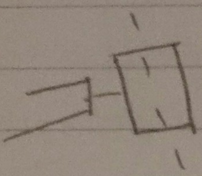
Using a shorter upper control arm:



- as the tyre drives ~~over a bump~~ round a corner!



flat



cornering ~~over a bump~~

- induced negative camber

∴ more ~~grip~~ mechanical grip

∴ Adv

- increased negative camber on inside tyres when roll & positive camber on outside tyre = MAX contact with tyre & road ∴ max grip

- Can handle large deflections - larger bumps on the road - larger travel of wheel moving up & down
- Versatile - any configuration of suspension system.

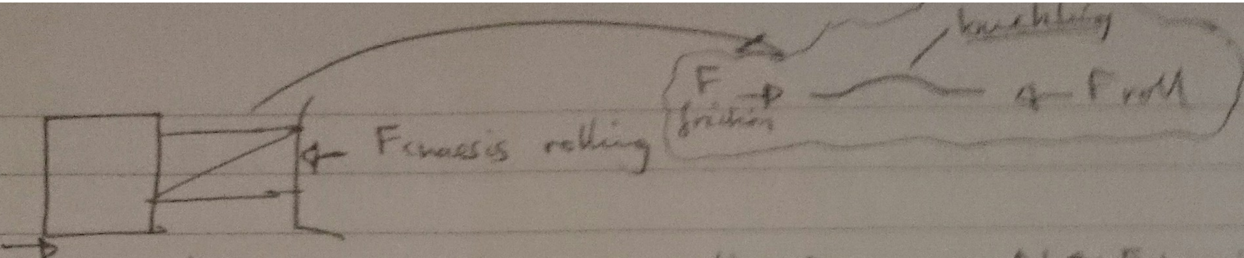
Formula 1 car - 2012 Lotus

- Suspension must be soft enough to maintain contact with the road over bumps - high mechanical grip
- Too soft - slow response of driver input to car output e.g. driver turns hard left, car responds sluggishly

- Normal cars suspension is designed to hold the force of the car (weight)
- ∴ - Formula 1 cars suspension is designed to hold the forces in all directions (not just up & down) & holds 3 x weight of the car (due to aerodynamical force)

2 types of movements in suspension system

- Chassis moves in the same time with the wheels
  - called Heave movement
- Chassis moves relative to the wheels (opposite direction)
  - 2 situations where this occurs:
  1) Cornering! chassis (car) rolls against one side of the wheels.
     ∴ Lateral forces in the suspension

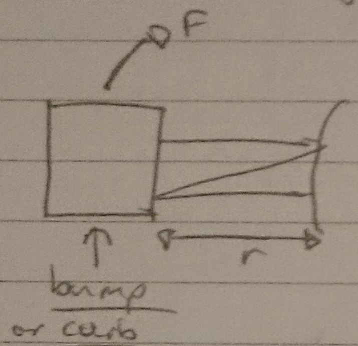


Friction ($= \mu N$) of tyre + road opposes rolling Force → $N \propto F_{chassis\ roll}$

~~rods~~ Control rods + Pull/push rod must be able to withstand lateral forces of the car turning/rolling + friction

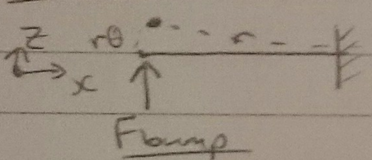
- prevent buckling

2) Bumps : 1 tyre moves vertically relative to the ~~th~~ chassis



- distance travelled of tyre (vertical) = $r\theta$

- This, in essence can be simplified into a cantilever problem



← assume chassis remains fixed (due to very high stiff spring + damper system)

Solving the 2 situations

1) use anti roll bar

- neutral (ineffective) when 2 wheels on either side is Moving together - e.g. when Heave movement occurs
- prevents (limits) (1) situation as there'll be less $F_{chassis}$ rolling, and as Friction force is ~~rela~~ proportion to $N (\simeq F_{chassis\ roll})$
∴ less friction force as well THEREFORE less buckling

• normal road cars has both situations/movements in their suspension sytem. In F1 car, there's a third element (central element)

• Third Element (central)

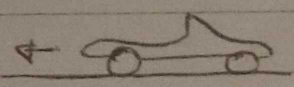
• for any race cars with wings/downforce
• does the opposite of what anti-roll bar does
- for AR bar, it only acts when the wheels are moving independently from each other, i.e. when 1 wheel moves up.
- Central element only acts when the 2 wheels are moving relative to each other (does nothing during roll).

[1] - www.formula1 - dictionary.net/fric.html

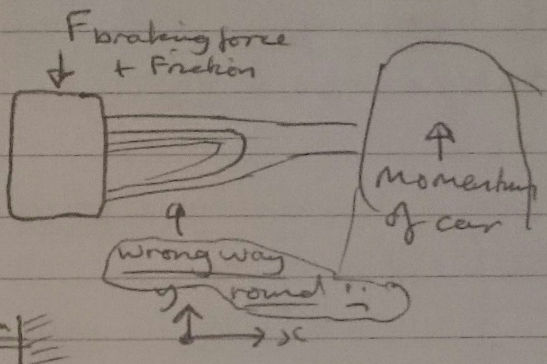
Third Element

Called FRIC (Front to Rear Interlinked Suspension)

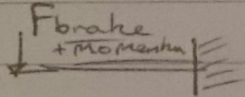
- produced by Mercedes + Lotus in 2012
- F1 car goes through number of movements
- Car pitches when braking



braking:



∴ for control rods:



different to bump cantilever as axis is $\uparrow^{z} \rightarrow x$

- rolls when turning (shown on previous page)

- Car is unstable during these handling movements

- goal is to keep vehicle stability through a manoeuvre, optimise aero ~~downforce~~ aerodynamics (through not changing ride height during manoeuvres), → due to instability of vehicle, car ride height is also unstable ∴ aerodynamics is affected

  and maintaining downforce.

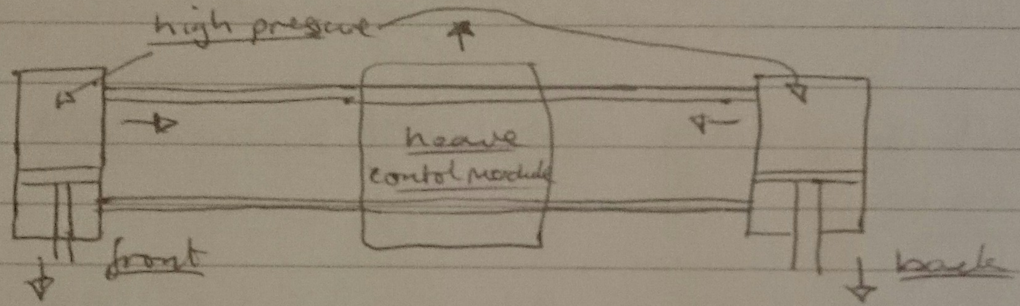
- FRIC suspension system links front + rear suspension of the car using hydraulics
  - Keeps all 4 corners of the car at constant ride height under braking
  - inertia based - doesn't use mechanical/electronic input from the driver. ∴ passive
- You want soft springs for more grip → but too much instability in car ∴ aero is affected/hampered & driver control + responsiveness reduced

- FRIC controls heave (↑↓ movements), ~~roll~~ pitch (forward movement - when braking & backward when accellerating) and roll (↔ movement) ∴ grip + aerodynamics are maximised

- The Dampers on the front & back are connected via pipes therefore damper fluids can change from 1 end to the other

In Heave

- when the car brakes, the car pitches forward therefore front suspension compresses & rear suspension rises.



- pressure builds up on one side of the centre element on the front suspension and this pressure is transfered to the rear centre element.

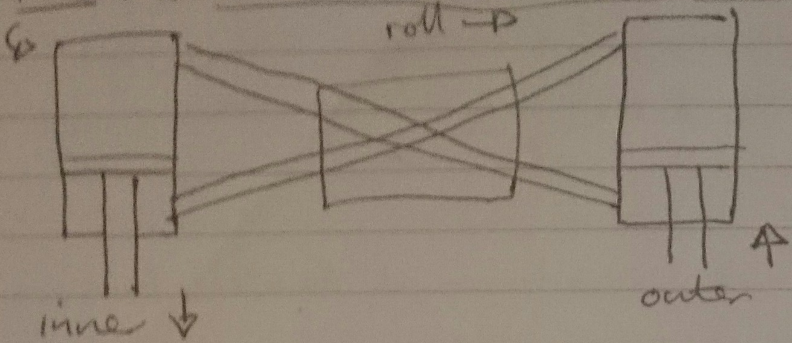
- This increases suspension spring effect at the front and reduces it at the back ∴ car wont dive nose down under braking

- In heave, both front + back dampers has a high pressure field on the top (due to piston moving down). But as both of them are connected together, the pistons will resist any more downward movement, hence in effect, increases the damping stiffness of the car

- Therefore more rigid chassis when in heave

In Roll

- when rolling (e.g. turning left), the outer hydraulic will compress and the inner element will rise.
- This will increase damper coefficient ∴ stiffer car when turning



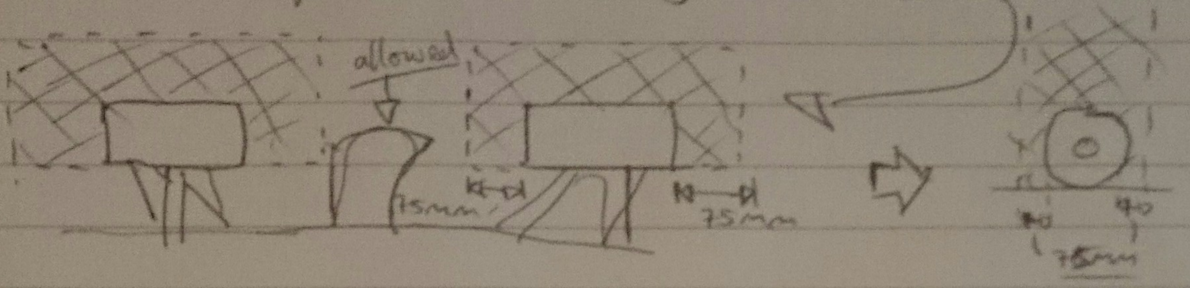
- Same effect in pitching, from front side to back side

∴ front 2 wheel Dampers are cross-linked to prevent roll along with AR bar

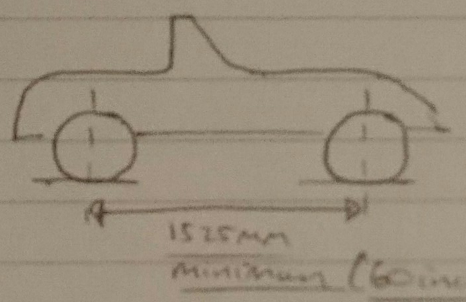
∴ LHS front wheel Damper is parallel connected to the LHS back wheel Damper to prevent heave movement (up + down of car). Same with RHS front + back dampers

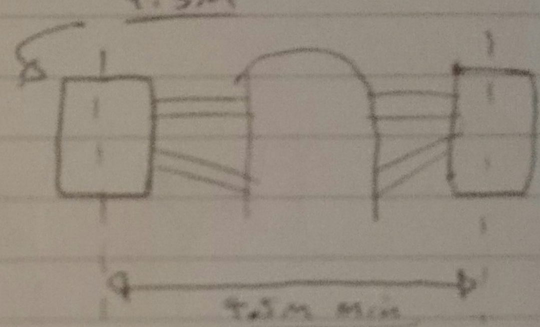
Formula Student Rule

- No part of the vehicle may enter the keep out zone:

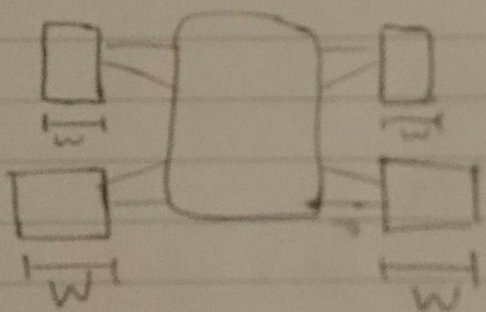


- Wheelbase - at least 1525mm long
- Track width - at least 4.5M





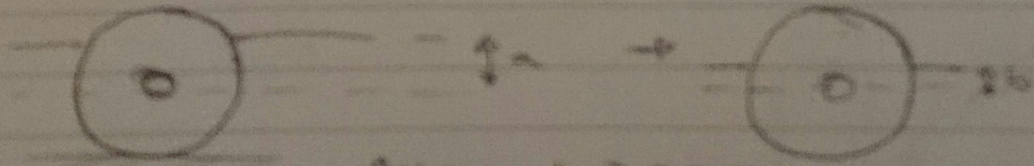
- Vehicle Track - smaller track width of vehicle (front / rear) must be no less than 75% of the width of the larger one.



$w \geq 0.75W$, where $w \geq 203.2$mm

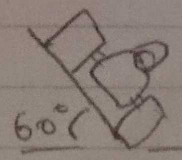
or vice versa: front larger than rear

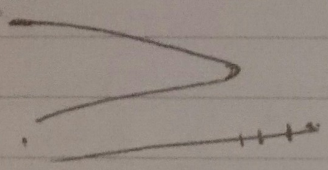
- Suspension - must be equipped with fully functional suspension system with shock absorbers (dampers) in front + rear wheels
- usable wheel travel of at least 50.8mm, 25.4mm jounce and 25.4mm rebound (1-inch) WITH DRIVER SEATED
- All suspension mounting points must be visible at technical inspection.

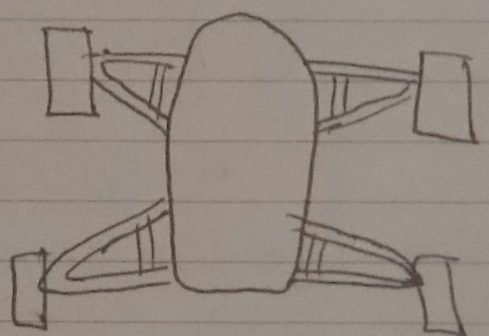


$\Delta x = a - b \geq 50.8$mm

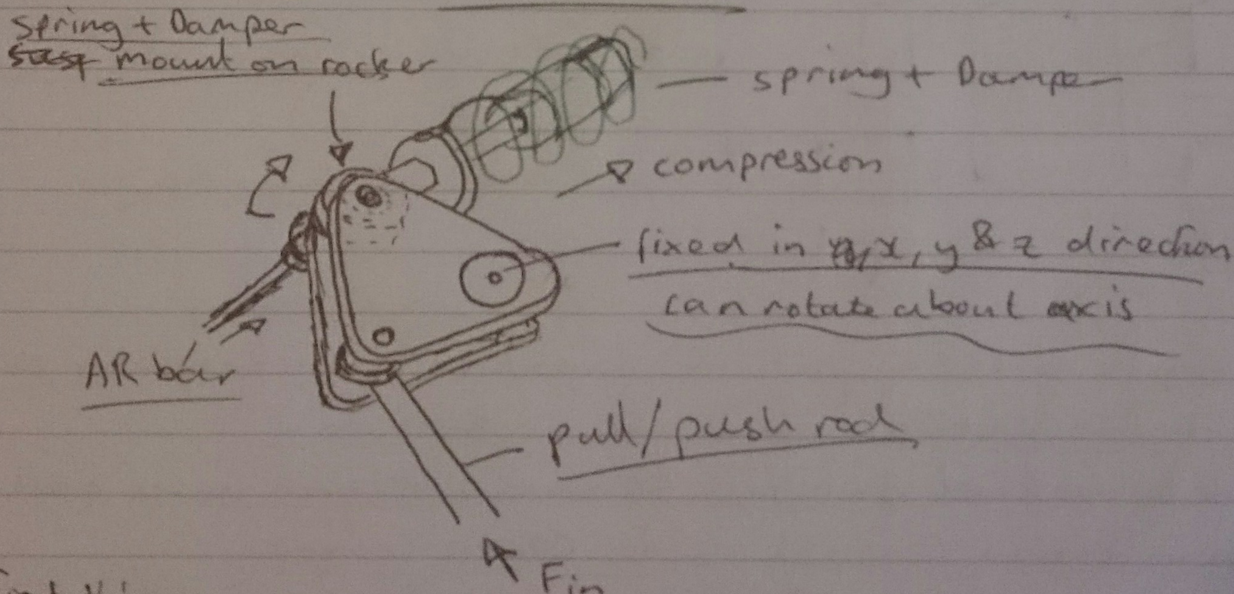
• Rollover Stability – vehicle must not roll when inclined at 60° from horizontal (~~[illegible]~~) (= 1.7 G's) with the tallest driver in the normal driving ~~posit~~ position



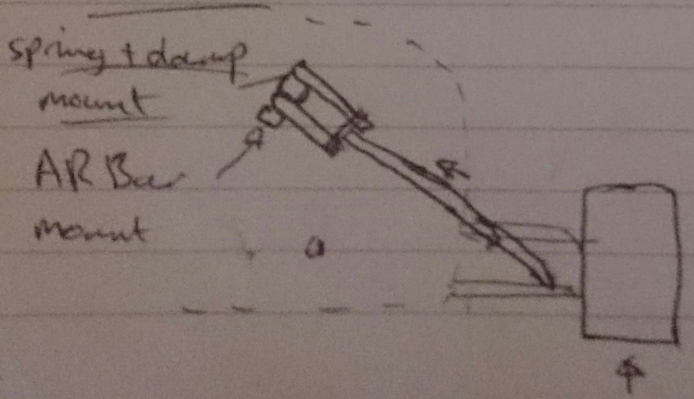




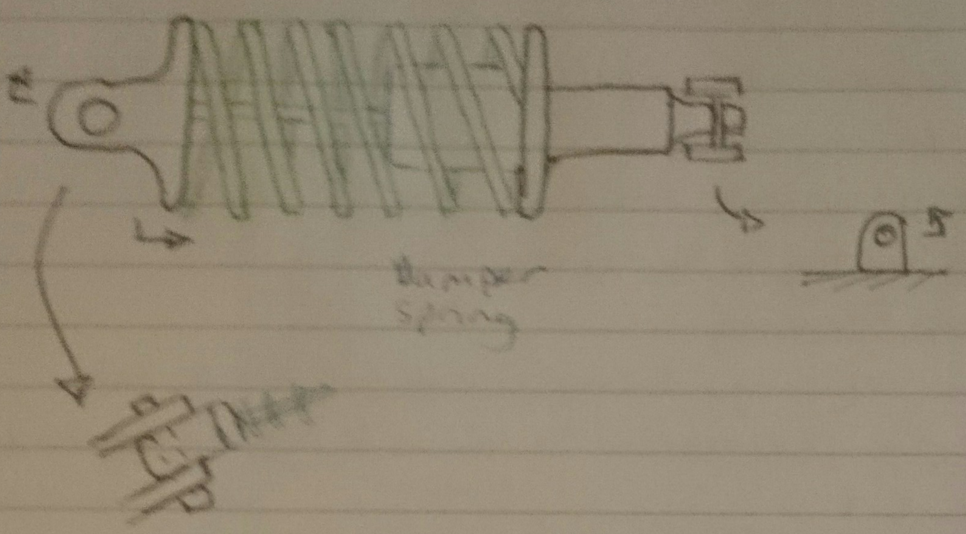
ROCKER



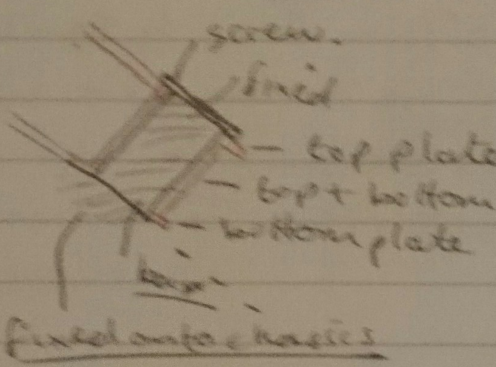
Front View



Spring + Damper



Fixed Mount

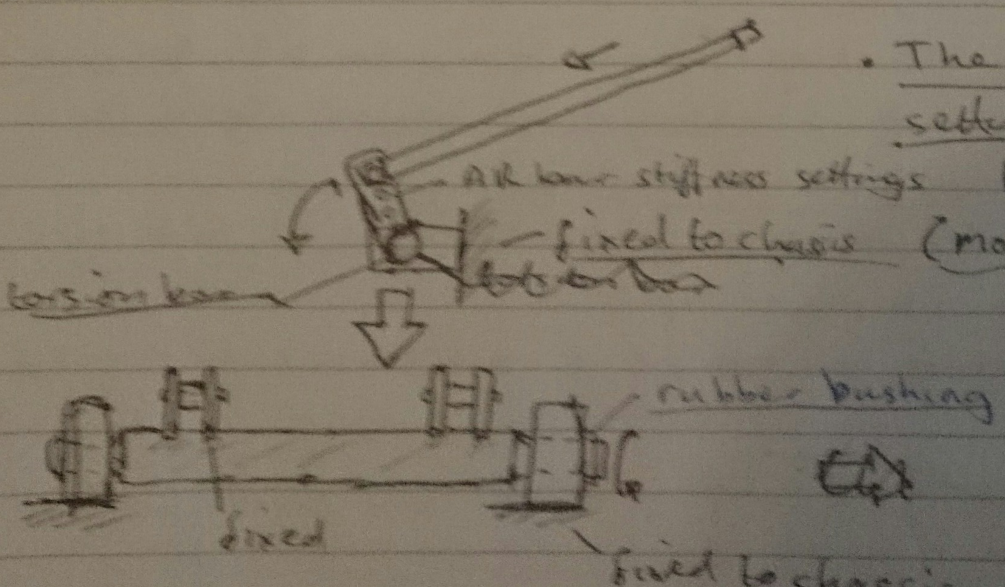


top + bottom plate connected around fixed bar, allowed to rotate not move in x, y or z axis.

θ = angle of pull/push rod.

AR Bar

- The higher the AR bar setting, the stiffer the bar (more moment force)



- Target - Max suspension travel of 10cm ...?

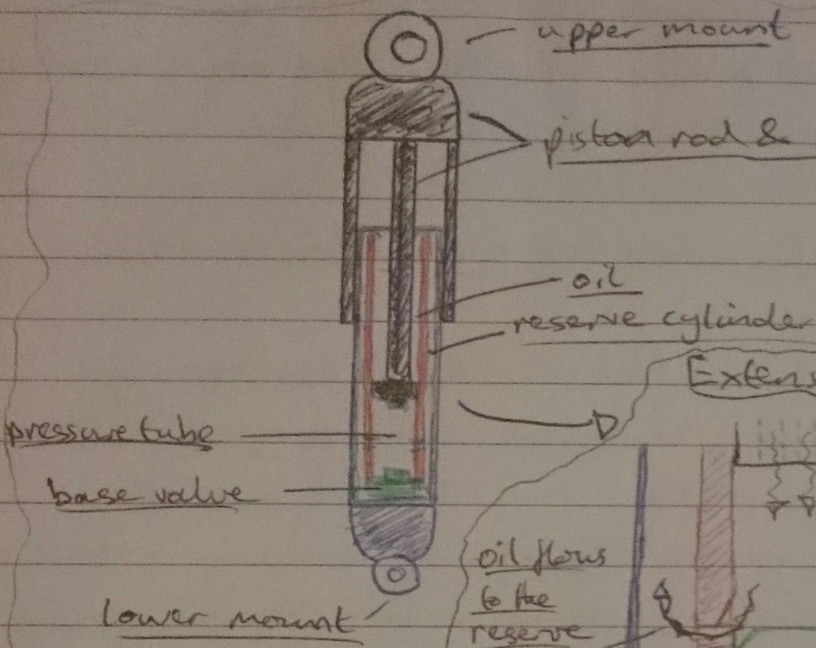
[1] - forum.wscc.co.uk/forum/index.php/topic/93372-selecting-the-correct-springs-dampers-for-my-car/
↳ google → 'racing spring damper suspension' → 7th link

- Selecting the right valving for the damper
- selecting a 'Bounce Frequency'.
  - lower bounce frequency, the more comfortable & more mechanical grip, however, the car will feel unresponsive to driver input [1]
  - 0.5 - 1.5 Hz for passenger cars, 1.5 - 2 Hz for sports / Track cars, and 3 - 5 Hz for aero cars. [1]
  - Bounce frequency is usually set different from Front to Rear by a small margin as the front of the car hits the bump first before the rear, so the rear needs a higher frequency to 'catchup'.
  - For race cars, higher front bounce frequency for good cornering in and ~~out~~ exit grip [1]

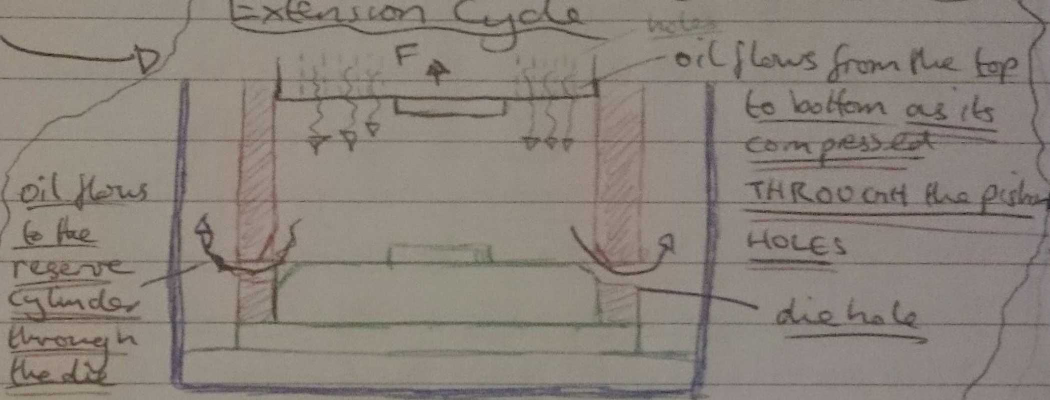
- Calculate spring rates using sprung & unsprung mass supported by that wheel and the motion ratio of the spring (angle it's inclined) at... [1] - this lets us select correct springs.

- Damping Ratio
  - $\zeta = 1$ is not desirable ~~when~~ because when you hit a series of ~~bumps~~ small bumps (e.g. racing curbs on a track), the suspension locks and you end up running on the bumps ~~as~~ as the spring cannot return to it's open length quickly enough.
  - Lower damping ratio, more comfortable the car feels, but more unresponsive the car is to driver input.
  - 0.2 - 0.3 Comfortable road cars, 0.4 - 0.6 Track cars, 0.7 - 0.8 for race cars.
    - this lets us select a TARGET damping ratio, we can use this to equate our damper characteristics

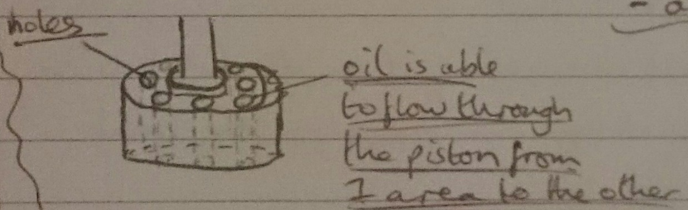
- Force vs Velocity Graph
  - shaft velocity of the damper & force of Damper



Extension Cycle



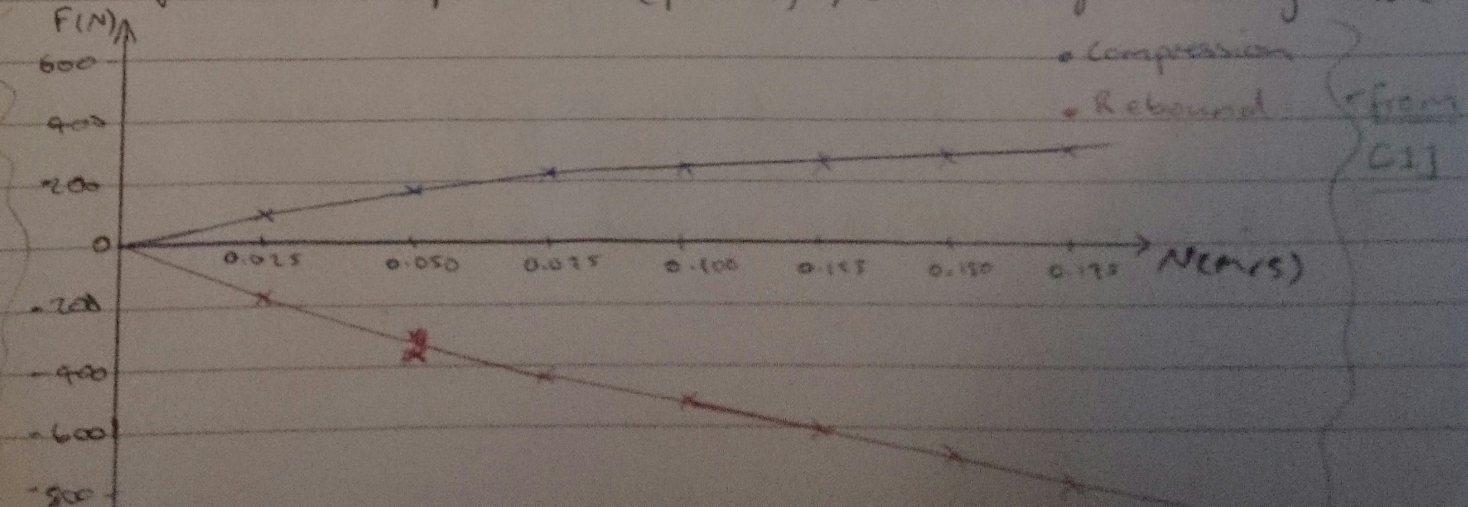
Piston Head



Compression Cycle
- arrows are inverted

[2] - auto.howstuffworks.com/car-suspension2.htm
↳ google images → 'car shock absorber how it works' → 1st image

- the faster the shaft moves (piston), the more force it'll generate



- Velocity: The axis is split into 2 areas - low speed damping (below 0.075 m/s) and the high speed area. The low speed is what the driver feels when cornering, braking/accellerating. The damper is moving relatively slowly in comparison to the high speed area which's when the car travels over a bump.

• How do we choose a curve for our Force vs Velocity Graph?

- If it's a track day car, we would be aiming for a damping ratio of around 0.6, which can be entered into an equation to obtain an 'initial slope' of our graph. ← First part of graph
- We then need to modify the graph. Compression damping controls the unsprung mass, Rebound damping controls the sprung mass hence we normally run more rebound damping then compression.
- Last part is tuning high speed area. Higher damping will make the low-speed area control + feel better, lower damping will make the higher speed area feel + control better. For race cars, we'd run as much rebound damping as much as possible before 'jackdown' occurs - where damping doesn't allow spring ~~[illegible]~~ to return to normal length quickly enough before the next bump. ← Last part of graph ~~(High speed~~

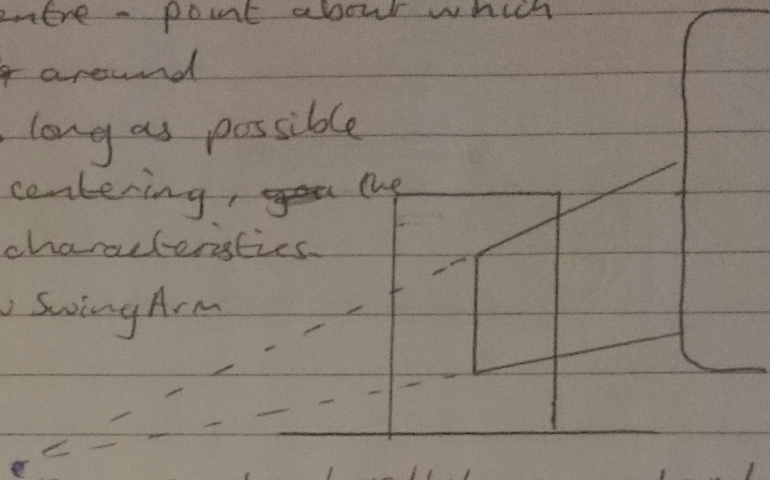
• This is why we have 2 different gradients of lines for both compression + rebound curves.

• The shape the curve makes are also given different names.
(1) Progressive - shaft speed increases, so does damping rate
(2) Linear - shaft speed increases, damping remains constant
(3) Digressive - shaft speed increases, damping rate decreases.

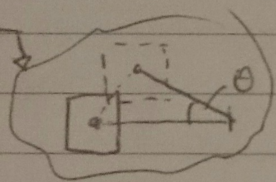
∴ Most important is Rebound Damping for Formula Student. We want the car to quickly compress when going over bumps, but slowly rebound that effect.

- Kingpin Angle , • Tyre Scrub
- IC = Instantaneous Centre - point about which suspension ~~system~~ linkages ~~moves~~ pivots around

→ ~~made~~ make 'd' as long as possible

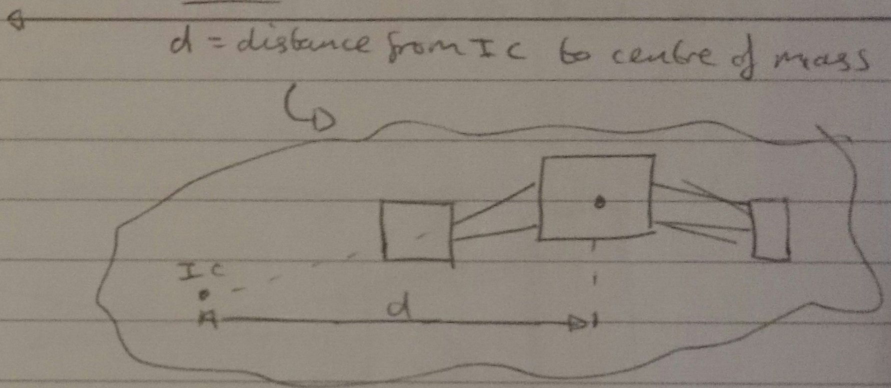


- IC controls the camber centering, ~~goo~~ the tyre strut, and wheel characteristics.
- d is also called Side View Swing Arm (SVSA)
- increasing SVSA length decreases angular travel



IC can be above/below ground - not an issue

d = distance from IC to centre of mass



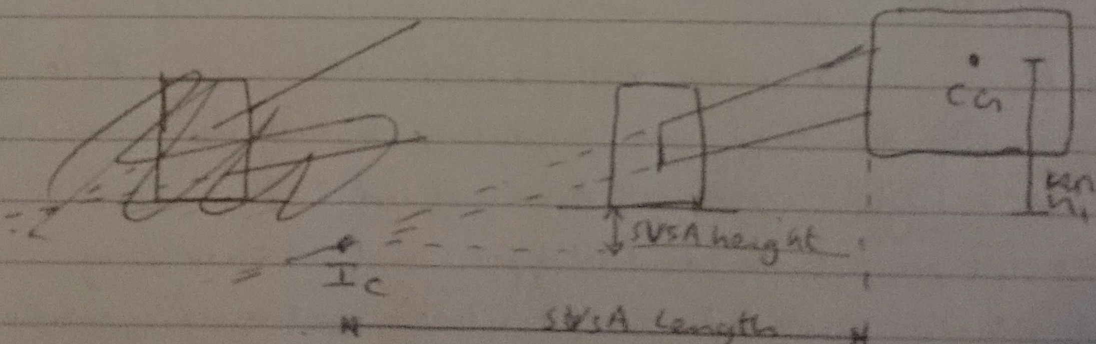
Anti-Dive & AntiSquat

- when the car pitches forward/backwards
- Dive & Squat has to be as small as possible

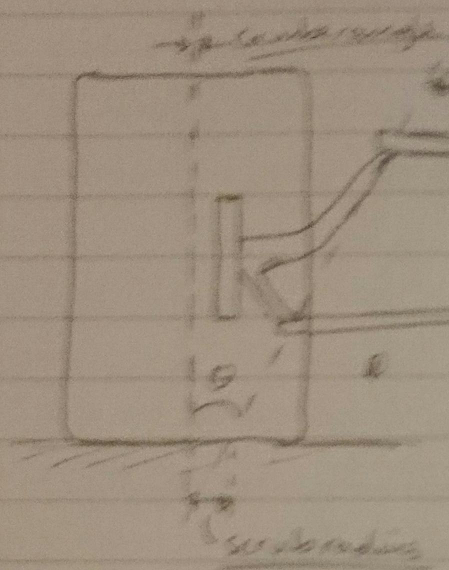
$$\%\,\text{AntiDive} = (\%\,\text{braking Force of Front}) \times \left(\frac{\text{SVSA Height}}{\text{SVSA Length}}\right) \times \left(\frac{L}{h}\right)$$

h = Centre of gravity height from ground

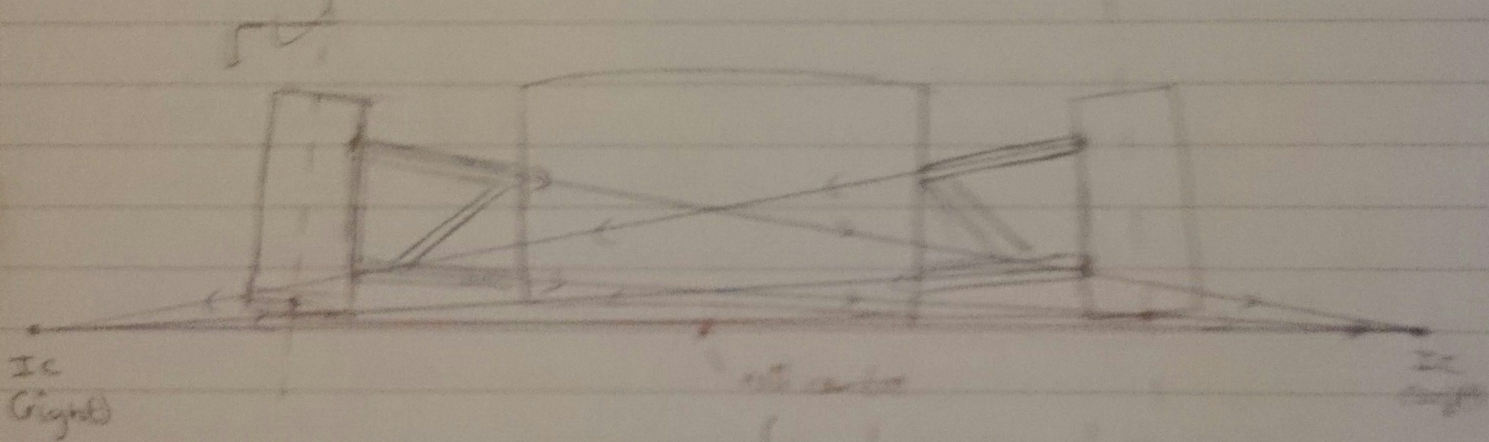
L =

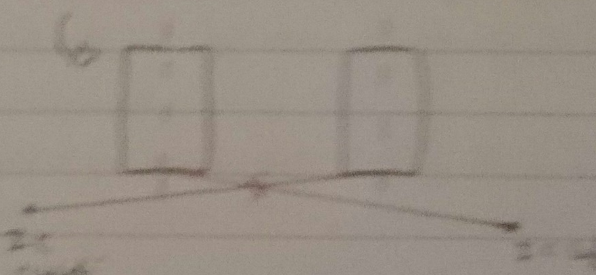


The rocker is also called the Bell Crank



- Camber Angle – Angle of wheel with respect to the vertical.
- θ = Kingpin Angle =
- Scrub Radius – distance between steering axis and the wheel's contact point





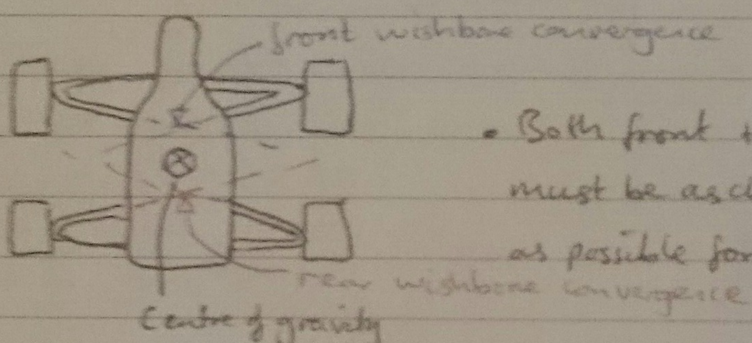
- Roll Centre – intersection of lines between tyre contact point & the instant centres of wheels
- Roll Centre defines the point at which the chassis rolls.

- The instantaneous roll centre only exists with unequal length wishbones
  [3] - www.rapid-racer.com/suspension.php ® Double Wishbone
- Pushrod has a higher roll centre than pullrod [3]
- Anti dive – helps prevent the car tilting forward when braking
- Anti squat – helps prevent the car from tilting backwards in extreme conditions

How does Anti-Dive / Squat Work? [3]

- By tilting the front + rear suspension mounts, by a couple of degrees towards the vehicle's centre of gravity, anti dive & anti squat characteristics can be achieved.
- This is purely achieved by geometric design, the suspension system itself cannot implement this affect.
- Care must be taken when deploying just anti-dive (front) or anti squat (back) on just one end of the vehicle. This is because the same setups to provide resistance to longitudinal weight transfer in one direction, can also have the reverse effect by aiding weight transfer in the opposite direction. This effectively improves weight transfer in one direction, but with negative effect on the other direction.
- Anti-Dive & Anti-SQuat are designed to keep suspension in check, and ~~also~~ helps aerodynamical stability as car stays parallel to the road.

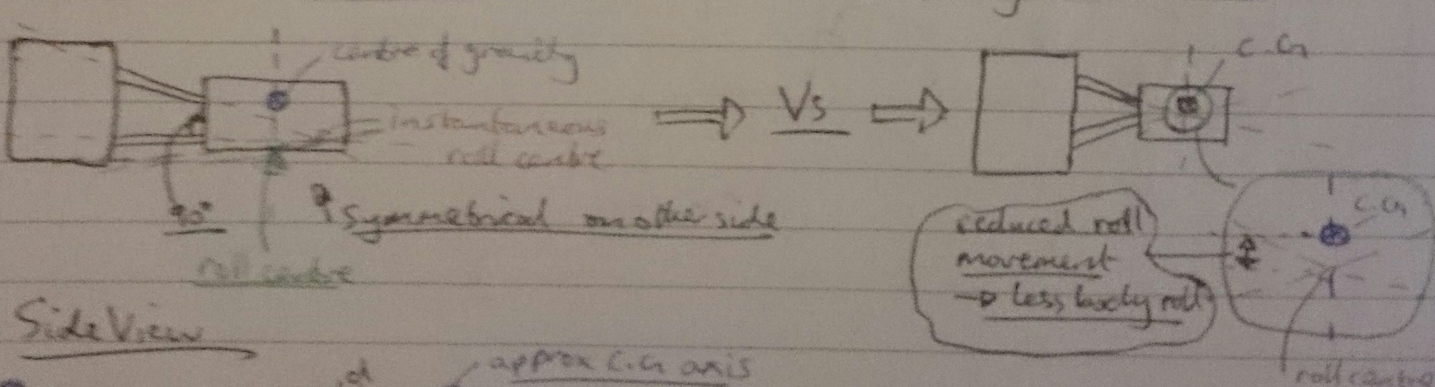
e.g.



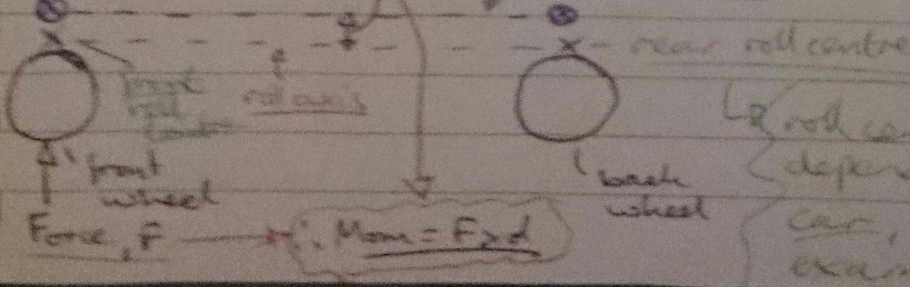
- Both front + rear wishbone convergence must be as close ~~to~~ to the Centre of gravity as possible for effective Anti-dive & squat.

Roll Centres - [4] Engineering Explained Youtube

- Roll Centre - the instantaneous axis about which the spring mass rotates

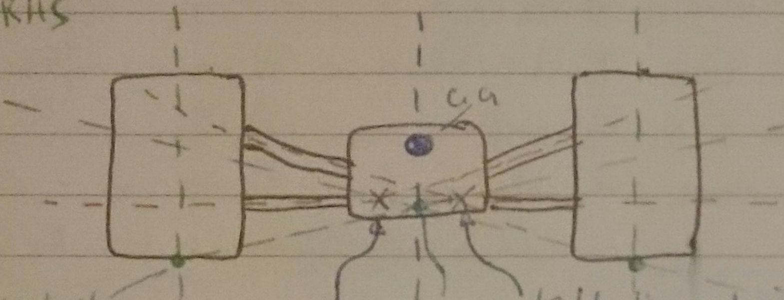


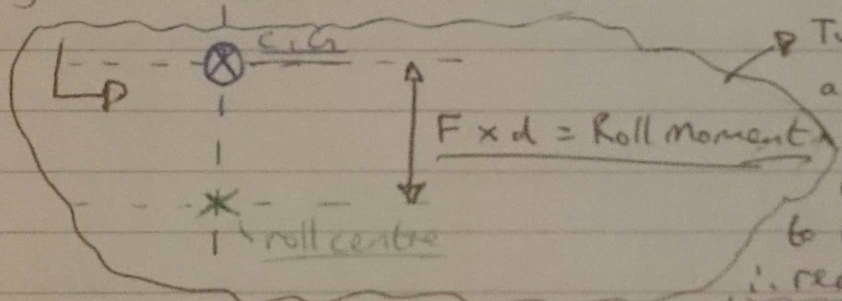
Side View



roll centre line always changes depending upon the angle of car, look at next page for example

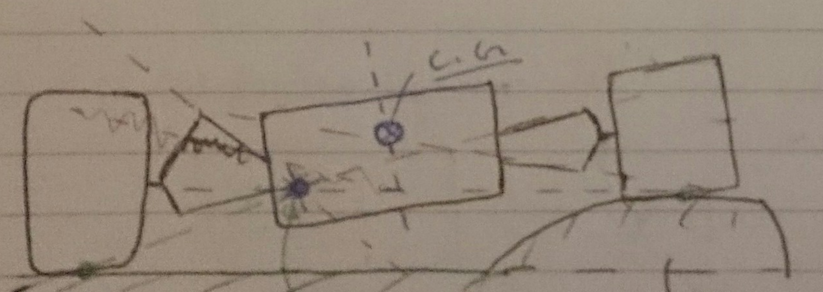
- The instantaneous centre point is where the A-Arms (or wheel) are rotating about at that very ~~inst~~ instant.
- Roll Centre — calculated by taking the line from the bottom contact point of the tyre to the instantaneous centre (straight green line), done on BOTH SIDES. The point at which the 2 green lines intersect is called the Roll Centre.





Turning forces are acting at roll centre, the mass of the car is at C.G, the car will roll due to the roll moment
∴ reduce the distance between roll centre & C.G, less roll & therefore decrease geometry changes in suspension, hence better handling

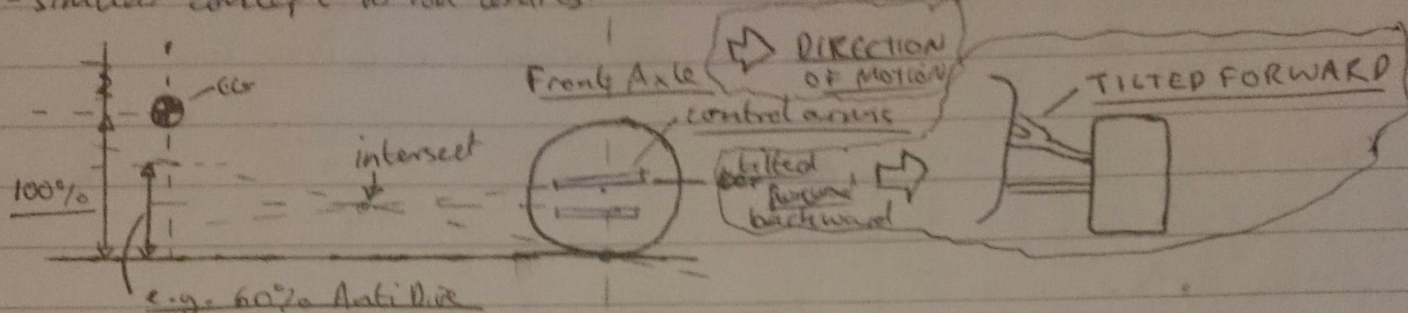
This is done by tilting lower arm up



Design Goals
- Minimise body roll → make roll centre & C.G as close to each other as possible
  → increasing angle of lower arm ~~[illegible]~~ improve roll resistance, but it'll change camber effect
- Minimise camber/geometry changes with suspension movement
- Minimise roll centre movement for a more predictable driving feel.
- Balance front/rear roll centre heights for desired slip angle characteristics
  → high C.G on one end & low C.G on the other, you may have a more slip angle.

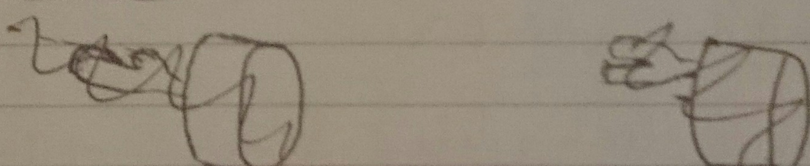
Anti Dive Geometry - [4] -

- prevents bodydive by loading suspension linkage (rigid)
- similar concept to roll centres.

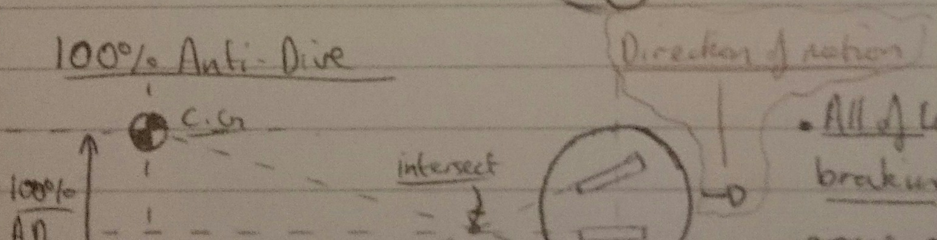


- Instead of parrallel control arms, have them at an angle for anti Dive characteristics.
- Red Line is control arm lines. The point at which they intersect, this is where the green line ~~also~~ passes through.
- Green line is a straight line from bottom of tyre contact point to the intersection of the 2 red lines. The vertical height at which the green line crosses the vertical position of the centre of Gravity is called the anti dive ~~line~~ length
- The ~~ratio~~ percentage between the vertical centre of gravity height and the anti dive ~~line~~ length is called the anti dive percentage of a suspension system.

(for this system → = 60% AD)



100% Anti-Dive



- All of load transfer (front pitching) when braking will pass through the control arms only, rather than the spring/damper

Design Goals

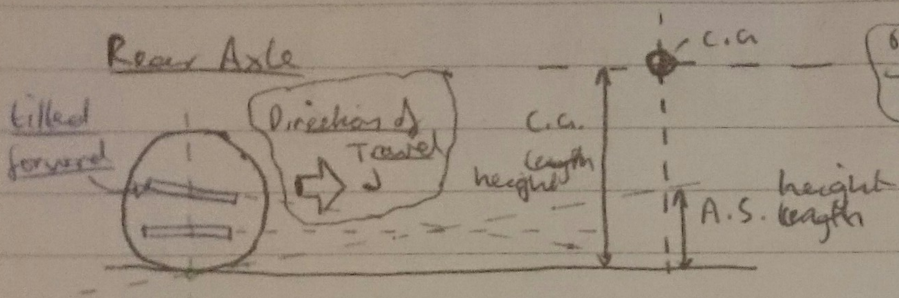
- Reduce suspension geometry changes associated with nose dive (e.g. increases in camber, wheel alignment issues where you won't have as much traction)
- Maintain aero characteristics of desired ride height

Drawbacks

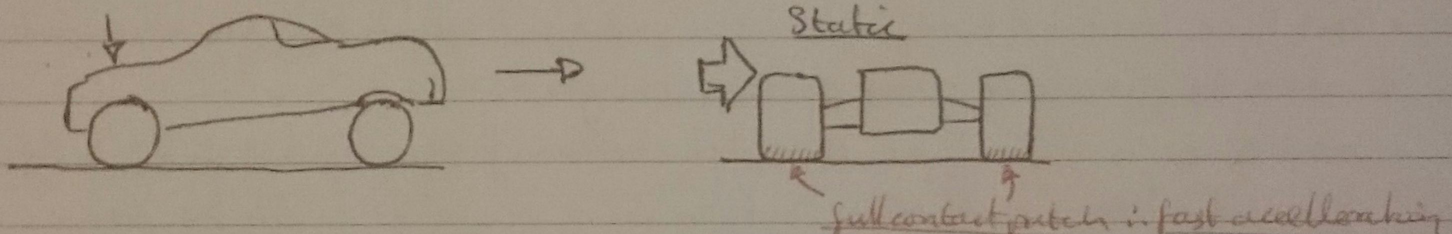
- Stiffen the front suspension components, making it less compliant to surface irregularities (reducing suspension input/affect)

Anti Squat -[4]-

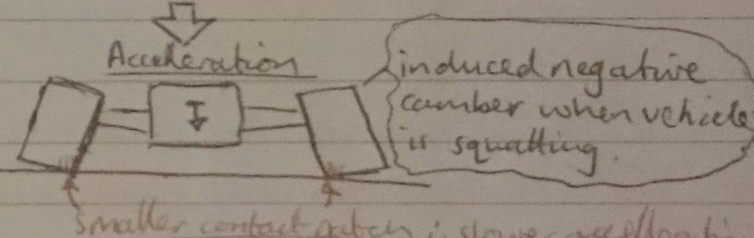
- prevents body squat by loading suspension linkage (rigid)
- same principle as Anti Dive, but for rear axle
- for vehicles with high power to weight ratios - e.g. Drag Cars



$$\% A.S. = \frac{A.S.\ \cancel{length}\ height}{C.G.\ height} \times 100$$

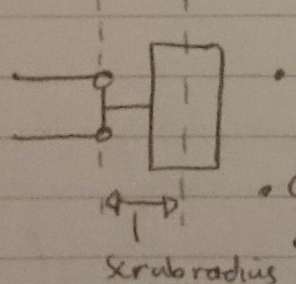


- Good for drag cars
- preffered lower A.S% for track cars as this is less influence of suspension system (refer to anti squat)



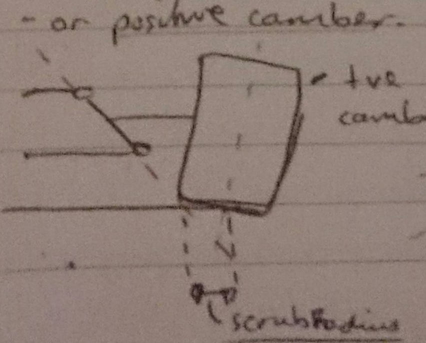
Same Adv & D-Adv as Anti Dive

Steering Axis Inclination -[4]-



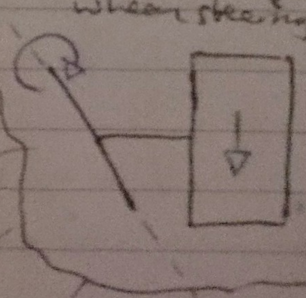
- Wheel rotates about scrub radius.
- Called scrub radius as when you turn the tyre, you'll have to scrub it to turn. - BAD.

Aim - reduce scrub radius as much as possible - quicker turn-in response
- by steering axis inclination
- or positive camber.



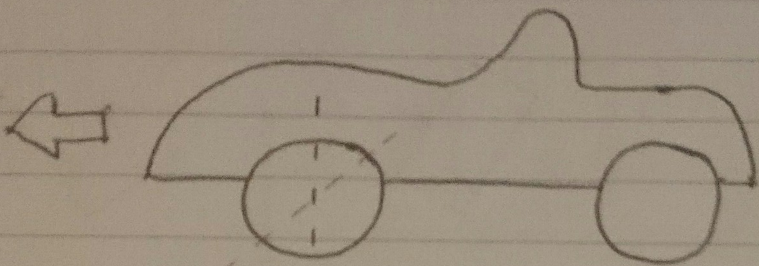
- This reduces effort at low speeds.
- Minimises tyre wear

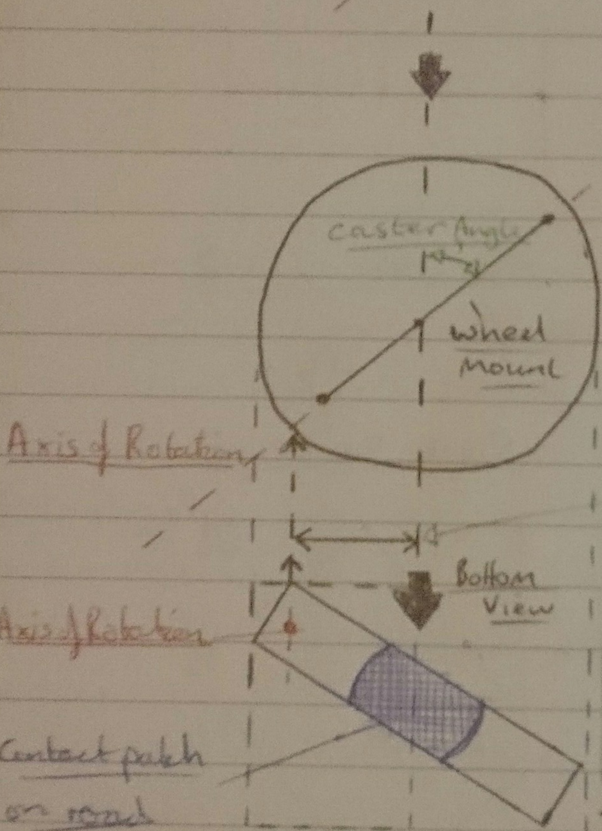
Added Benefit
Also, wheel goes straight when steering's released



Caster
~~Slip Angles~~ - [4]

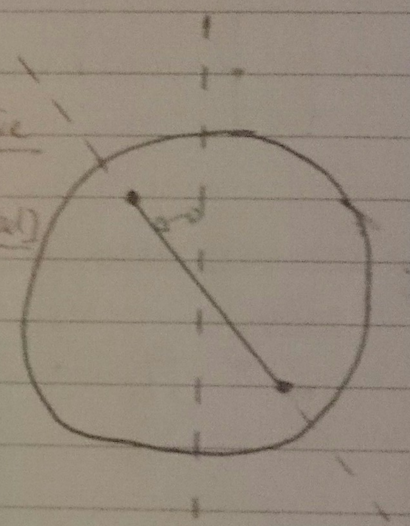
- Caster - Angle of steering axis wrt vertical axis
- Another angle at which the car is rotating about.





Positive Caster [Exaggerated]

Negative Caster [Exaggerated]



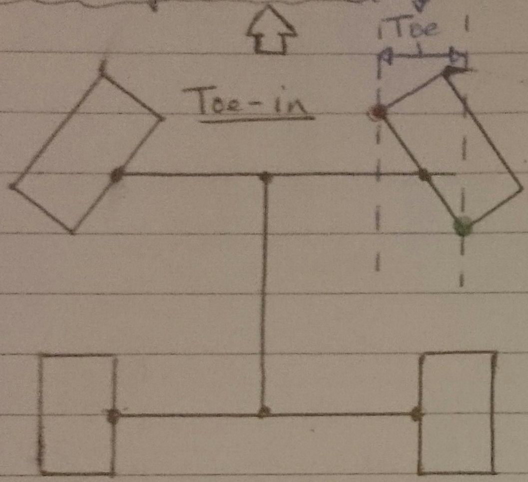
- The axis at which the tyre rotates is infront of the tyre patch on the ground.
- ∴ When you turn the wheel, the positive caster will create a Torque which'll want the tyre to straighten out

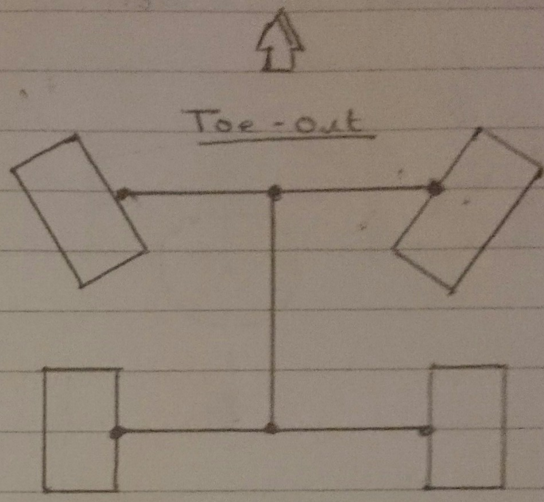
As you turn left or right, the contact patch is always behind the axis of rotation, so once the driver lets go of the wheel, it'll go back to being straight.

- Positive caster keeps tyre straight
- Negative caster makes the car unstable
- Positive caster angle is usually + 5°

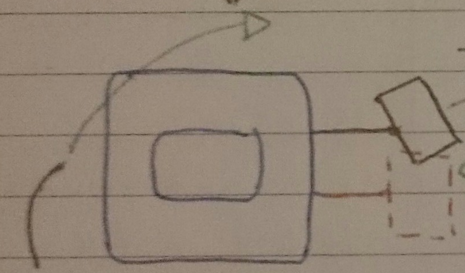
Toe -[4]-

- Toe - Distance from front wheels to the back of the front wheels when viewed from above ↴





- Toe-in used in RWD
  - Why?

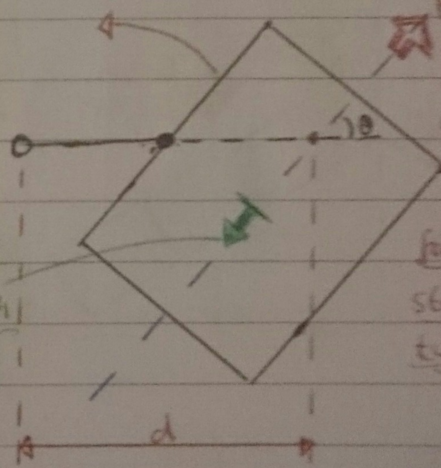


Tyre wants to move backwards during roll & straightens out.

Cornering Right, body starts to roll

- Toe-out used in FWD
  - Why?

Front-Right Tyre



F_R - Reaction Force which created Moment

Force that straightens tyre.

FWD Engine Force which Pushes car forward

Moment $= F_R \times d \times \sin\theta$

- [5] - www.enginebasics.com/Chassis%20Tuning/Understanding%20Toe.html

- Toe-in increases the cars straight line stability. A deflection of the suspension doesn't cause the wheels to initiate a turn.
- Toe-out decreases the cars straight line stability as any deflection will cause the wheels to initiate a turn.

∴ Toe in resists turning of the tyres whereas Toe-out quickly reacts to turning. - Racing cars usually have a small Toe-out angle (-1° - -2°)

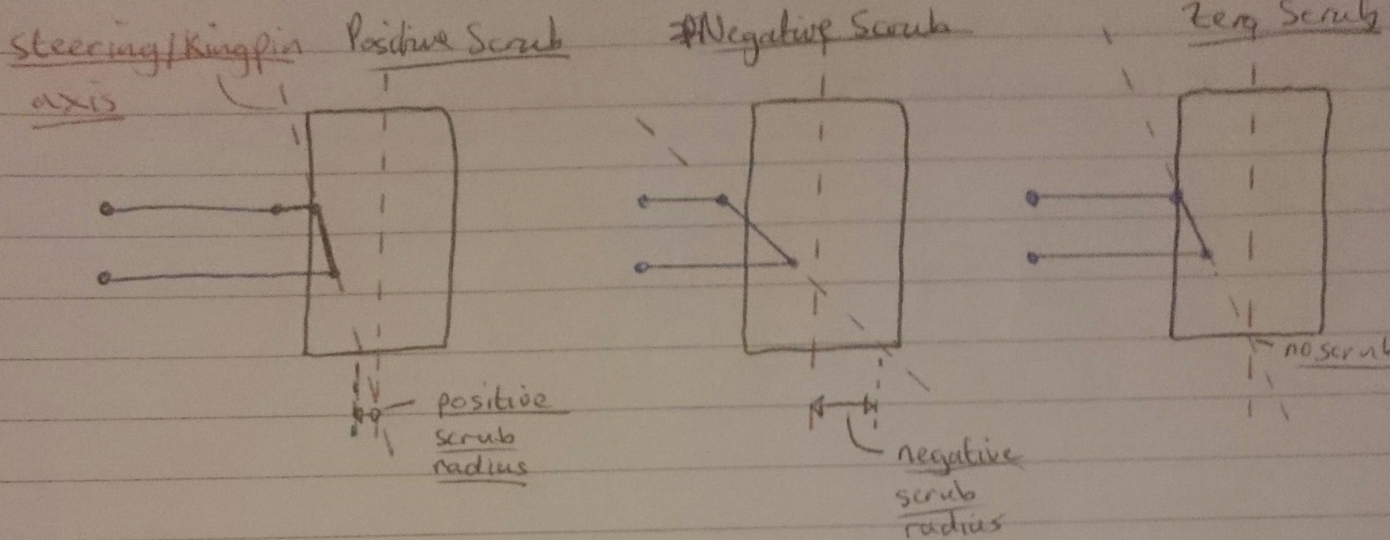
[- google search: 'Toe in vs Toe out' → 6th link]

- [6] - forums.miata.net/vb/showthread.php?t=44140

- For the rear wheels, it's usually very small toe-in angle (-1°) as toe-~~in~~ out makes the car spin & toe-in makes the car resist spinning.

[- google search: 'Toe in vs Toe out ~~car~~ for rear wheels' → 3rd link]

Scrub Radius -[4]-

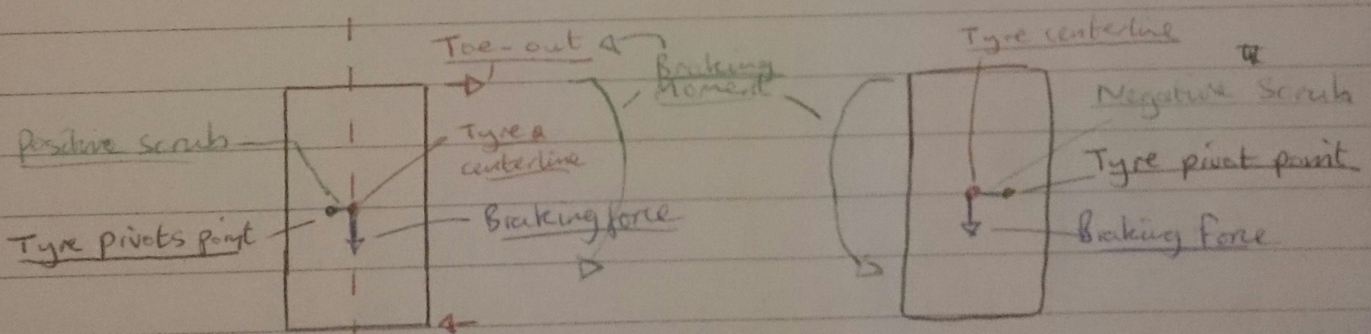


- Positive Scrub is common for double wishbone setup.
  - Why?

- Negative Scrub is common for McPherson Strut.
  - Why?

Bottom View of Front Right Tyre

Bottom View of Front Right Tyre



Braking Moment = Braking Force × Scrub radius.

When Accellerating:

FWD - induced Toe-in

RWD - induced Toe-out

When Braking:

Toe-out

↳ $\therefore$ wants to turn when braking

When Accellerating:

FWD - Toe-out

RWD - Toe in

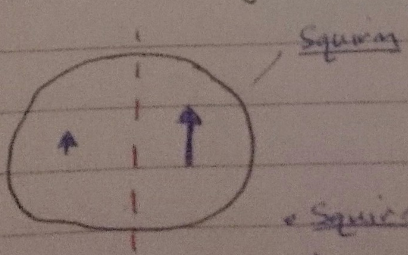
When Braking

- Toe - in

$\therefore$ Tyre resists turning when braking

Why dont we use zero Scrub?

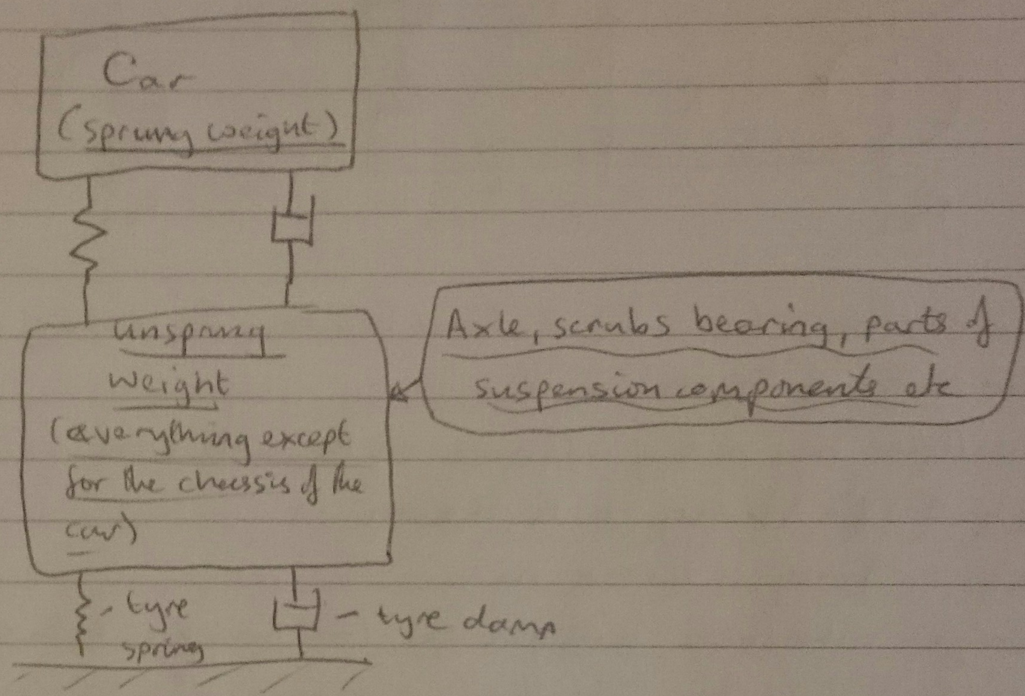
Bottom View - Tyre contact patch



- Stable in straight line
- Steering is unstable when cornering due to squirm + more tyre wear.
- Squirm - outside contact patch wants to spin faster than inner ⟶ like a differential. $\therefore$ Tyre wears.

Overall Goal:

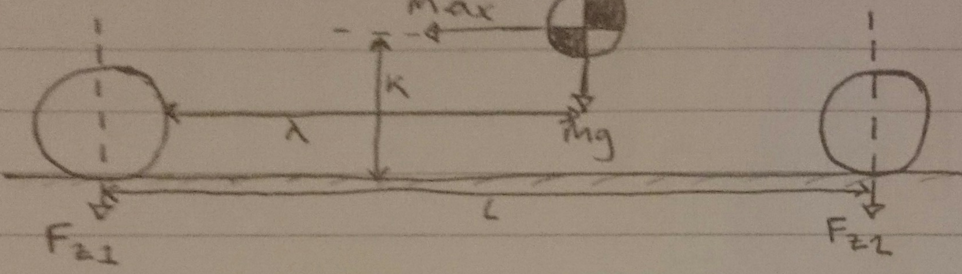
- Minimise scrub radius to reduce influence on steering & Toe characteristics for stable braking.



Adam Theander's 2004 Report

Suspension Design Aspects - [Pete's FB Link]&

Wheelbase



- The wheelbase, L, is the distance between the centre of the front axle to the ~~rear~~ centre of the rear axle.
- Wheelbase has a big influence on the axle load distribution:

  $F_{z1} = (L - \lambda)\cdot mg + K\cdot a_x \cdot m$

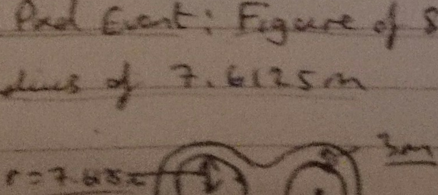
  $F_{z2} = \lambda \cdot mg + K \cdot a_x \cdot m$
- A longer wheelbase will give less load transfers between the front & rear axles than a shorter wheelbase during acceleration and braking ~~accordingly~~
- A longer wheelbase will therefore be able to be fitted with softer springs & more comfort for the driver.
- A shorter wheelbase has an advantage of shorter turning radius for the same input → too short = unstable when turning.
- Anti features can be built into a suspension which also effects the axle loads.

Track Width

- Influences the vehicles cornering behaviour & tendency to roll.
- Larger Track width = smaller lateral load transfer when cornering.
- Vice versa for smaller Track Width.

  Load Transfer of Rear Axle, $\Delta F_{z2} = \frac{M_{lat} \cdot h_{cg}}{t_{w2}}$
- Larger Track width has disadvantage of that more lateral movement is needed of the vehicle to avoid obstacles.

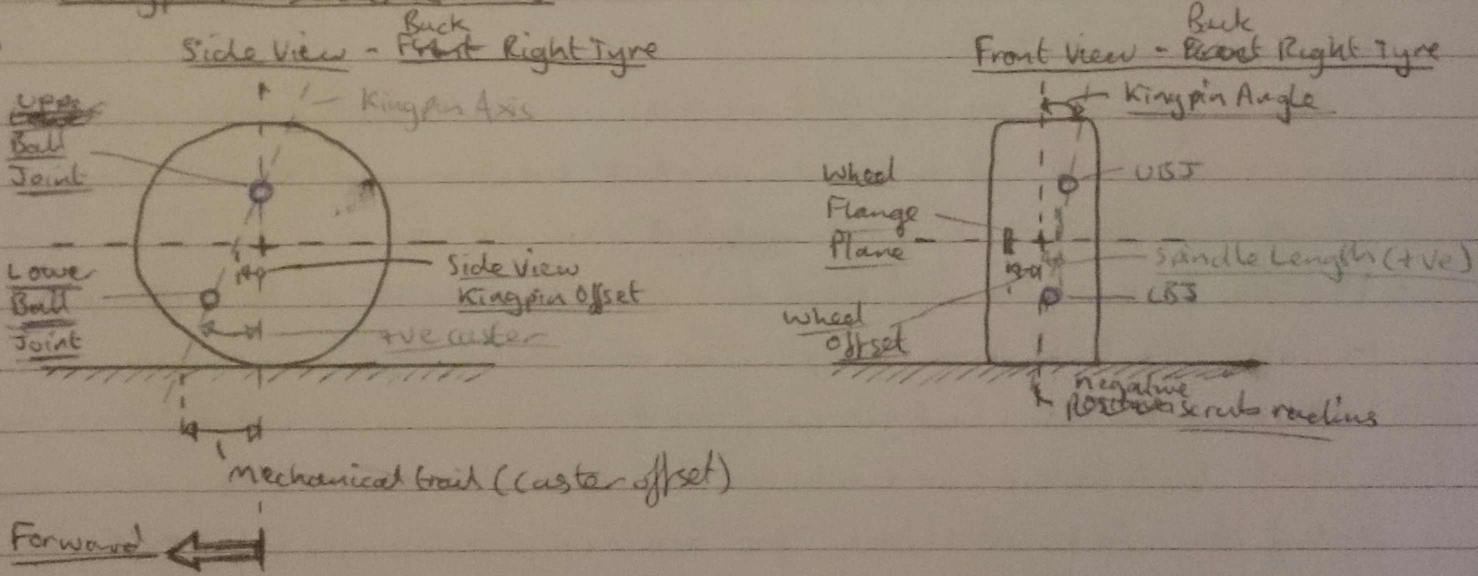
- For Accelleration Event: 75m long, 4.9m wide
- For Skid Pad Event: Figure of 8 cornering test, 3m wide track, cornering at a radius of 7.6125m



- For Autocross Event:
  - Straights: no longer than 60m with hairpins at both ends
  - Constant Turns: 23m to 45m diameter
  - Hairpin Turns: Min 9m diameter
  - Slaloms: cones in a straight line with 7.62m to 12.19m spacing
  - Miscellaneous: chicanes, multiple turns, decreasing radius turns etc, Min width is 3.5m

- For Endurance Event:
  - Average speed of 29.8mph (48Km/hr) to 35.4mph (57Km/hr) with top speeds of 68.2mph (105 km/hr), for 22Km (13.66 miles) long.
  - Straights: no longer than 77m with hairpin at both ends.
  - Constant Turns: 30m to 54m diameter
  - Hairpin Turns: Minimum of 9m diameter
  - Slaloms: 9m to 15m spacing
  - Miscellaneous: Min width is 4.5m

Kingpin & Scrub Radius



- Kingpin Axis is determined by the Upper Ball Joint (UBJ) & Lower Ball Joint (LBJ) on the outer ends of the A-arms.
- If the spindle length is positive, the car will be raised up as the wheels are turned and this results in a increase of steering moment at the steering wheel. The larger the Kingpin angle, the more the car will be raised regardless of which way the front wheels are turned. If there's no caster present, this

effect is symmetrical from side to side. The raise of the car has a self-aligning effect the ~~sel~~ steering at low speeds.

- The Kingpin angle effects the steer camber. When a wheel is steered it will lean out on the top, towards positive camber if the Kingpin angle is positive. This effect is ~~so~~ small, but not small enough to neglect if the track includes tight turns.
- If the driving or braking force is different on the left or right side, this will introduce a steering torque proportional to the scrab radius, which will be felt by the driver at the steering wheel.

Caster & Trail

- In the side view of the Kingpin angle is called the Caster angle. If the Kingpin axis doesn't pass through the centre of the wheel, then there's a side view Kingpin offset present. The distance from the Kingpin axis to the centre of the tyre print on the ground is called Trail or Caster Offset (side view)
  - The longer the trail is, the higher the steering torque needed.
  - Caster Angle will cause the ~~steering~~ wheel to rise and fall with steer. This effect is opposite from side to side and causes ~~the~~ roll & weight transfer. Leading to an oversteering effect.
  - Caster angle has a positive effect on steer-camber. With positive caster angle the outside wheel will camber in a negative direction and the inner wheel in a positive direction, causing both wheels to lean into a turn.
  - The size of the mechanical trail due to caster may not be too large compared to pneumatic trail from the tyre. The pneumatic trail will approach zero as the tyre reaches the slip limit. This will result in lowering the self ~~centering~~ centering torque that is present due to the lever arm between the tyre rotation point at the ground and point of attack for the lateral force. This "breakaway signal" may be lost if the mechanical trail is large compared to the pneumatic trail.

Instant Centres & Roll Centre