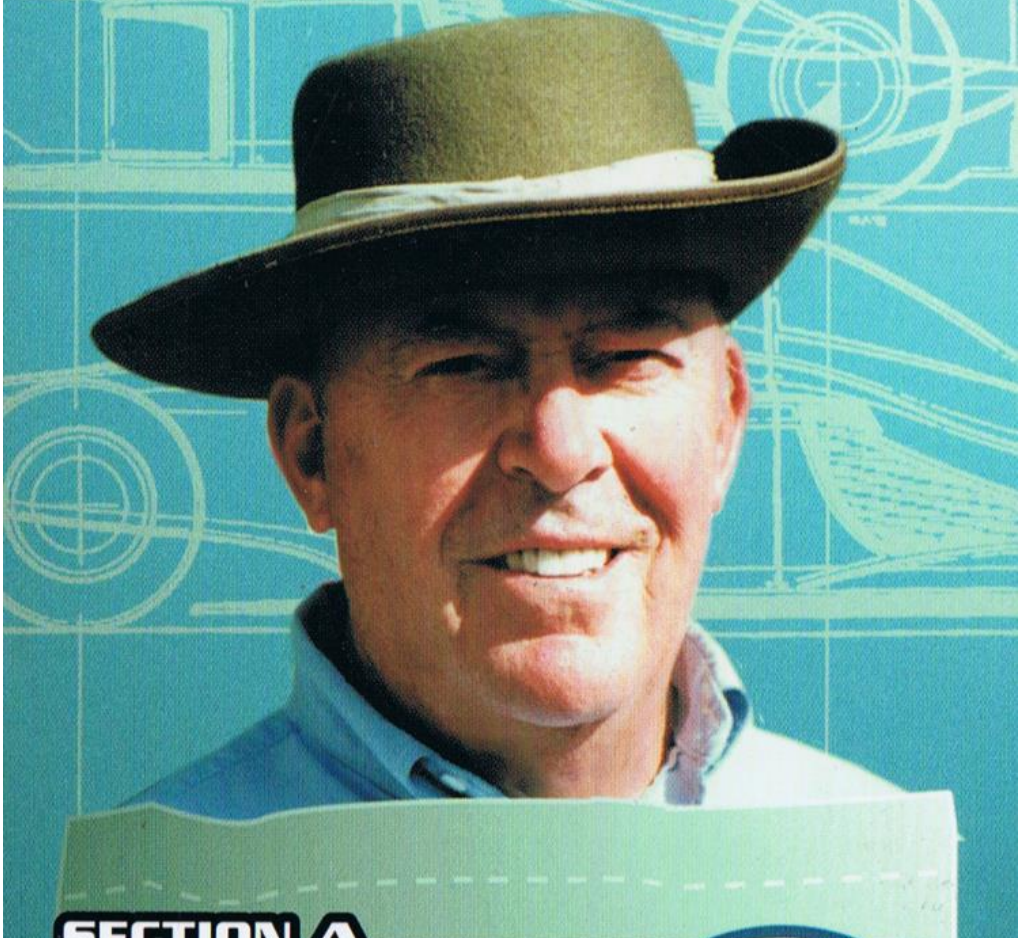
Carroll Smith's

Engineer in Your Pocket

A practical guide to tuning the race car chassis and suspension



SECTION A

PROBLEM → **CAUSE**

Problems listed first, then possible causes.

SECTION A

Problems Listed First Followed by Possible Causes. Turn the Book Over to Section B for Causes Listed First

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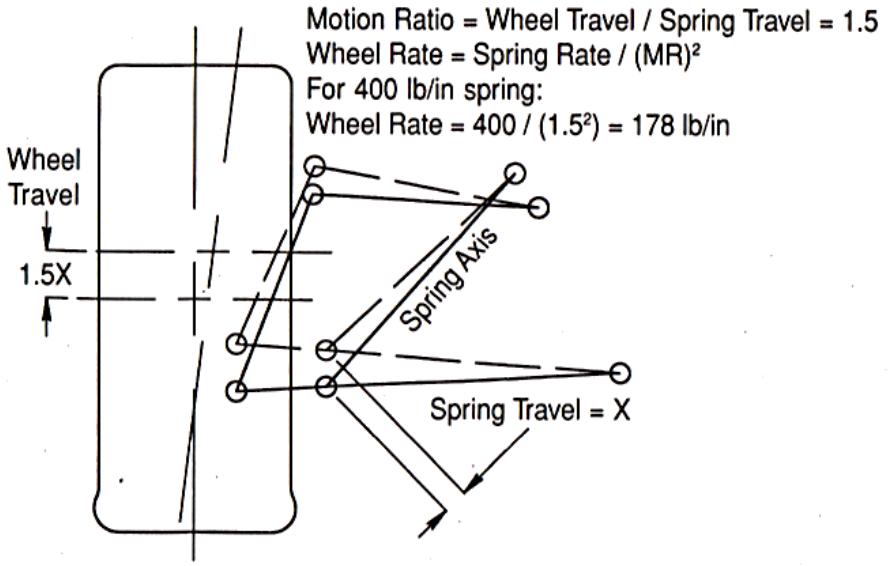
Problems Listed First Then Possible Causes

Note: there is a lot of confusion about the difference between "spring rate" and "wheel rate". The wheel rate of a suspension system is the spring rate divided by the square of the motion ratio.



Since front and rear motion ratios are often quite different, it is important to increase or decrease ride and roll rate by percentage of wheel rates rather than percentage of spring rate.

INSTABILITY

Straight line instability: general

- Rear wheel toe-out - either static due to incorrect (or backwards) setting or dynamic due to bump steer or deflection steer
- Vast lack of rear download or overwhelming preponderance of front download
- Wild amount of front toe-in or toe-out
- Loose or broken chassis, suspension member or suspension link mounting point
- Dead shock absorber

Straight line instability: under hard acceleration

- Malfunctioning limited slip differential
- Insufficient rear toe-in
- Deflection steer from rear chassis/ suspension member or mounting point
- Rear tire stagger (car pulls to one side)
- Dead rear shock absorber
- Wildly uneven corner weights

Straight line instability: car darts over bumps (especially single wheel bumps)

- Excessive Ackermann steering geometry
- Excessive front toe-in or toe-out
- Uneven front castor or trail settings
- Insufficient rear wheel droop travel
- Dead shock or uneven shock forces or incorrectly adjusted packers/bump rubbers
- Wildly uneven corner weights
- Front anti-roll bar miles too stiff

Instability under hard braking: front end wanders

- Excessive front brake bias or uneven corner weights or excessive front damper rebound force

Instability under hard braking: car wants to spin

- Excessive rear brake bias
- Insufficient rear droop travel
- Wildly uneven corner weight
- Excessive rear damper rebound force

Instability under hard braking: car wants to spin (continued)

- Unbalanced ride/roll resistance - too much at rear
- Insufficient rear camber (usually in combination with one or more of the above)

RESPONSE

Car feels generally too heavy and unresponsive

- Tire pressures too low
- Insufficient ride and/or roll resistance (springs and bars)
- Excessive aerodynamic download - or insufficient spring for the amount of download
- If high speed acceleration feels sluggish, the culprit is often a too large rear wing Gurney lip

Car feels sloppy, is slow to take a set in corners, rolls a lot, doesn't want to change direction

- Insufficient tire pressure
- Insufficient damper forces
- Car too soft in ride and/or roll

Car responds too quickly - has little feel - slides at slightest provocation

- Excessive tire pressure
- Excessive bump force in shock absorbers
- Car too stiff for inexperienced driver
- Excessive ride or roll resistance
- Excessive front or rear toe-in
- Insufficient aerodynamic download

UNDERSTEER

Corner entry understeer: car initially points in and then washes out

- Excessive front toe-in or toe-out (car is usually "darty")
- Insufficient front droop travel (non droop limited cars only)
- Incorrectly adjusted packers (car rolls on to packers)
- Insufficient front damper bump resistance (similar feel to above roll stiffness example)

Corner entry understeer: car initially points in and then washes out (continued)

- Insufficient front roll stiffness - car may feel like it is pointing in but may actually be falling over onto the outside front tire due to insufficient front roll stiffness or diagonal load transfer under heavy trail braking. Initial understeer can often be cured by increasing front roll resistance, even though doing so may increase the amount of lateral load transfer.

- Non linear lateral load transfer due to spring and/or bar geometry, or to non-optimum lateral roll axis inclination

Corner entry understeer: car won't point in and gets progressively worse

- Driver braking too hard, too late
- Relatively narrow front track width
- Excessive front tire pressure
- Excessive front roll stiffness (spring or bar)
- Relative lack of front download (excessive rear download)
- Incorrectly adjusted packers or bump rubbers (car rolls onto packers)

Corner entry understeer: car won't point in and gets progressively worse (continued)

- Insufficient front toe (in or out)
- Insufficient Ackermann effect in steering geometry
- Front roll center too high or too low
- Insufficient front damper bump force
- Insufficient front toe (in or out)
- Excessive dynamic positive camber on laden (outside tire)

Corner entry understeer: car points in and then darts

- Incorrectly adjusted packers or bump rubbers (car rolls onto packers)
- Excessive front toe-in or toe-out
- Insufficient front wheel droop travel (non droop limited cars only)
- Nose being "sucked down" due to ground effect
- Excessive Ackermann steering geometry

Carroll Tip - Always debrief, in detail, after every session - even if you have to debrief yourself.

Corner entry understeer: car points in and then darts (cont.)

- Can also be caused by unloading the front tires due to rearward load transfer under acceleration - cures include:
  - → Increasing front damper rebound force
  - → Increasing rear damper low speed bump force
  - → Increasing rear anti-squat
  - → Droop limiting front suspension (will also make turn in more positive and will reduce overall understeer)

Mid-corner (mid-phase) understeer

- Excessive front tire pressure
- Excessive relative front roll stiffness
- Excessive front toe (in or out)
- Excessive Ackermann steering geometry
- Insufficient front dynamic camber
- Relatively narrow front track width
- Insufficient front wheel travel (car rolls onto packers or bottomed shock)
- Insufficient front droop travel (non droop limited cars)

Corner exit understeer: slow corners

- Often a function of excessive corner entry and mid-phase understeer (whether driver induced or car induced) followed by throttle application while maintaining the understeer steering lock. The first step must be to cure the corner entry and mid-phase understeer. If this is impractical, then the corner entry speed should be slightly reduced in order to allow early throttle application. Sometimes we have to be patient.

Corner exit understeer: fast corners

- Relative lack of front download - often caused by negative dynamic pitch angle (squat) due to rearward load transfer on acceleration. Can be helped by increasing rear anti-squat and/or by increasing rear low speed bump force, increasing front droop force and by limiting the front suspension droop travel.

- Relatively narrow front track width

- Excessive ramp angle or pre-load on clutch pack or plate type limited slip differentials

Understeer stronger in one direction than other

- Uneven corner weights (especially front)
- Uneven castor
- Uneven camber (especially front)

OVERSTEER

Corner Entry Oversteer

- Excessively heavy trail braking
- Excessive rearward brake bias
- Severe rearward ride rate/roll resistance imbalance
- Rear roll center too high
- Diabolical lack of rear download
- Severely limited rear droop travel
- Broken or non-functioning outside rear damper
- Broken or non-functioning front anti-roll bar

Note: a slight feeling of rear "tiptoe" type hunting on corner entry can be due to excessive rear toe-in or to excessive rear damper rebound force.

Mid-corner (mid-phase) oversteer

- Driver threw car at corner to get through initial understeer - only cure is to educate driver and/or decrease understeer
- Excessive rear tire pressure
- Excessive relative rear ride and/or roll stiffness
- Rear suspension bottoming in roll
- Insufficient rear droop travel (non droop limited cars only)
- Very loose rear anti-roll bar linkage

Corner exit oversteer: gets progressively worse from the time that power is applied

- Worn out limited slip differential
- Excessive anti-squat geometry
- Excessive rear ride and/or roll stiffness
- Insufficient rear spring, bar or shock (low piston speed bump force) allowing car to "fall over" onto outside rear tire
- Excessive rear negative camber

Corner exit oversteer: gets progressively worse from the time that power is applied (cont.)

- Too little dynamic rear toe-in
- Relatively insufficient rear download

Note: If car feels as though it is sliding through the corner rather than rolling freely, reduce the rear toe-in and see what happens.

Corner exit oversteer - sudden - car seems to take a normal exit set and then breaks loose

- Insufficient rear suspension travel (lifting the inside rear tire on non droop restricted cars or bottoming the outside suspension due to lack of bump travel)
- Incorrectly adjusted packers
- Dead rear damper
- Sudden change in outside rear tire camber
- Too much throttle applied too soon - often after driver's confidence has been boosted by car taking a set

Carroll Tip - The time to waterproof your electrical system is when you build the car - not when it starts to rain.

Car does not put the power down on the exit of smooth corners

- Worn out limited slip differential
- Excessive rear ride/roll resistance
- Excessive anti-squat geometry
- Excessive rear tire pressure
- Tires gone
- Excessive rear damper low piston speed bump force
- Excessive rear dynamic camber - either from download or from camber change on squat
- Relative lack of rear download

Car does not put the power down on the exit of bumpy corners

- Any or all of the above for smooth corners
- Excessive rear damper high piston speed force
- Excessive rear damper rebound force (jacking down)
- Insufficient rear droop travel

TRANSITIONS

Understeer in, snap to oversteer on power application

- The most common complaint of all! Usually caused by too little front roll resistance - car falls over on entry and then snaps

  → Increase front bar and/or spring and/or front damper low piston speed bump force. Stiffening the bar will also transfer some load on to the inside rear tire on acceleration

  → If suggestion above cures the understeer but the car still snaps, the culprit is almost always the car falling over on the outside rear tire on longitudinal plus lateral load transfer. Add rear bar or spring. Bar will transfer load away from inside rear tire. Spring will not. Spring will, however, decrease traction over exit bumps while bar will not.

- Loose anti-roll bar linkage/blade sockets can have exactly the same effect.

Carroll Tip - save money on motels, restaurants, glitter and flash, not on the critical parts of your race car.

Car is slow to change directions in chicanes or esses

- Insufficient ride/roll stiffness, especially at front
- Relatively narrow front track width
- Insufficient front damper low piston speed bump forces

BRAKES

Brake pedal gets soft, spongy and/or long during session or race

- Fluid boiling in caliper(s). Not pad fade! Upgrade fluid and/or cool calipers

Brake pedal is soft, spongy and/or long before car is even run

- Air in system - bleed brakes
- Brake pads badly taper worn - replace

Reduced stopping power with normal brake pedal

- Pad fade - due either to unbedded new pads or to temperature beyond pad capacity. Upgrade pads

Carroll Tip - Have your tire pressure gauge calibrated - frequently.

Long brake pedal with little effort required

- Master cylinder(s) too small or pedal mechanical advantage too great

Rough braking - pedal vibrates under pressure

- Organic pick up on discs - clean discs with garnet paper (not aluminum oxide sandpaper) and upgrade pads
- Warped (not grooved) rotors. Grind (or, if you must, turn) rotor surfaces
- Insufficient (or no) axial float on floating discs

Uneven braking - car pulls to one side

- Stuck piston(s) - rebuild calipers

Carroll Tip - "Trail Braking" means trailing off the brakes as you enter the corner. Many schools don't teach trail braking because the learning process is liable to dent some machinery. Every winning driver trail brakes in some corners. This has been true at least since front wheel brakes were put on racing cars.

Brake bias changes during application

- Excessive clearance between master cylinder push rod clevises and bias bar bearing housing
- Rod end bearings used instead of clevises on master cylinder push rods
- Bias bar incorrectly adjusted. Bar must be perpendicular to the vehicle longitudinal axis with full foot pressure applied. Contrary to popular opinion, relative length of master cylinder push rods is immaterial

Carroll Tip - If you are going to use Nitrogen in your tires (and you should), evacuate the tires first with a vacuum cleaner (DRIVE TO WIN, pp 2-12). Leave the vacuum cleaner hooked up for at least five minutes.

Carroll Tip - Engines and gears are for accelerating. You stop the car with the brakes. Rowing down through the gears sounds great, but is a waste of time and effort. Get all of your downshifting done at the end of the braking zone and don't be afraid to skip gears.

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SECTION B

CAUSE → EFFECT

Causes listed first, then possible effects.

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SECTION B

Causes Listed First Followed by Possible Effects. Turn the Book Over to Section A for Problems Listed First

Cover photo by Andrew Freeman

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Causes Listed First Then Possible Effects

Note: Many of the gear charts in common use are inaccurate simply because they were calculated for a different tire diameter. To check you gear chart use the formula:

$$\text{mph} = \frac{(.072)\ (\text{engine rpm})\ (\text{tire rolling radius})}{(\text{gear ratio})\ (\text{ring and pinion ratio})}$$

If the gear chart is correct for one gear ratio, it will be correct for all (and vice-versa).

Statement of Non-liability

This book is a sincere effort to suggest realistic solutions to common racing car handling problems based on 40 plus years of experience. The suggested solutions point the way – they are not absolute fixes. So if in attempting to implement any of my suggestions, you should come unstuck, it will be as a result of your own conscious decisions. I disclaim responsibility for your action – and for your accident.

RIDE AND ROLL RESISTANCE - SPRING

Too much spring: overall

- Harsh and choppy ride
- Much unprovoked sliding
- Car will not put power down on corner exit - excessive wheelspin

Relatively too much spring: front

- Understeer - although car may initially point in well
- Front breaks loose over bumps in corners
- Front tires lock while braking over bumps

Relatively too much spring: rear

- Oversteer immediately on application of power
- Excessive wheelspin

Carroll Tip - Your race car should be easier and more pleasant to drive than your street car. If it isn't, someone is doing something wrong.

Too little spring: overall

- Car contacts race track a lot
- Floating ride with excessive vertical chassis movement, pitch and roll
- Sloppy and inconsistent response
- Car slow to take a set - may take more than one

Relatively too little spring: front

- Chassis bottoms under brakes
- Excessive roll on corner entry
- Initial understeer - car does not point in (Although it may feel as if it points in as it falls over onto the outside front tire.)
- Mid-phase understeer

Relatively too little spring, rear

- Excessive squat on acceleration accompanied by excessive rear negative camber leading to oversteer and poor power down characteristics
- Tendency to fall over on outside rear tire and "flop" into oversteer and wheelspin

Carroll Tip - The King of late brakers seldom wins.

ANTI-ROLL BARS

Too much anti-roll bar: overall

- Car will be very sudden in response and will have little feel
- Car will tend to slide or skate rather than taking a set - especially in slow and medium speed corners
- Car may dart over one wheel or diagonal bumps

Relatively too much anti-roll bar: front

- Corner entry understeer which usually becomes progressively worse as driver tries to tight corner radius

Relatively too much anti-roll bar: rear

- If imbalance is extreme can cause corner entry oversteer
- Corner exit oversteer. Car won't put power down but goes directly to over-steer due to inside wheelspin
- Excessive sliding on corner exit
- Car has violent reaction to major bumps and may be upset by "FIA kerbs"

Too little anti-roll bar: overall

- Car lazy in response, generally sloppy
- Car is reluctant to change direction in chicanes and esses

Relatively too little anti-roll bar: front

- Car "falls over" onto outside front tire on corner entry and then washes out into understeer
- Car is "lazy" in direction changes

Relatively too little anti-roll bar: rear

- My own opinion is that on most road courses a rear anti-roll bar is a bad thing. Anti-roll bars transfer lateral load from the unladen tire to the laden tire - exactly what we don't want at the rear. I would much rather use enough spring to support the rear of the car. The exception comes when there are "washboard ripples" at corner exits - as in street courses and poorly paved road circuits.

Carroll Tip - Horsepower may sell motorcars, but torque wins motor races. In the rpm department, don't confuse noise with power.

SHOCK ABSORBER FORCES

Too much shock: overall

- A very sudden car with harsh ride qualities, much sliding and wheel patter
- Car will not absorb road surface irregularities but crashes over them

Too much rebound force

- Wheels do not return quickly to road surface after displacement. Inside wheel in a corner may be pulled off the road by the damper while still loaded
- Car may "jack down" over bumps or in long corners causing loss of tire compliance. Car does not put power down well at exit of corners when road surface is not extremely smooth

Too much bump force: general

- Harsh reaction to road surface irregularities
- Car slides rather than sticking
- Car doesn't put power down well - driving wheels hop

Too much low piston speed bump force

- Car's reaction to steering input too sudden
- Car's reaction to lateral and longitudinal load transfer too harsh

Too much high piston speed bump force

- Car's reaction to minor road surface irregularities too harsh - tires hop over "chatter bumps" and ripples in braking areas and corner exits

Too little shock: overall

- Car floats a lot (the Cadillac ride syndrome) and oscillates after bumps
- Car dives and squats a lot
- Car rolls quickly in response to lateral acceleration and may tend to "fall over" onto the outside front tire during corner entry and onto the outside rear tire on corner exit
- Car is generally sloppy and unresponsive

Too little rebound force: overall

- Car floats - oscillates after bumps (the Cadillac ride syndrome)

Too little bump force: overall

- Initial turn in reaction soft and sloppy
- Excessive and quick roll, dive and squat

Too little low piston speed bump force

- Car is generally imprecise and sloppy in response to lateral (and, to a lesser extent longitudinal) accelerations and to driver steering inputs

Too little high piston speed bump force

- Suspension may bottom over the largest bumps on the track resulting in momentary loss of tire contact and excessive instantaneous loads on suspension and chassis

Dead shock on one corner

- A dead shock is surprisingly difficult for the driver to identify and/or to isolate
- At the rear, the car will "fall over" onto the outside tire and oversteer in one direction only
- At the front the car will "fall over" onto the outside tire on corner entry and then understeer

WHEEL ALIGNMENT

Front toe-in: too much

- Car darts over bumps, under heavy braking and during corner entry - is generally unstable
- Car won't point into corners, or, if extreme, may point in very quickly and then dart and wash out

Front toe-out: too much

- Car wanders under heavy braking and may be somewhat unstable in a straight line, especially in response to single wheel or diagonal bumps and/or wind gust
- Car may point into corners and then refuse to take a set
- If extreme will cause understeer tire drag in long corners

Rear toe-in: too little

- Power on oversteer during corner exit

Rear toe-in: too much

- Rear feels light and unstable during corner entry. Car slides through corners rather than rolling freely

Rear toe-out: any

- Power oversteer during corner exit and (maybe) in a straight line
- Straight line instability

Front wheel castor or trail: too little

- Car too sensitive to steering (twitchy?)
- Too little steering feel and feedback

Front wheel castor or trail: too much

- Excessive physical steering effort accompanied by too much self return action and transmittal of road shocks to driver's hands
- General lack of sensitivity to steering input due to excessive force required

Front wheel castor or trail: uneven

- Steering effort harder in one direction than in the other
- Car will "pull" towards the side with the less castor - good on ovals, bad on road courses

Carroll Tip - The single most common cause of engine failure the "rod stretcher" over rev caused by early downshifting.

Camber: too much negative

- Inside of tire excessively hot and/or wearing too rapidly. At the front this will show up as reduced braking capability and at the rear as reduced acceleration capability. Depending on the race track and the characteristics of the individual tire, inside tire temperature should usually be 10-25 degrees F. hotter than the outside. Use a real pyrometer with a needle, not an infrared surface temperature device.

Camber: not enough negative

- Outside of tire will be hot and wearing. This should never be and is almost always caused by running static positive camber at the rear in an effort to prevent the generation of excessive negative camber under the influence of download at high speed

- A better solution is improved geometry and increased spring rate. Dynamic positive camber will always degrade rear tire performance and if extreme, can cause braking instability and/or corner exit oversteer

Bump steer, front: too much toe-in in bump

- Car darts over bumps and understeers on corner entry

Bump steer, front: too much toe-out in bump

- Car wanders under the brakes and may dart over one wheel or diagonal bumps
- Car may understeer after initial turn in

Bump steer, rear: too much toe-in in bump (same as solid axle steer on outside wheel)

- Roll understeer on corner entry
- Mid-phase corner understeer
- "Tiptoe" instability when trail braking
- Darting on power application on corner exit

Bump steer, rear: toe-out in bump (same as solid axle steer on outside wheel)

- Instability on acceleration
- Good turn in followed by a tendency towards oversteer at mid-phase and exit

Carroll Tip - In order to win you have to be aggressive - with your car, with the race-track, and with the competition. But you don't have to be stupid about it.

TIRES

Too much tire pressure

- Harsh ride, excessive wheel patter, sliding and wheelspin
- High temperature reading and wear at center of tire

Too little tire pressure

- Soft and mushy response
- Reduced footprint area and reduced traction
- High temperatures with dip in center of tread

Front tires "going off"

- Gradually increasing understeer - enter corners slower, get on power earlier with less steering lock

Rear tires "going off"

- Gradually increasing power on oversteer - try to carry more speed through corner and be later and more gradual with power application

Carroll Tip - If you are steering into the corner after the apex, you are doing something wrong.

LIMITED SLIP MALADIES

Limited slip differential wearing out

- Initial symptoms are decreased power on understeer or increased power on oversteer and inside wheelspin. The car might be easier to drive, but it will be slow

- When wear becomes extreme, stability under hard acceleration from low speed will diminish and things will not be pleasant at all

Excessive cam or ramp angle on coast side of plate (clutch pack) limited slip differential

- Corner entry, mid-phase and corner exit understeer. Incurable with geometry or rates - must change differential ramps. Virtually everyone is now (1998) running 0/0 or 80/80 ramps

SUSPENSION GEOMETRY

Excessive front scrub radius (steering offset)

- Excessive steering effort accompanied by imprecise and inconsistent "feel" and feedback

Excessive roll center lateral envelope: front or rear

- Nonlinear response and feel to steering input and lateral "g" (side force) generation

Rear roll center too low (or front relatively too high)

- Roll axis too far out of parallel with mass centroid axis leading to nonlinear generation of lateral load transfer and chassis roll as well as the generation of excessive front jacking force
- Tendency will be toward understeer

Rear roll center too high (or front relatively too low)

- Opposite of above, tending toward excessive jacking at the rear and oversteer

Front track width too narrow relative to rear

- Car tends to "trip over its front feet" during slow and medium speed corner entry evidenced by lots of understeer (Remember trying to turn your tricycle.)

Front track width too narrow relative to rear (cont.)

- Crutch is to increase front ride rate and roll resistance and increase the camber curves in the direction of more negative camber in bump (usually by raising the front roll center.

FAVORITE PRODUCTS 1998

Plumbing: Earl's Performance Products

Bearings, rod end and spherical: AURORA

Brake pads: Performance Friction

Brake fluid: (extreme conditions) Castrol SRF; (normal conditions) AP 55 or 600

Engine oil: Mobil One, Valvoline Synthetic Racing Oil

Gear Oil: Mobile One, Valvoline Synthetic, NEO 75/90, EHD/MVL

Engine threaded fasteners: ARP

Chassis threaded fasteners: AN or MS

Blind rivets: Cherry "Q", Avex, USM closed end

Suspension software: William C. Mitchell's, "Racing by the Numbers"

On board data systems: Pi, Stack, CDS

Chassis scales: Ruggles, Longacre

Alignment equipment: Bubble level camber gauge and string

Clutches: Tilton

Coil springs: Hyperco

Shocks: Penske, Koni