Suspension Tuning & Development

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Suspension Tuning and Development

- Part art, part science, and a little luck (but not much)
- Successful organizations take methodical approach
- Thoughtful development saves time and money
- Development is the means for discovery of all of the stuff we didn’t think about when we designed the vehicle
- “ Development is only required to correct the ignorance of the designers.”— the late Keith Duckworth, co-founder of Cosworth Engineering

Today's Topics

- A Methodical Approach to Testing
- Care and Feeding of Tires
- Dampers
- Tuning Your Suspension Using Driver Feedback

A Methodical Approach to Tuning and Development

- We need a plan…..testing or racing is more than just driving around
- Know your parts
- Know your car
- Line up support

We Need A Plan

- Program objectives
  - Realistic, aggressive team goal
    - New teams- research successful teams
    - Established teams- build on experience
    - Document and transfer knowledge to future teammates
    - Scoring points in design event important, performance and reliability in dynamic events *more important*
  - Timeline with key milestones
    - The race will be run whether or not you're ready
    - Stay on task and hit your key dates
- Winning programs "front load" development activity
- Testing is expensive- every test should take a step toward the goal
  - We wear out tires, brakes, diffs, engines. Make it count!
- Agree on priorities, test procedures <u>before</u> you go test [Communication among the system engineers!]

Know Your Parts

•**Every part** should be inspected, labeled, measured and/or performance checked

•**Component testing** may seem boring, but it is the foundation for a winning car

•**History**- how much running time, design level of part?

•**Quantity**- do we have enough to cover us for stuff wearing out, an accident, or race prep rebuild?

•**Organize stuff** so your team can find it quickly

•**Create Inventory or Bill of Laden** (You really need this to run outside the U.S.)

Know Your Car

- Visual, functional inspection of all systems
  - Brakes, Fuel, Steering, Suspension, Structure, Safety Gear
- Record static corner weights and suspension friction
- Physically measure center of gravity location (x,y,z)
- Physically measure bending and torsional stiffness of chassis (e.g. the 5th spring)
  - Torsional gradient plot axle CL to axle CL should not have large notches

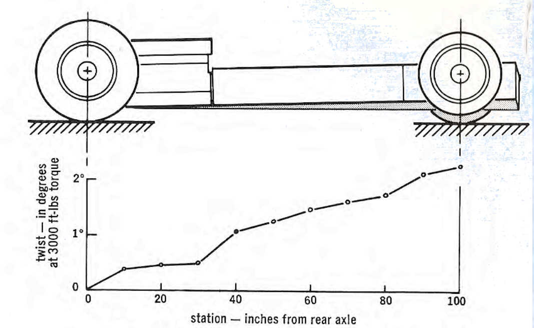


Figure 42. Chassis Torque Deflection Curve

From "Race Car Engineering and Mechanics, Paul Van Valkenburgh,2000

Know Your Car

- Measure and plot front and rear hub motion through full bump and rebound travel
  - Toe change
  - Camber change

- Design for adjustability (use “known” shims, adjustable dampers if budget and rules permit), saves time (your most important resource)

- Use a damper dynamometer to characterize range of adjustments and damper component changes

- Keep a logbook, record all changes to car

Line Up and Delegate Support

- Hero Driver
- Data acquisition whiz
- Laptop computer
- Helpers/spotters/timers
- Radios
- Timing equipment
- Vehicle measurement equipment
- Weather station (really helps your engine calibrator)
- Tow vehicle/trailer
- Portable power source
- Source of compressed dry air or N^2
- Tools
- Proof of liability insurance
- Permission to use track or lot
- Restrooms
- Refreshments
- Enough fuel? Tires?

Take Some Opinion Out of Testing

- Stop watches, 2-3, digital
- Quality tire pressure gauge, 0-60 psi (2)
- Tire pyrometer- probe type (IR not as accurate)
- Durometer-Shore hardness A
- 4 bathroom scales
- Steel tape measure 12 ft, English/Metric
- Digital inclinometer
- Simple g-g measurement box (g-Tech,Escort, or part of data acquisition system)

How to Test

- Warm up vehicle at part throttle to get fluids, tires, brakes up to operating temps
- Check for fluid leaks before entering test surface
- Make two short low speed brake applications in pits, check for pedal travel and firmness
- The engine should be performing well to make meaningful chassis adjustments
- Driver should be prepared to work the edges of the friction circle
- Stay out just long enough to feel the change (or not), 1-2 hot laps
- Make one change at a time, don't be afraid to make big changes initially
- "Bracket in" on what seems to work

More Suggestions for Productive Testing

- Record every lap time (segments if you have more helpers) and on-course driver comments (if radio)
- Create a track map/ driver debrief sheet for each session and use them
- Evaluate chassis performance only on new or scrubbed tires
- Evaluate chassis performance only after you have established good throttle response
- You can always go back to the last iteration that worked when you keep good records
- Take corner and straight segment times to find out where you are gaining and losing time (don't trust subjective judgments or lap times alone)
- No excuses should be made or accepted—"we're a half second slower, but we have our weak motor in the car or if we had new tires or if the sun wasn't in the driver's eyes…."
- Try to work with a physically and mentally rested driver

Care and Feeding of Tires

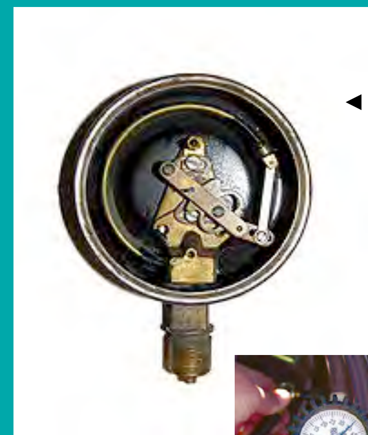
- Keep a 3 X 5 card on each tire
- Record popping pressures to seat beads when mounting tires to wheels
- Check durometer at each test along with ambient temperature
- Monitor inflation pressures before and after each run
- Monitor tread temps (O/C/I) and total number of heat cycles
- Monitor tread and shoulder wear (chunking, blisters, rubber flow, color change, fast wearout, uneven wear)
- When adjusting pressures more than 3 psi, recheck after one minute
- Use dry air for inflation
- Record tire temps and pressures right after each test
- Scrape junk off tread w/ hacksaw blade, not your hands

Tire Valves

- Valve cores can and do leak
- Metal caps and stems more robust than plastic and rubber
- Setups can be sensitive to small air pressure losses during extended runs

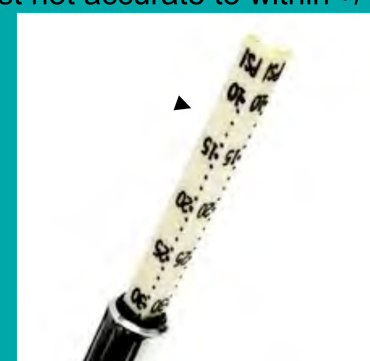
Air Gauge

- Interpretation of tire pressure requires an accurate gauge
- ANSI Commercial Grade B gauges (meets ANSI B40.1 Grade B specifications) recommended
- A digital gauge may be no more accurate than an analog gauge



Unlike piston-plunger-type gauges, the bourdon tube movement is not affected by changes in temperature, humidity, altitude or air stream contaminants. Also requires proper calibration for accuracy

Piston, plunger gauges are inexpensive, but you may have to test a boxful to find an accurate one (most not accurate to within +/- 5 psi)



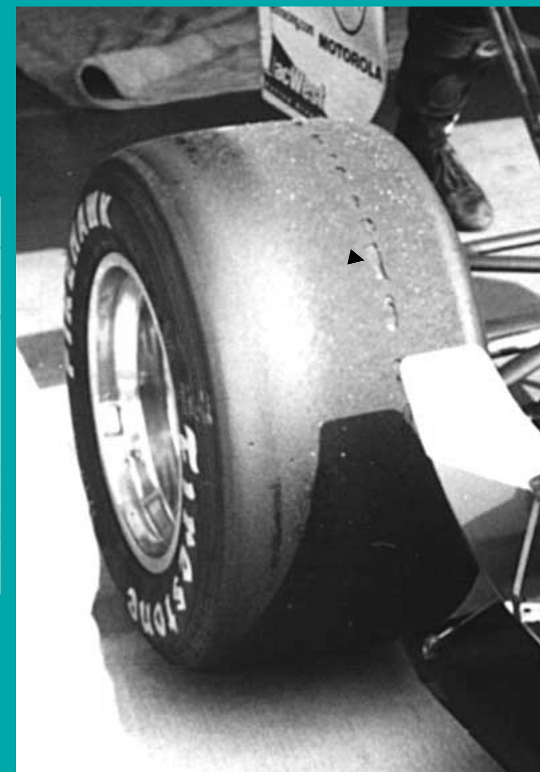
Digital gauges are reliable and accurate IF the strain gauge is properly calibrated and fresh batteries are maintained

How To Interpret Tread Wear

Insufficient camber gain in roll, too little static camber

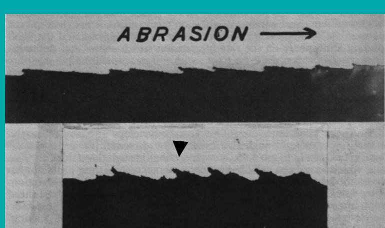
Example of good tire wear, small grain pattern and even wean across full tread arc

Blistering from excessive inflation pressure (also note the narrow grain pattern)

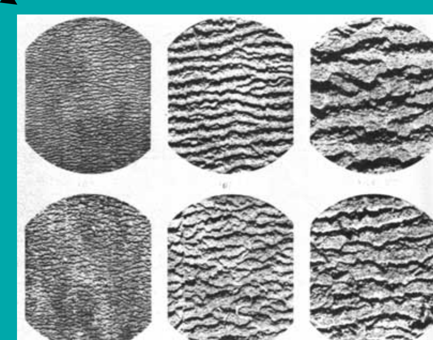


Small camber adjustment to reduce graining, optimize grip

Source of marbles (Directional saw tooth tips break off in shear, they can ruin your day off the racing line)



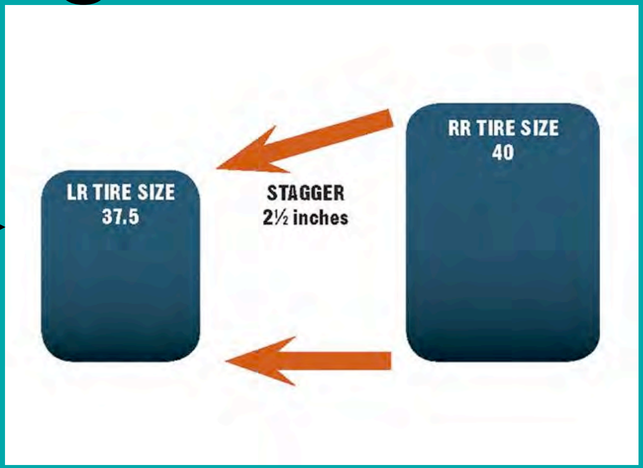
The tire does not lie. Severity of grain pattern can be evidence of driver compensation , driver abuse, or poor setup (excessive throttle, or steer inputs, wheelspin, etc.)



Photos from "The Racing and High Performance Tire by Paul Haney, 2004

Stagger Handling Effects

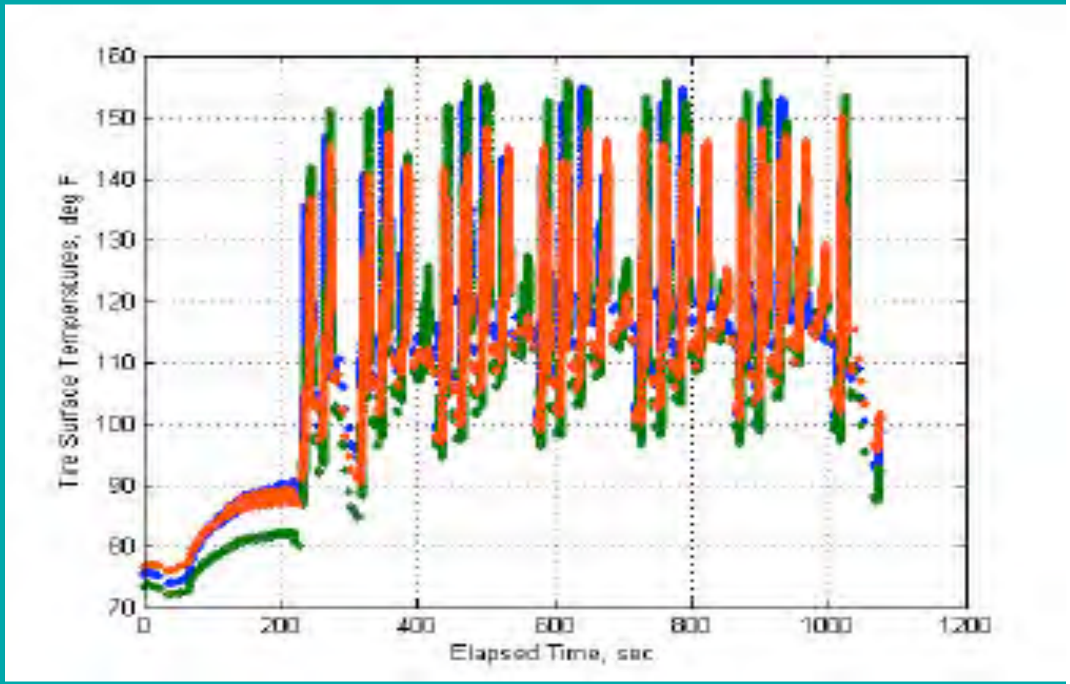
- Tire stagger may have a performance benefit in road racing or autocross depending on course layout, if you know how to use it
- Tire stagger is the center of tread circumference delta across an axle tire pair
- Set cold pressure, use a steel tape measure to determine each tire's circumference, measuring at the center of the tire. When checking hot pressure, re-measure circumference to check for change in stagger during run
- (**Negative influence**)
  - Asymmetric left-right handling in corners, slalom, or chicanes, and slow straightline speed, tire stagger could be a contributor
- **(Positive influence)**
  - If you tune for stagger, helps left or right corner entry under braking (front), depending on the direction of stagger
  - Aids corner turn-in response (front)
  - Depends on your rear differential
    - Spool or live axle (aids all phases)
    - Locker style (aids accel only)



Jeff Honeycutt photo credit

Heat Cycling and Tire Temps

- Tire Scrubbing
  - Mold release compound removed
  - Tread compound is altered
  - Tread durometer increases a few points after cool down
  - Running temp is reduced a few degrees F
  - Slower wear rate than stickers
  - Time wise, scrubs are slightly slower on the out laps, but are usually more consistent and faster throughout a long run than stickers



From "SAE Paper 2001-01-3606, The Formula SAE Tire Test Consortium-Tire Testing and Data Handling" , Kasprzak and Gentz.

- Diminishing Returns
  - Once the tire had exceeded its "cured out" phase (too many heat cycles), performance drops off
  - Time to go to a fresh set

Camber and Tire Temps

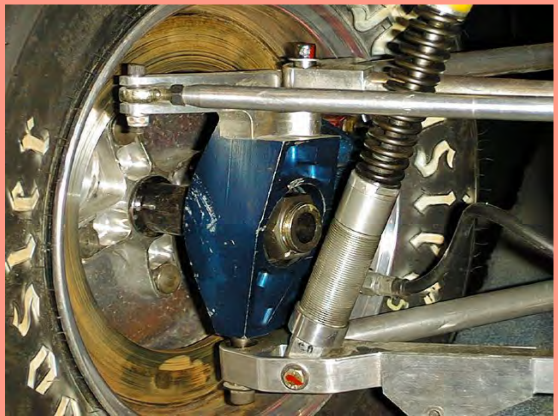
- Try to achieve camber settings that provide uniform temperature distribution in the mid-corner phase (can be determined on skid pad)
- Depending on the rest of your setup, this could mean an aggressive static camber setting
  - May not be optimized for corner entry/exit
  - Inside of tread at front and rear should be 5-10 deg F hotter than the outside when measured in the pits
  - More caster and/or camber may be used in cold temps or a cold track to build temp more quickly
- Consider more camber gain if it looks like you are running too much static camber

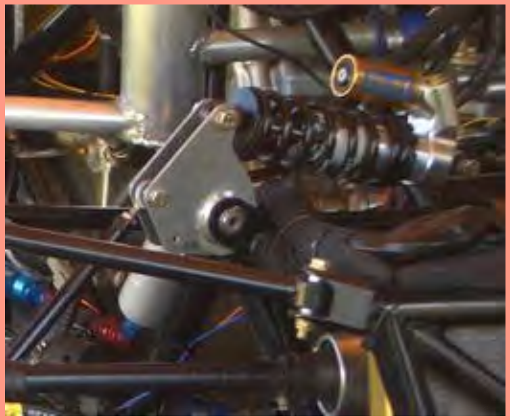
Photo credit: Brian Snelson

Keep Good Records!

- Method not important
- Use computer, notebook, or other device
- Keep hard copies as backup
- Use a form or spreadsheet for fast comparative analysis
- Bring your stuff when presenting your car at Design Judging!
- We are impressed by organized data that supports your claims and hard work!

Dampers





- Primary function of damper, along with the spring, is to keep the tire footprint in contact with the track surface
- We generate tire mechanical grip by damping spindle excitation due to road and body inputs
- The damper is our main tool to control the conflicting requirements of maximum grip and balance

A Few Words About Mountain Bike Dampers

- Suitable for forces generated by FSAE car
- Off the shelf MB dampers suitable for Rocky Mountain boulder jumping, not suitable for FSAE car
- Basic MB valving develops too much compression force, adjusters do not have enough range to adapt to FSAE application

- MB dampers need to be custom valved for FSAE application, start with baseline 3:1 rebound to bump control force ratio, scale the control force range based on your car's sprung and unsprung masses and anticipated piston velocities for the race track in question
- For road course and autocross, match damper control forces as front pairs and rear pairs
- Request dynamometer control force curves for soft-mid-firm high speed and low speed compression and rebound adjustments @ 1, 3, 5, 10, 15, 25 ips and 1.5" stroke and gas force measurement after warm-up cycle

The Compression Stroke

As the shock compresses, oil is forced up through the inner tube and through the compression valving.

The small volume of oil displaced by the shaft is forced into the fluid reservoir.

The rest of the oil then travels between the inner and outer tubes and returns to the opposite side of the piston.

The Rebound Stroke

As the shock rebounds, oil is forced down through the inner tube, up between the inner and outer tubes, and into the rebound valving.

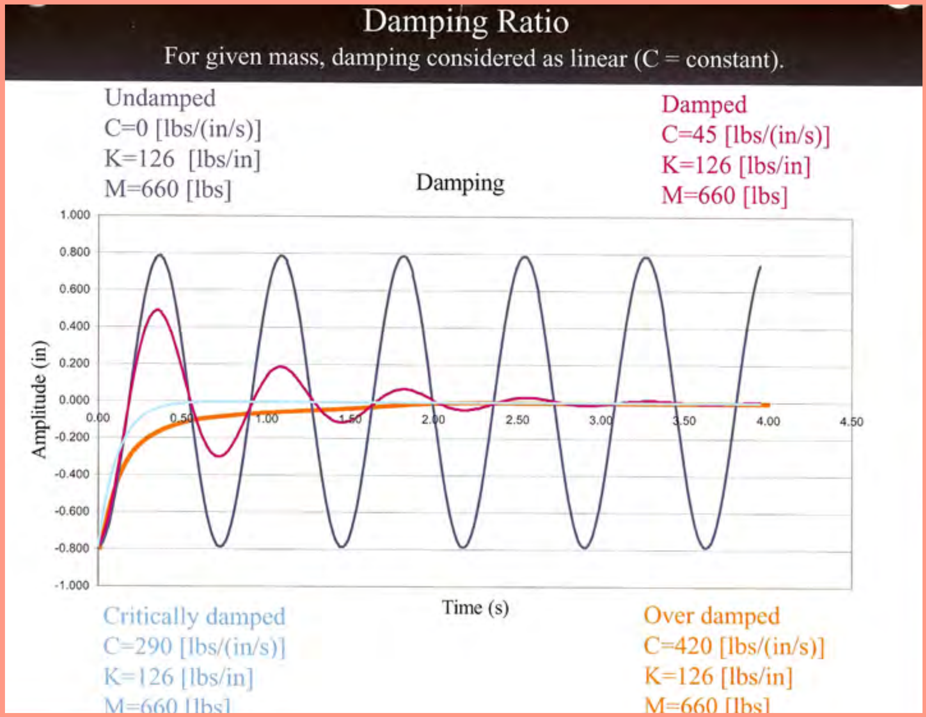
The oil returns to the inner tube through the top of the cylinder head.

The volume of oil displaced by the shaft on the compression stroke is drawn back into the inner tube from the reservoir tube.

Damper Basics

- Start with a base valve code that provides about 3:1 rebound to bump control force ratio
- Account for the gas force of the damper in the overall spring rate and wheel rate of the suspension corner   Note: Gas charge can effect ride height
- Damper stiction increases as a function of charge pressure (don't get carried away with the N^2 bottle)
- We need less bump since it damps the movement of the unsprung mass and doesn't vary much due to dynamic loading, the rebound side damps the sprung mass reaction after the bump or weight transfer
- <u>Dampers control rate of weight transfer, not the amount</u>
- Overdamped- tire chatters over bumps, body control will be choppy, car will have nervous, darty feel, may lack progressivity in cornering with road camber, surface changes
- Underdamped- body floats, steering response is sluggish, bouncing off bump stops

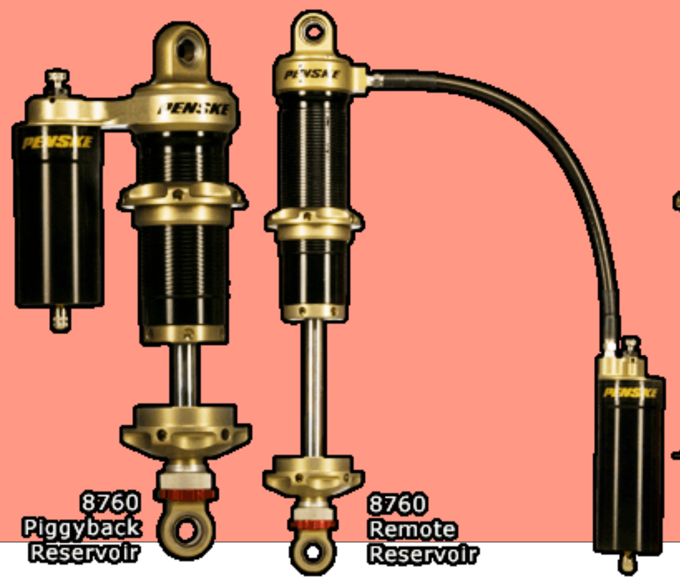
How Much Damping Do We Need?

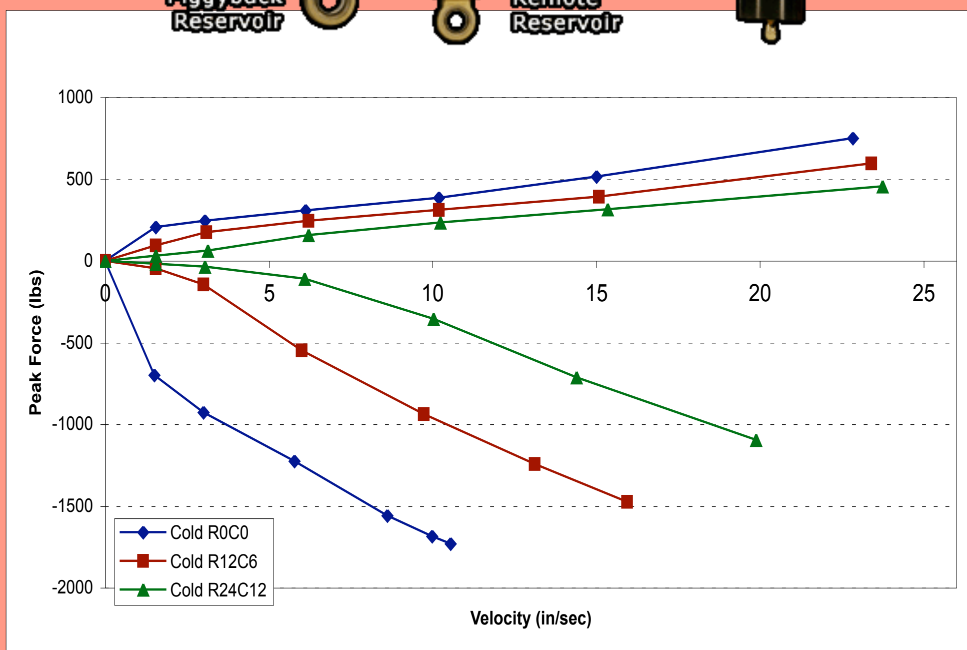


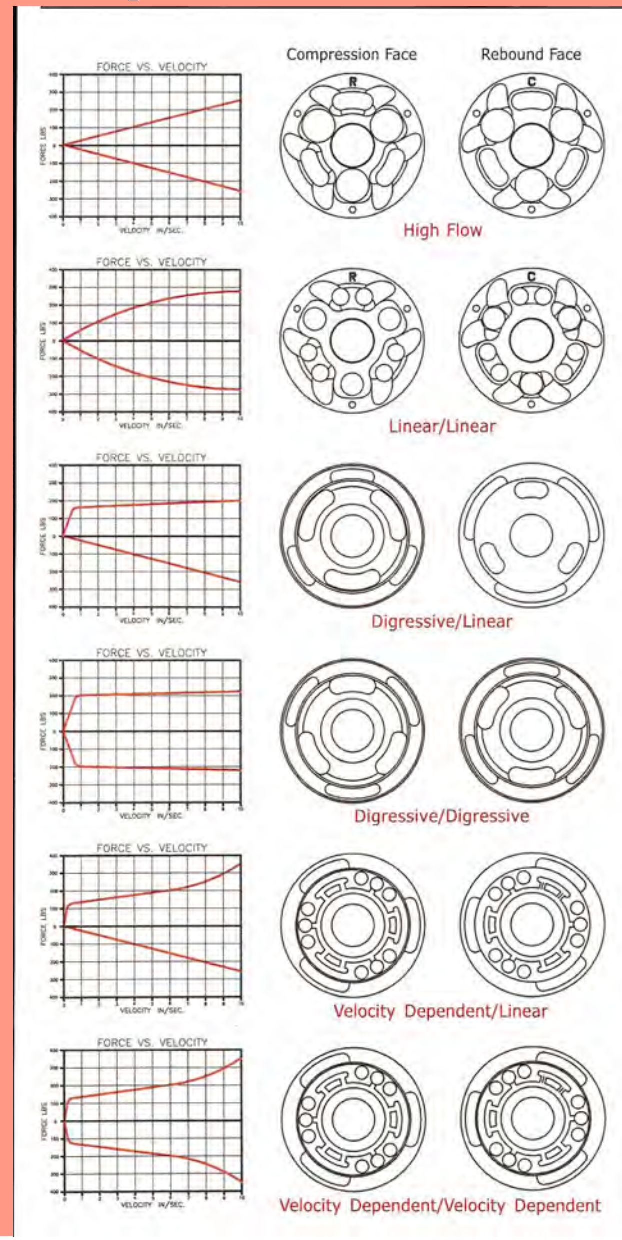
From Optimum G, Claude Rouelle, 2002

- Depends on mass and spring rate (example shown)
- The answer lies between 'damped' and 'critically damped'

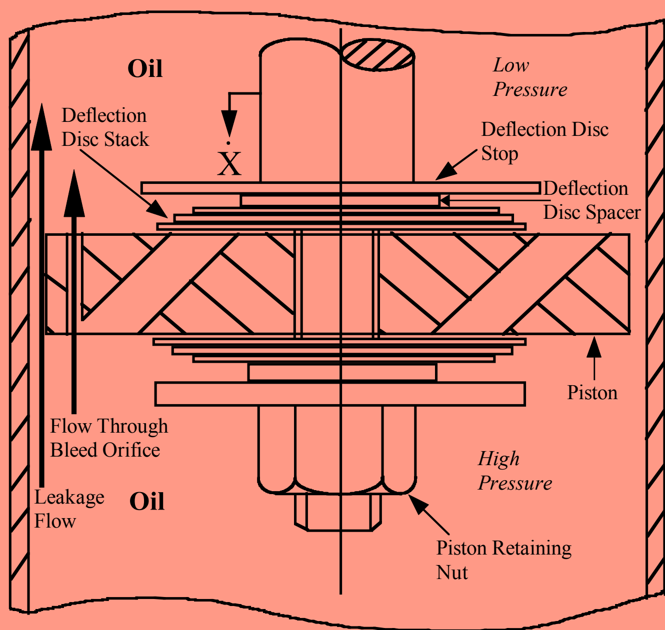
Adjustable Dampers







Monotube Low Speed Damping Force



Schematic of low speed compression valve flow.

At low speeds, total DAMPER force might be influenced more by friction and gas spring than damping.

Low speed flow is normally controlled by an orifice.

Types of orifices:

- **Hole in piston (with or without one way valve)**
- **Notch in disc**
- **Coin land**

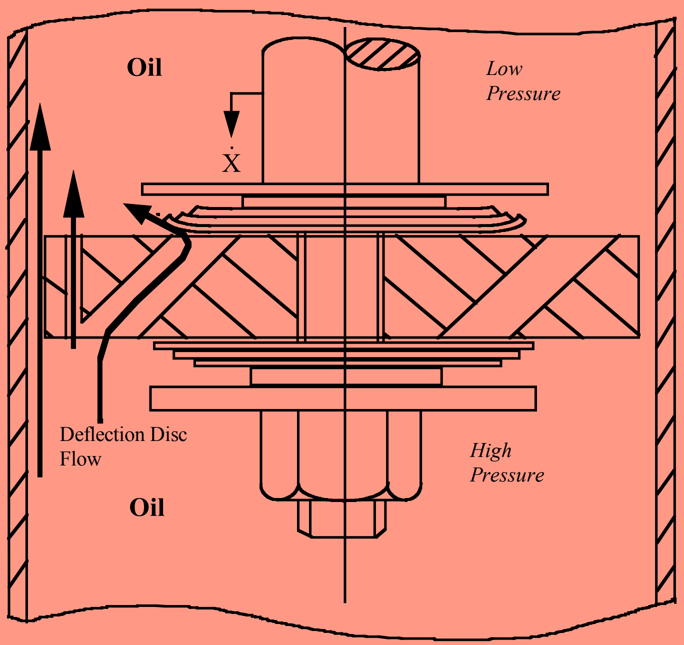
For turbulent flow:

$$P = \left(\frac{Q}{C_d \lozenge A_{eff}}\right)^2 \lozenge \frac{\ }{2}$$

As flow rate Q is equal to relative velocity of the piston times the area of the piston in compression (piston area – rod area in rebound):

Orifice damping force is proportional to the square of the piston speed.

Monotube Mid Speed Damping Force



Schematic of mid speed compression valve flow.

Mid speed flow is normally controlled by a flow compensating device.

Types of flow compensating devices:

•Deflection Discs (typically stacked)

•Blow off valve (helical spring)

Preload on the valve determines the cracking pressure, and hence the force at which they come into play. Define the knee in FV curve.

Preload:

•Disc, shape of piston, often expressed in degree.

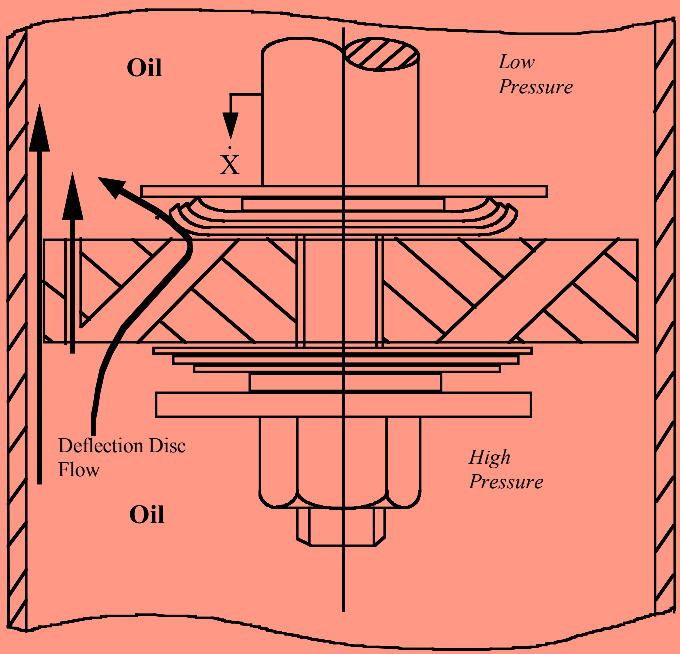
•Disc, spring to preload (sometimes found in adjustable race dampers)

•Spring, amount of initial deflection.

•Torque variation on jam nut can often vary preload. Undesired for production damper,

With flow compensation pressure drop and force are proportional to velocity.

Monotube High Speed Damping Force



Schematic of high speed compression valve flow.

High speed flow is controlled by restrictions in effective flow area. i.e. effectively orifice flow.

Flow restrictions, typically which ever has smaller effective area:

- **Limit of disc or blow off valve travel.**
- **Orifice size through piston.**

As per low speed damping, pressure drop and force are proportional to velocity squared.

Rebound damping and pressure drops across compression heads (foot valves) are similar to those discussed here.

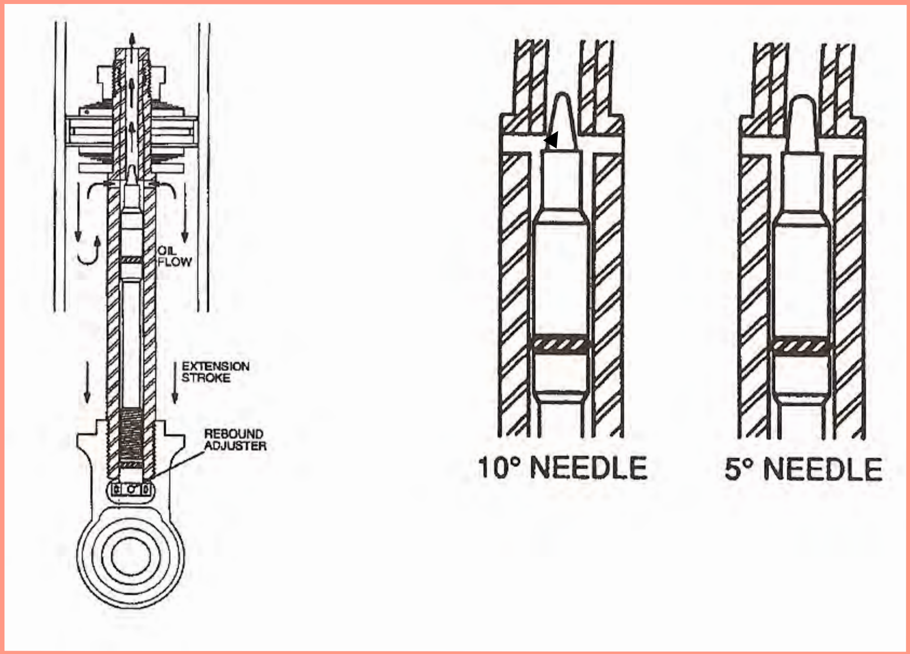
Tuning to Develop Damping Map

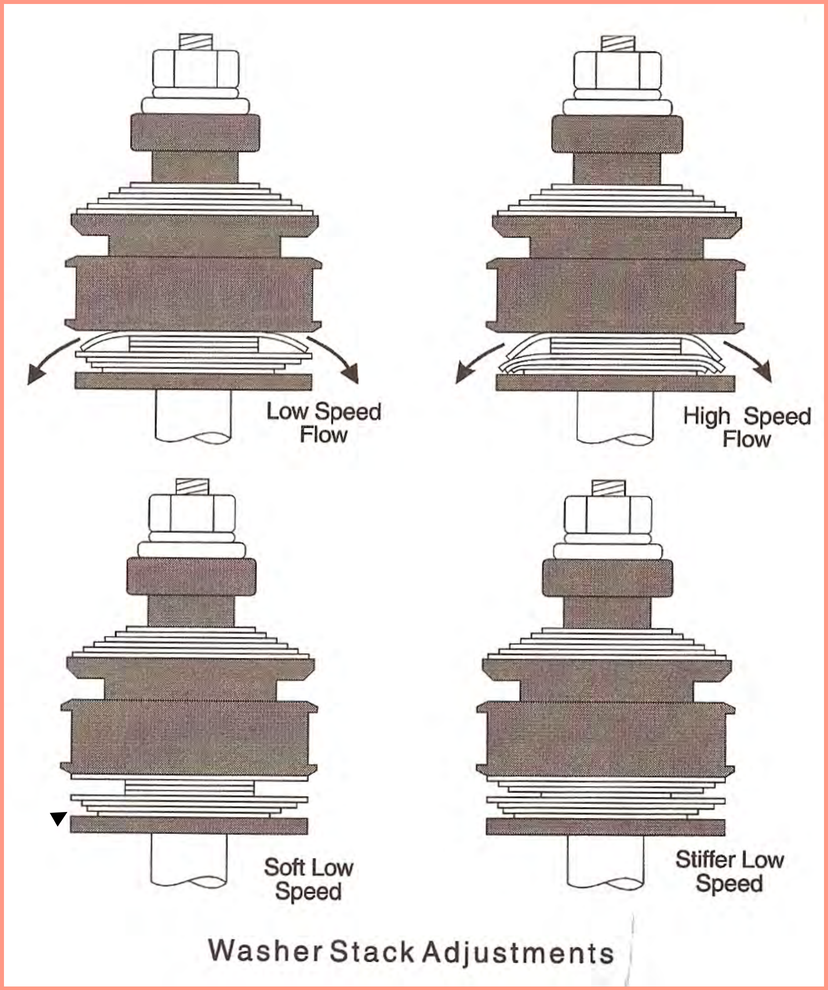
- Current designs permit up to 4 way control force adjustment
  - Low speed compression
  - High speed compression
  - Low speed rebound
  - High speed rebound
- We're referring to damper piston speed, not vehicle speed

Starting Out

- Set up basic vehicle course to “rough in” damper settings (I use a figure 8 with 2 different radii circular segments)
- Evaluate vehicle first for wheel end control, then ride, roll, and pitch control
- Use your most experienced driver
- Start with all dampers set at full soft for LSC,LSR,HSC,HSR
- Work with one axle pair at a time, sweeping HSC full soft-->mid-->full firm (Note: HS change can effect LS force characteristics)
- Back off HSC ‘X’ number of sweeps until tire bounce/dribble and ride harshness subsides, then repeat with other axle pair
- Continue with LSC same method as HSC
- Check gas charge setting to provide additional support, if needed) to the front end for initial roll control and corner entry
- Continue with HSR and LSR, looking to tighten up body motion and stabilize the platform for roll, squat and dive weight transfer
- With rebound, back off HSR ‘X’ sweeps when car breaks traction or if jacking down/cavitation is observed

Shim Stack and Adjusters





The needle taper determines the sensitivity of the adjuster detent

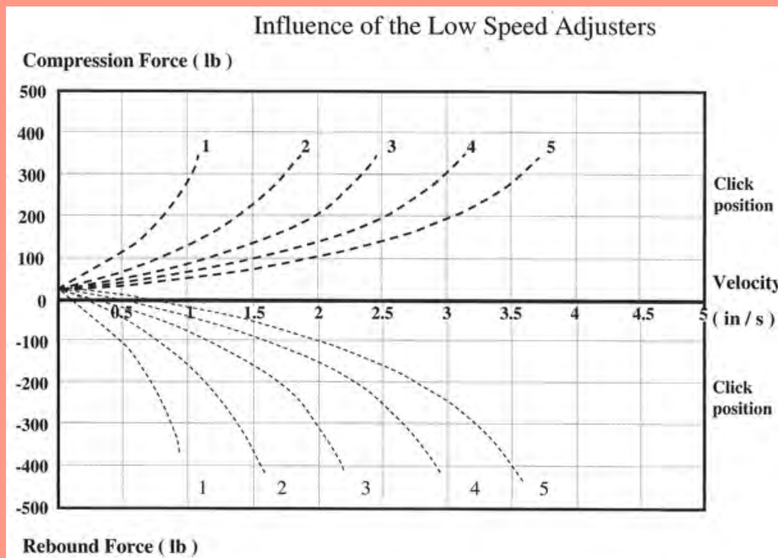
The section profile of the shim stack determines the transition curve shape between low speed and high speed control forces

From "Inside Racing Technology, Braun and Haney, 1995

Building a Damping Map

The adjuster usually consists of an angled needle metering fluid flow across a hole

1)



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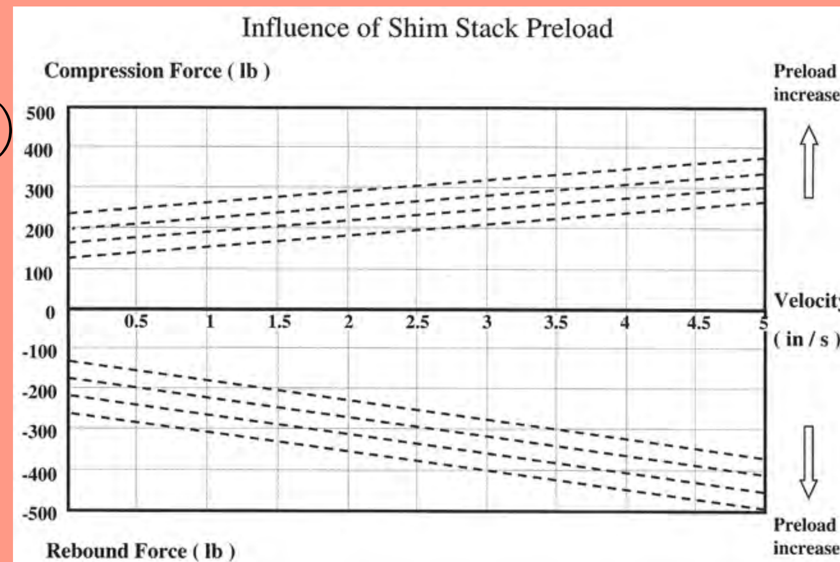

From Optimum G, Claude Rouelle, 2002

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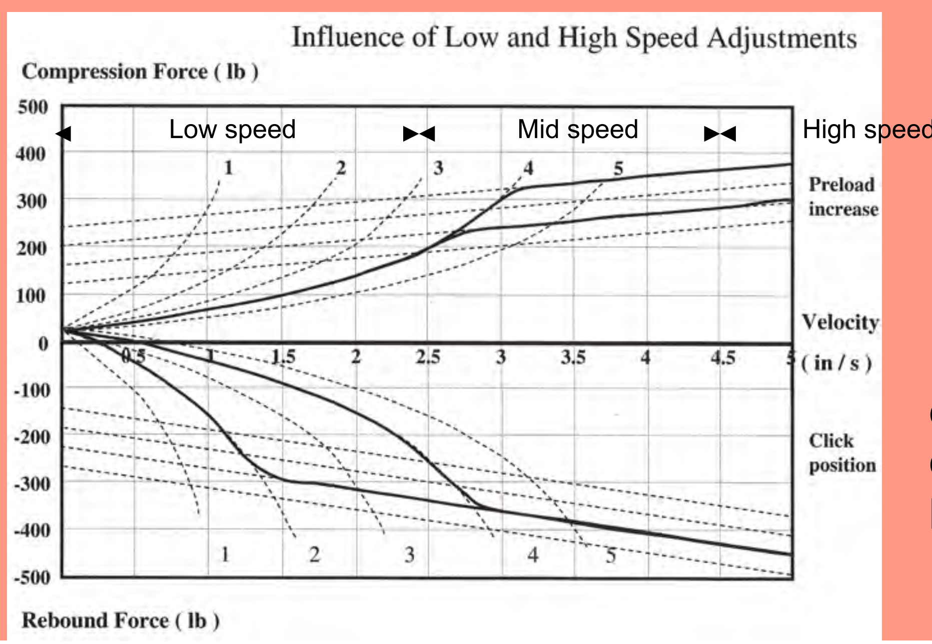


FYI:

- Low, mid and high speed are relative terms depending on the type of car (Indy car, off road buggy, rally car, etc.). Off road/rally cars plot up to 120 ips @ 10” stroke

1) Piston bleeds,coined lands, and piston dish determine LS and nose, 2) shim stack determines MS and F-V slope, 3) piston holes/slots determine HS end point

Tuning Your Car with Driver Feedback

DRIVER'S DEBRIEF SHEET

CIRCUIT ____
SESSION# ____
DATE ____ TIME ____

COCKPIT:
PEDAL POSIT ____ LEFT FT REST ____
HEEL PLATE ____ WHEELPOSIT ____
SHIFTER POSIT ____ HAND CLEAR ____
SEAT/KNEE SUPPORT ____ HARNESS ____
MIRRORS ____
COMMENTS ____

BRAKES:
PEDAL FEEL ____ FORCE REQ'D ____
FT TO R RATIO ____ VIBRATION ____
PULL ____ FADE ____ BOIL ____
STABILITY-SMOOTH ____
STABILITY-ROUGH ____
COMMENTS ____

TIRES:
BALANCE ____
COMMENTS ____

TRANS AND FINAL DRIVE:
RATIOS:
I ____ II ____ III ____ IV ____ V ____
UPSHIFT ____ DOWNSHIFT ____
JUMP OUT ____
FORCE REQ'D ____
CLUTCH ____
COMMENTS ____

ENGINE:
OP ____ OT ____ WT ____ FP ____
LAMBDA ____ THROTTLE RESP: TIP IN ____
UPSHIFT ____ DOWNSHIFT ____

FEEL ____

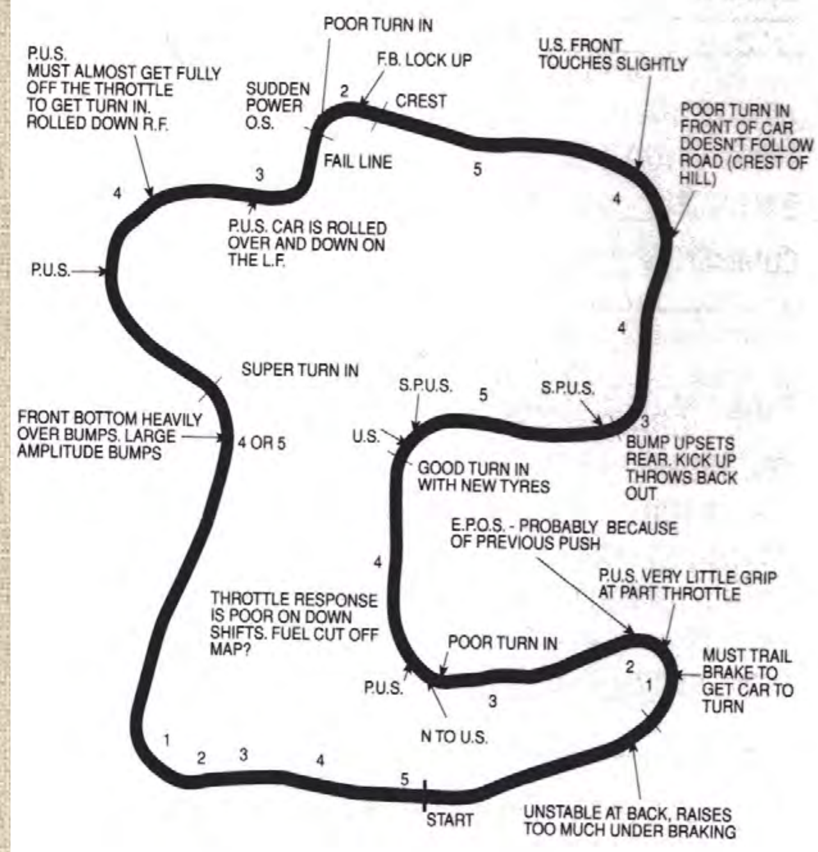
COMMENTS ____

CHASSIS:
ST LINE STABILITY ____
OVER BUMPS ____
SLOW - MEDIUM - FAST
INITIAL TURN IN ____
CORNER
ENTRY ____
TRANSITION ____

CORNER
EXIT ____
RIDE QUALITY ____
WHEELSPIN ____
BOTTOMING UNDER
BRAKES ____
BOTTOMING AT
HIGH SPEED ____
BOTTOMING OVER
BUMPS ____
COMMENTS ____

FILL IN THE TRACK MAP ON THE NEXT PAGE.

5 – 8



From "Tune to Win", Carroll Smith, 1978

Breaking Down The Course

or Only the Driver Can Balance the Car

- **Corner Entry-** turn in response, weight transfer under braking, pitch/dive, brake pull or weave, transient roll balance, understeer/ oversteer, steering efforts
- **Corner Apex-** understeer/oversteer , steer corrections, throttle applications, path firmness
- **Corner Exit-** understeer/oversteer, rate of power application coming off the corner (diff torque distribution, weight transfer under acceleration, wheelspin, weaving)
- **Straightaways** : straight line tracking, pitch attitude (stiction leaving the corner)-can affect steering and aero lift/drag
- **Slaloms and chicanes-** Front to rear steering coherence, lateral grip and roll rates in transitions, ability to maintain tight line with cones, oversteer/understeer balance, steering efforts
- **Skidpad**- Amplitude and frequency of steering corrections and throttle modulation to maintain circle at peak lateral acceleration, watch for oil pressure and fuel pressure fluctuations

Straight Line

- Driver: "The car pulls or wanders"
  - Too much static rear toe-out or dynamic bump steer or compliance steer
  - Extreme front toe-in or toe-out
  - Failed pickup point
  - Damper with no control
- Driver: "Unstable under hard accel"
  - Too little rear toe-in
  - Rear tire stagger
  - Failed rear damper
  - Pickup point or suspension component compliance
  - Very asymmetric corner weights
- Driver: "Very darty over single wheel bumps"
  - Too much Ackerman steer
  - Too much toe-in or toe-out
  - Caster stagger
  - Front anti-roll bar rate too high
  - Jounce bumper block height too tall or nose rate too high
- Driver: "Car is a POC"
  - Time for a break or driver change
  - Revert to last setup combination that worked

Hard Braking

- Driver: “Front end weaves”
  - Too much front brake bias
  - Too much low speed rebound control (jacking down)
- Driver: “Wants to spin”
  - Too much rear brake bias
  - Not enough rear suspension rebound travel
  - Too much rear damper low speed rebound control
  - Too much rear roll stiffness
  - Not enough rear camber

Corner Entry

- Driver: “The car points initially then plows” [Undertseer]
  - Too much front toe-in or toe-out
  - Too little front rebound travel
  - Front spring shims misadjusted
  - Too little front damper low speed compression force
  - Too little front roll stiffness {the outside front tire rolling over}
- Driver: The car wants to over-rotate on turn-in” [Oversteer]
  - Heavy trail braking by the driver
  - Way too much rear brake bias
  - Rear ride/roll stiffness too high relative to front
  - Rear roll center too high
  - Non-functioning front anti-roll bar

Corner Apex

- Driver: "Too much push in the middle of the turn"
  - Front tire pressures too high
  - Front roll stiffness too high
  - Too much toe-in or toe-out
  - Too much Ackerman correction
  - Not enough camber-in-turn (static caster)
  - Front track width too narrow
  - Not enough front jounce travel (damper bottoms out or spring not shimmed properly)

Corner Exit

- Driver on slow corner: “I keep plowing off the corner” [Understeer]
  – Patience! Condition probably originated at corner entry or apex (chassis or driver induced). Driver uses throttle stabs to try to rotate the car. Tell driver to carry less speed at corner entry
- Driver on fast corner: “The nose is heading for the fence on exit”
  – Not enough squat control resulting in rearward weight transfer with hard throttle
  – Need more rear damper low speed jounce force, maybe coupled with more front damper low speed rebound force
  – Too much preload on differential clutch pack

Chicane or Slalom

- Driver: “Steering feel is heavy, response is sluggish”
  - Tire pressure too low
  - Ride and roll rates too low
- Driver: “ The chassis feels floppy. It rolls a lot. Doesn’t take a set when I turn-in, I can’t point the car”
  - Low tire pressure
  - Low and mid speed damper forces too low, not enough “nose” on the curve
  - Ride and/or roll rates too low
- Driver: “ The steering response is hyper” or “ the car wants to get out from under me”
  - Tire pressure too high
  - Damper low and mid speed compression force to high
  - Ride and/or roll rates too high
  - Too much toe in (front or rear)

For More Help On Chassis Tuning Cause and Effect

Chassis Setup Review

- Remember Maurice Olley→ shoot for 20% delta front to rear ride frequencies to achieve "flat ride"
- Suspension tuning hierarchy: springs, anti-roll bars, dampers
- Wheel alignment hierarchy: toe, camber, caster
- Limit anti-dive to about 30%, anti-squat to about 40% (IRS) if you use them in your suspension geometry
- My philosophy: the springs contribute 60-75% of roll stiffness, use anti-roll bars to "trim out" the roll couple distribution, not a big advocate for rear anti-roll bars
- Dampers: Start at 3:1 rebound to bump ratio, bracket damping, charge dampers with dry air or N^2 to about 200 psi (monotube), 100 psi (twin tube) to avoid cavitation or dumping. Control force ratios above 6:1 prone to jacking the car down on ripples, washboard, or longer cold patch asphalt sections. With adjustable dampers, start at full soft LSC,HSC,LSR,HSR and build your damping map
- Tires: Use old tires for training, new tires/scuffs for testing/racing, use tire maker cold inflation and working pressure recommendations to start chassis sorting. Take hot pressures and tread temps as soon as the car rolls to a stop. Check for evidence of stagger, compare hot to cold tire measurement

Thanks for Your Attention