A primer on Miata limited-slip differentials plus my experience with them:

Since we've been discussing limited slip differentials, here is the Miata.net Garage page by Lance Schall as a reference: http://www.miata.net/garage/diffguide/

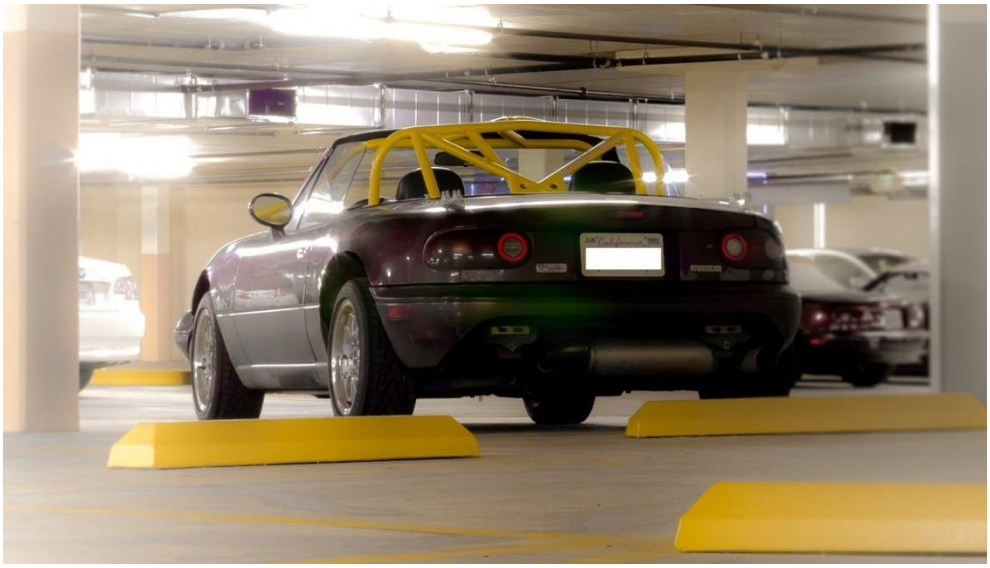
I've done my homework over years of Miata ownership to study the nuances separating the years and packages. The newer Tochigi Fuji Super (aka TFS) LSD differential found on 2003+ NB cars has a torque bias ratio (TBR) of about 2.0 : 1 vs. the slightly over 2.5 : 1 TBR of the TorSen Type1. This means the newer diffs won't put power down as well as the earlier Type 1s. Don't settle for cheaper less robust imitators! You can always put a bigger / newer motor into a Miata, but getting the right connection from the drive wheels to the ground is the most important choice you can make. Many people go nuts and get the OS Giken, a Cusco, or an RX-7 clutch-type diff. While each of these has advantages, the first two are expensive, will require assistance to fine-tune, and certain OS Giken models have had a reputation for grenading. The RX-7 clutch type can be a good choice but it will require servicing as the clutches wear out.

Having felt the differences between a factory viscous (blah), Type 2 TorSen (annoying understeer on throttle) and the elegantly-capable Type 1 TorSen, I have not found compelling reasons to use anything else in the past 2 Miatas I've competed with. Unfortunately, for many people driving and racing Miatas using a worn viscous, inferior Type 2, or impressive-sounding but not highly-capable Tochigi Fuji there is definitely a huge improvement going to an OS Giken or Cusco. If you're looking for the last few percent when tuning a competition car, a purpose-built diff makes sense. But becoming familiar with the Type 1 TorSen is first order of business, in my experience!

It was hard to stay away from driving Ron, even with 'Christina', our new-to-us '02 BMW sedan also in the stable. He was a blast as a street and light-duty autocross car with the compliant yet grippy 195 wide 200 treadwear tires. In the process of developing our Elite valving from 2011 to 2012, he'd helped us improve our stock-class autocross setup by testing a new 'droop limiter' technology that we would provide to E Stock racers who felt the advantages of it. He also wore several iterations of our Comfort and GT coil-over suspension offerings. But I had an itch to take him faster and lighter, to drive him for longer than 40 seconds at a time, to add more grip and even enjoy the magical benefits of aerodynamics! Our collective futures lay in preparing for higher-speed endeavors, making ideal use of all the technical advantages his '95 M-Edition package provided, the experience I'd gained in suspension tuning, and the car control skills I'd learned for driving at the limit.

Ron had outgrown his name and was ready for a moniker befitting our intentions. Inspired by the recent documentary of the same name, we rechristened him 'Senna' in honor of Ayrton Senna do Brasil. His is as epic and tragic a story as you're likely to encounter although we hoped our Senna would live a long and successful life.

The first step after his re-naming was to get him ready for his track debut. In February 2012, I drove our 'Senna' to LA to receive a work of art – a Blackbird FabWorx 12-point Street cage.



Blackbird FabWorx 12 point 'Street Cage' after installation in Los Angeles

I made a video of ingress / egress (yes, without the hard top!) and posted it here:

https://www.youtube.com/watch?v=pxbKy-FbSEE

Granted, with the hardtop it's a bit slower but the Blackbird design touches on this cage are very thoughtful. The central 'wishbone' between driver and passenger provides excellent head clearance which isn't a consideration with always found with typical cages. I've never hit my head on anything which is vitally important for street driving. We have a box of SFI padding available if the new owner wants it (although SFI is intended for maximum effectiveness when used with a helmet).

Note higher clearance to cage tubing running fore/aft

Designed to accommodate factory seat belts

Robust construction and inspired design choices by master fabricator Moti Almagor

I remember planning to get the cage from and installed at Blackbird FabWorx in San Fernando Valley. This was Moti's area of expertise – it made no sense to try and DIY! I needed it done correctly, and also before the Miatas at Mazda Raceway event coming up in a few weeks at Laguna Seca (see wet photos below!) where we were a sponsoring vendor.

Because I didn't have a hard top yet I'd have to drive back home in true roadster fashion – the soft top had to be removed entirely to fit this 12-point cage. The install took a day with all the fine touches Moti puts on his work. He was cheerful and efficient, offering me Turkish coffee which I accepted and jittered the rest of the day from!

Wow, the difference in chassis rigidity was extreme! Going in and out of driveway produced nary a creak or groan. The car was truly a solid unit now in a way just a roll bar and chassis bracing will never provide. Plus, I had much more confidence in case something catastrophic might ever happen (knock on wood).

Once the work was done, I dropped by a KINOD event (acronym for “Krispy Kreme, In ‘n Out & Drive”) event where I met friends, fans, customers, and had these beautiful pictures taken.

Then, time for the drive back! Forecast said rain and sure enough, driving north I was caught in a spring downpour that soaked me good! I was warm enough overall with windows up and heater at full blast but I couldn’t keep all the rain out. So there I was, laughing like a maniac, passing cars (yes, I was in the fast lane!), thrilled the transformed chassis while watching the looks of amazement as folks wondered was with this guy driving topless in a rain storm!

Once home, dry, and done admiring the naked cage, we knew he needed a hardtop for best aerodynamics and security. We found one in black which was a nice complement to the Merlot Mica. Along with the Garage Star security Torx bolts to keep thieves at bay, Senna closer to track ready. With a new Koyo Race radiator, OE radiator hoses, 50/50 coolant mix, oil and filter change (10w30 Mobil 1), Redline water wetter, new timing belt / belt tensioners / water pump, new stock 1.8L rotors and Porterfield R4-Spring pads (streetable track / autocross compounds ideal for lighter cars), we really WERE ready!

The tires we decided to use for that event (since rain was forecast) were the 195/50-15 Toyo R1R on 15x7.5 6UL wheels we’d been enjoying on the street. Even if the weather warmed up and track dried out, the Toys should still serve well as a cooler-weather track day tire. This is still our favorite Miata tire / wheel combination for cold / wet / lower temperature conditions. To make sure he was able to put power down and had greater high speed stability, we re-installed the rear dual-element wing that was removed prior to the cage installation.

Senna at his first track day – smooth, fun, and quick!

He was certainly quite at home, debuting in the wet as Ayrton had on a wet Monaco Grand Prix. During this wet day, we weren't racing for times and we had fun giving many demo rides. Other than one track day at Thunderhill with Graham (our 1.6 93LE with ABS) years before, I'd never driven a Miata with anti-lock brakes at the track and certainly never in the wet. Gradually, I played more and more with braking - how hard, how late? It was quite fun and eye-opening to feel consistent ABS-enhanced stopping power and predictable rear-end response from the TorSen Type 1 (even when transitioning into oversteer!) plus our FCM Elite tuning on a wet track - especially with walls around! It was, in a word, delightful!

Of note, this particular Laguna Seca suspension setup for Senna was with no sway bars and higher-than-usual spring rates (in fact, the highest we'd ever used): 1000 lb/in front springs, 500 lb/in rear springs. This was a 'maximum grip' setup – definitely NOT producing Flat Ride! – and intended to allow the most traction and curb compliance in wet conditions. He indeed worked beautifully the first day in the rain and quite well the following day in the dry … but I could feel that having some front sway bar would have helped keep the rear under better control in full-throttle corner exit situations. Using a front bar would let us keep him balanced mid-corner and on-throttle at corner exit, while also allowing use of a

higher rear ride frequency vs. front to provide Flat Ride (which had numerous advantages). Later revisions of his suspension and our tuning for all subsequent track / high-performance customer would see a focus on Flat Ride. In Senna's case, we added a moderately sized front bar (24mm current vs. 19mm factory, or about 2.5x stiffer than stock) and retained the stock 11mm rear bar which helps keep the roll center migration consistent front and rear which is especially important in slower corners. With the rear bar removed, the vehicle will experience dynamic understeer. This may be good for a novice driver but it's not good for maximum grip and fastest lap times. [1]

The second day conditions warmed as expected and I was able to see how the R1Rs did in 60-70 deg dry conditions. The tires worked just fine, grip was definitely up and we were all much faster through the course. I could imagine the Toyo R1Rs overheating during a truly hot summer day. That's what the BF Goodrich Rival (or Hoosiers) were for!

Even though Senna had the driving feel of an exceptional Miata, he didn't quite have the appearance I wanted as an emissary of our Fat Cat Motorsports brand. The idea of getting a wrap was suggested and, seeing as the BMW was going to serve as a more street-focused car, I decided that yes, let's make him look as amazing as he feels! So on a couple hot August days, we contracted with John Wolf of Wolf Vinyl to give him a beautiful custom wrap that really made him pop!

Shaikh Jalal Ahmad (Fat Cat Motorsports) and John Wolf (Wolf Vinyl) with the new Senna!

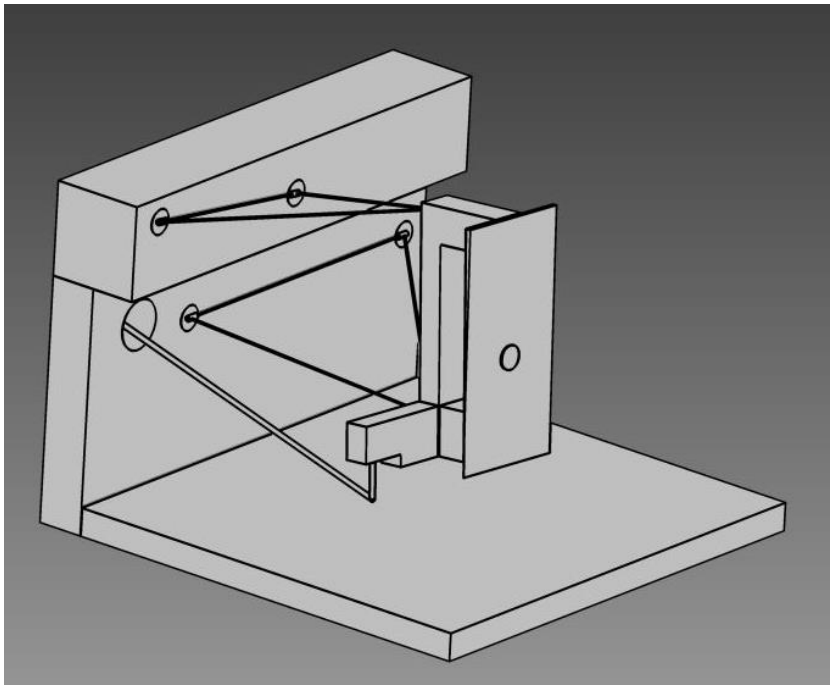
[1] As of October 2016, Senna's current spring rates are 450 lb/in front, 375 lb/in rear, giving approximate ride frequencies of 1.95 Hz front, 2.15 Hz rear - chosen to give Flat Ride (which all my wonderful customers hear me prattle on about ad infinitum!). Flat Ride works, what can I say!

With his new eye-catching appearance, you knew what Senna was about. I was getting more intrigued with optimizing for "massive grip + serious aero". For years we'd been working with V8, turbo- and super-charged Miatas putting out over 300 wheel HP and having good success with our Elite builds, often driving local cars ourselves before and after Elite suspension upgrades. However, I wanted to see for myself all the mods required to make a setup with, say, 275/35-15 Hoosier A6 autocross tires work. So, while the more comfortable setups were fun to play with for street, backroads, and were reasonably fast at the track, to get into the 1.3+ g range and we'd need to further lower him, reduce roll, and make changes that brought out a more tenacious character.

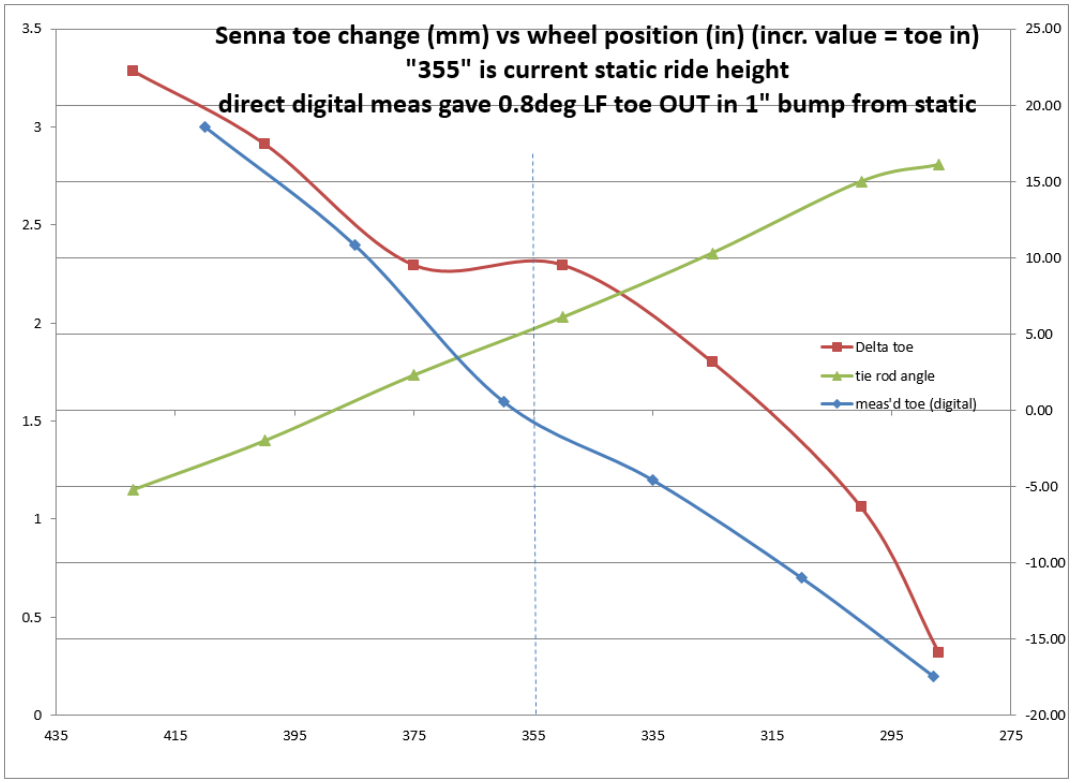
From measurements I'd done with Jyri Virkki years ago, we knew the Miata had less camber gain in roll on the front suspension vs. rear. This was typical for all production car we'd ever measured and made sense if you wanted to ensure the car would understeer (safer from a manufacturing standpoint) when cornering at the limit instead of oversteer (which a racer usually preferred but required more driver attention). There was a solution from ISC Racing (later sold by Mazdaspeed Motorsports) to both increase front static camber and shorten the upper control arm which increase the front suspension camber gain. The method used a Delrin bushing machined with an offset for the inner sleeve. This offset position would allow you, by rotating the alignment cam, to shift the upper arm inboard and provide up to 1.5 deg more negative camber vs. a standard control arm. We set the Delrin offset bushing to its extreme 'inward' setting (maximum static camber) and immediately saw over -4 degrees! This much camber was very effective in keeping our 275 Hoosiers planted, giving tire temps that were essentially even across the tread. No small feat as anyone using that much tire and wheel would attest! For less aggressive grip applications, more like -2.7 front negative camber was enough at the low ride heights Senna was running.

ISC Racing Delrin offset bushings, sold by Mazdaspeed Motorsports, installed on Senna's front upper control arm bushing position

Being aware that Mazda designed new tie-rod ends for the ‘93LE and ’94-97 R-package Miatas (which ran lower ride heights than standard models), we installed 94-97 R-package tie-rod ends on Senna to reduce toe change during cornering (i.e. bump steer). Then, not satisfied we had fully optimized the system, we went further by shimming the steering rack upward via custom aluminum blocks under the steering-rack-to-subframe brackets to bring the steering rack angle nearer to horizontal. Both changes made him much more stable when dealing with rough surfaces even lowered significantly from stock.

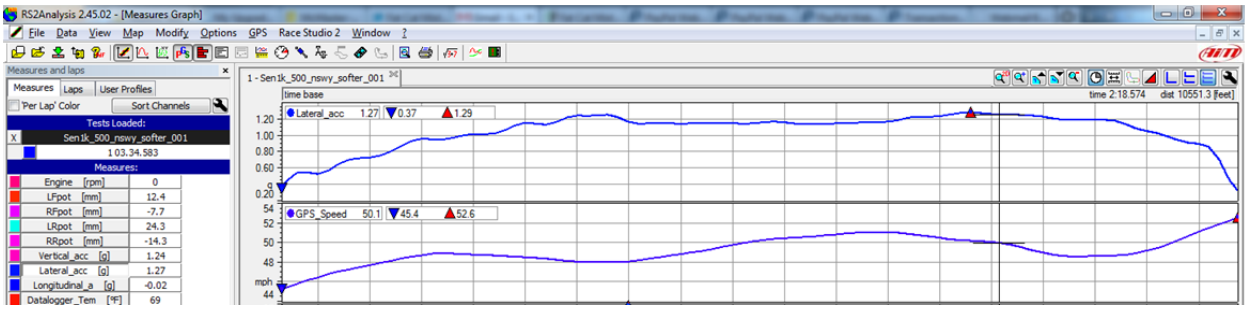


Model of front upper and lower control arms plus steering rod to simulate camber and toe changes



Senna's bump steer curve, flat section of red curve indicates an optimal range of minimal toe change with ride height

To help plant the front end via more front downforce, we made a custom splitter, exhaustively planned to be structurally sound as well as capable of handling abuse at the track. Reviewing various material choices, we went with birchwood which was strong enough to handle contact with berms or the track surface while being flexible enough to not shatter or warp with repeated contact or loading. We sourced the material from a neighbor who did high-end carpentry, created a template from cardboard, measure then measured again, cut with a jig saw, sanded and shaped the surface to provide the desired contour, applied sealant over two rounds, then painted (also in two rounds). The new splitter, born from much loving attention, was mounted to Senna via custom brackets. It saw some scrapes on the street as well but after 3 years has proven its worth.



Pulling 1.29g (in several spots) on 195 street tires (with lots of aero and great suspension tuning!)

With the wing and splitter installed, we found amazing grip! First we ran a no-sway bar configuration as we had at Laguna Seca in early 2012. Senna pulled an instrumented 1.29 peak g on our favorite Holly Street cloverleaf! This was on the same 195/50-15 Toyo R1R tires mounted to 15x7.5" tires used at the same track day! But a front bar was needed for putting power down coming out of tight turns and we initially used a Racing Beat 1 1/8" tubular bar that, along with 850/450 spring rates, helped keep the body roll under control so we could make use of the massive grip from 275/35-15 Hoosier A6 autocross tire wrapped around 15x9 6UL wheels. It was spring and sway bar combination which helped us win a Time Attack competition during another track day at Laguna Seca in late 2014!

MASSIVE GRIP and strong aero even at 45 mph!

Senna sporting 275 wide Hoosier A6, custom birchwood splitter and Ciro Design Racing dual-element rear wing, autocrossing at Marina with Porsche Club of America, Loma Prieta Region

Fat Cat Motorsports, Senna Run 6 on Hoosier 275 A6, PCA @ Marina 4-29-12

https://www.youtube.com/watch?v=u49URABtJjc

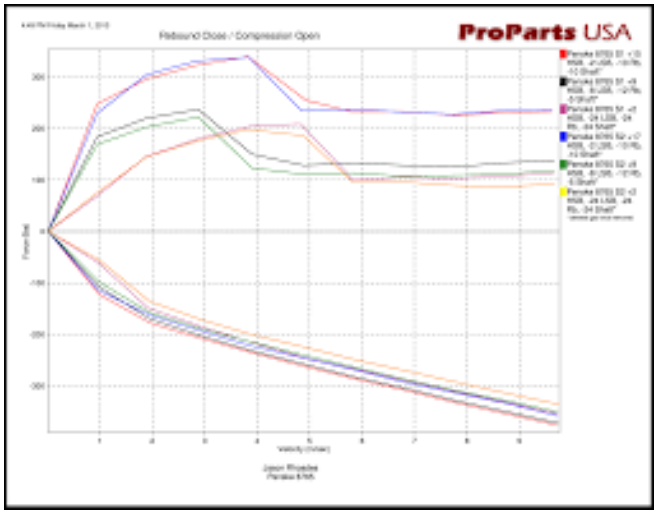
Although much stiffer at 850 / 450 spring rates he was still surprisingly tractable on the street. When I added KBO v1.0 the following fall, then Ripple Reducer in early 2014, plus retuned his spring rates with attention to Flat Ride he rode and handling even better.

We purchased a set of track wheels and tires – 205/50-15 Hoosier R6 with Konig Flatout 15x8 wheels. After purchasing of an AiM EVO 3 data acquisition system and 4 Penney and Giles (professional grade) suspension potentiometers, we could see in greater detail how he was behaving on the street and at the track. In examining the histograms of suspension velocity at each corner vs. the damping force, we observed that compression damping was related to track the specific corner weight to provide the most optimal contact patch. We also saw the effects of jacking down in dynamically lowering the ride height (and reducing grip) vs. a more neutral jacking setup. I could see from lateral g traces where I whether I was making full use of the tire's capacity or holding back. We kept these observations and mnemonics in mind during future revalves for Senna and our customers' cars. Data acquisition is such an important part of getting the most from your suspension and your own abilities and we applied it to Senna in truly getting him dialed to new levels of details.

We also observed the impact of spring rate choice on tire grip – stiffer rates caused oscillations in the suspension potentiometer which indicated the spring was forcing the tire sidewall to 'bounce' (a 2.5-2.8 Hz feature was visible in the shock position data!). That behavior was compromising maximum grip. It led me to reduce the maximum ride frequency to about 2.4 Hz and to ensure – whatever it took – we would use Flat Ride in our Elite suspension designs to prevent the 'pitching' (front to back excessive movement like in a boat tossing around at sea) that would further decrease contact patch consistency and grip.

<u>The continuing pursuit of the Perfect Ride:</u>

Through some friends, I was introduced to the concept of 'regressive' damping, which Penske was utilizing in Formula 1 and tuning for their high-end customers. I was blown away by the fact that a damper could increase force strongly then DECREASE force and finally provide a low build-up!



Example of damping behavior for Penske regressive valve (upper part of graph is compression)

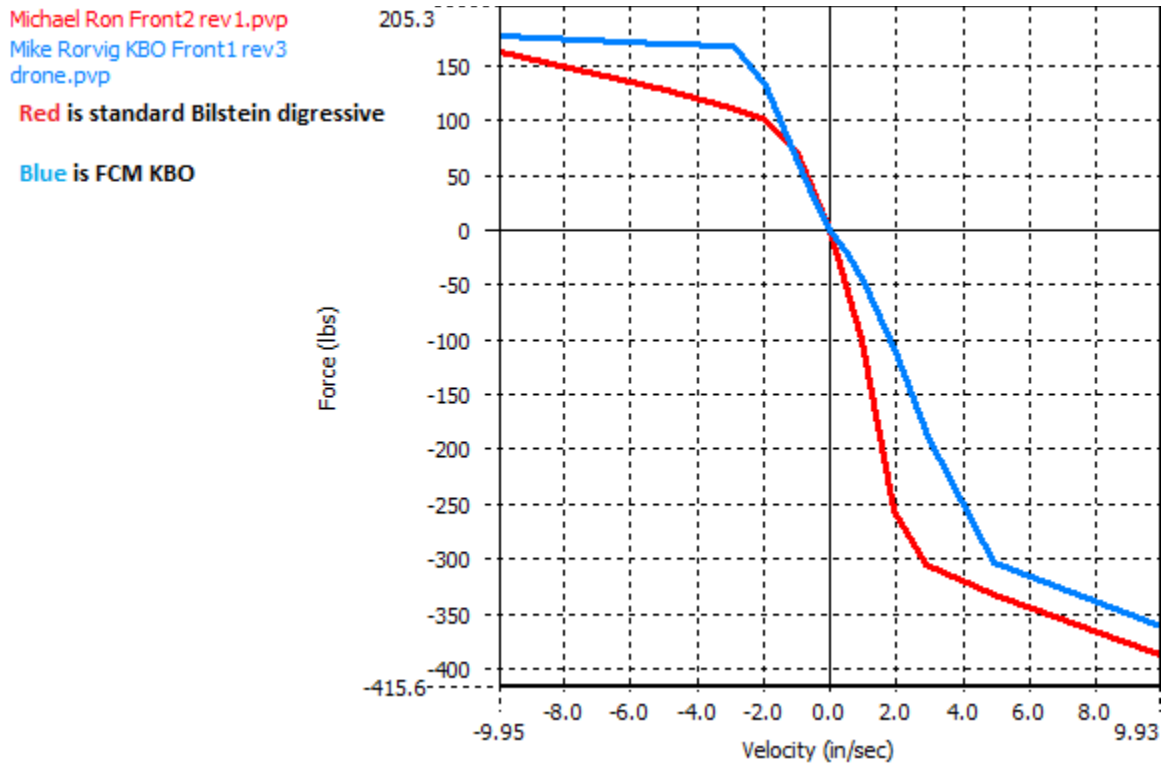
This regressive behavior would feel great for transitional control with the stronger low speed shock damping but also give excellent compliance on curb hits at higher shock velocities. The Penske design was effective although it seemed complicated (and was certainly expensive at $450+ just for the valve let alone the damper and tuning which I heard from a tuner could take many hours to achieve matched results between pairs of front and rear dampers!). So my former boss (who was now a freelance PhD mechanical engineering consultant) and I set about to create our own blow-off valve that would work with Bilstein monotube dampers.

Within a few months of my return in summer 2013, we had a prototype ready for testing and I would call it KBO (Kerb Blow-Off).

How Shocks Work - Introducing KBO, A Leap Forward in Suspension Tuning

https://www.youtube.com/watch?v=-T_ms_S7Y1E

My intention with KBO is to provide strong low-speed compression damping with a much-flatter-than-typical-digressive (nearly flat) blow-off and minimal build-up of high-speed compression force.



Note the strong low speed compression force build-up while the high speed compression force is significantly softer than the standard digressive piston response

KBO version 1.0 was first installed on Senna and given the torture test of a ~500 mile round-trip on rough highways, backroads, and finally run at a City Tech track day in February 2014 at Thunderhill Raceway Park.

On the drive up, I clearly recall how smooth Highway 505 seemed – except it hadn't been repaved! I could hear the sharp micro impacts of the tire at highway speeds but the chassis was just moving gently up and down, following the macro character of the road. As a customer would poetically say later, 'KBO chops the off of bumps!' A perfect description for its intention and ability.

That was a really fun track day especially as it had been a long time since I'd driven Thunderhill and now had more grip and a more communicative chassis. I gave one Miata buddy a ride and he was amazed at how I could drive Senna up the inside onto the berms at turns 14 and 15 (the sharp two corners leading on to the main straight) which every instructor tells you to avoid so you don't get launched into a tank-slapper and the wall along the main straight! "I could never do that in my Miata!" [2] It was an eye-opening experience as I realized I was changing the rules right then and there. We had a game-changing technology and Senna was my trusty steed helping me explore what was possible so others could benefit as well.

Incidentally, he was winning his class before I left for the day but in the last session someone bested his time. This was a motivator for me to have the custom Lexan windows made (with quick-release Dzus fasteners) so he would retain the ample engine warmth during longer drives in cold weather.

[2] I'm happy to report he later became an FCM Elite customer!

After that fun and successful track event, I was eager to get this technology into more customers' hands. There was a new season of autocross coming up and KBO would provide exceptionally useful for a Street-class racer who was limited to softer (stock) springs but could use firmer damping. We helped several customers win National Tours (and now in 2016 one even won her first National Championship!), plus racers in other classes. KBO would prove itself on the street most of all, where even our National Tour – winning customer Mike Rorvig comments that the street ride of the KBO setup was his favorite part!

Mike R. giving a testimonial about his KBO Elite dampers for his Mazda Miata

https://www.youtube.com/watch?v=JFhpAOSrOlA

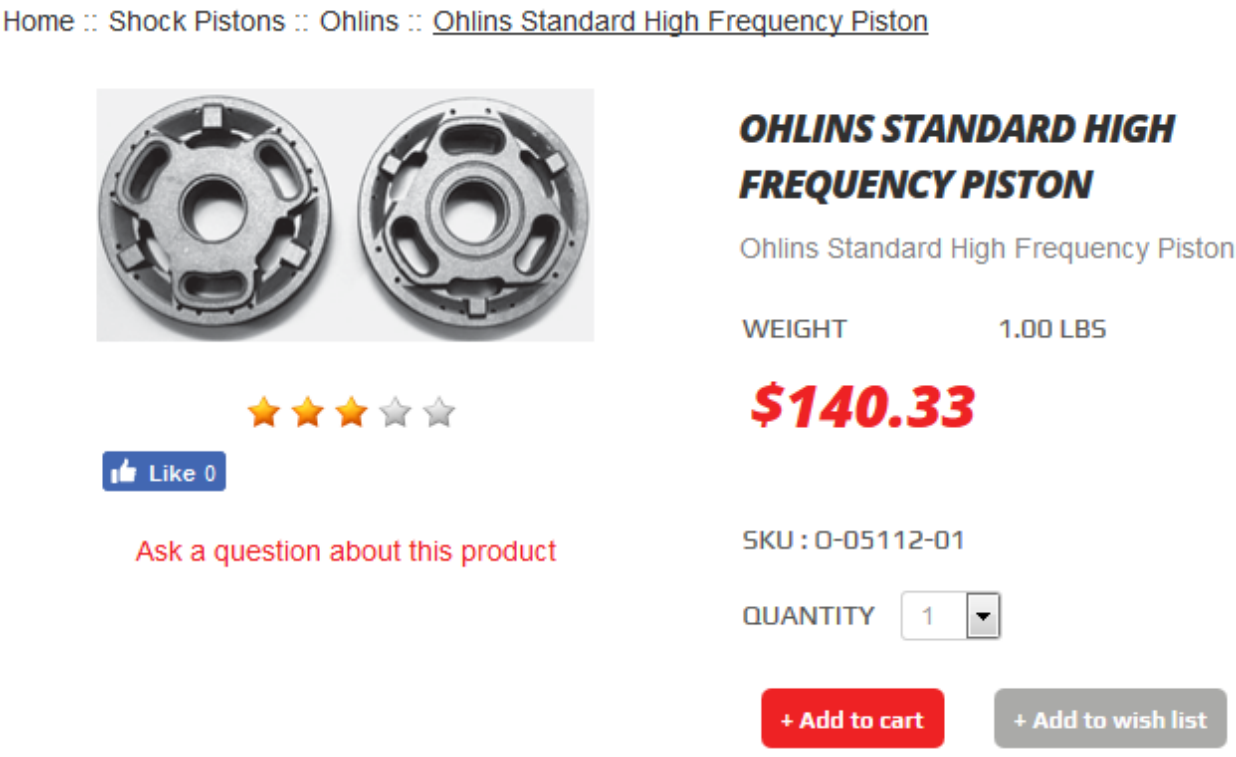
For street, track, or autocross use, KBO worked together with our proprietary and industry-leading approach to bump stop tuning. The combination created suppleness on sharp track or road features with sufficient protection for times the suspension naturally wants to bottom out and you need to build compression resistance - such as at the bottom of the Corkscrew at Laguna Seca!

How's that for confidence in suspension tuning! Driving hard through the bottom of the Corkscrew, splitter just contacting the track at full compression, everything working together in perfect harmony!

Zooming in on that great picture by Dito Milian of GotBlueMilk Photography, for the configuration pictured, Senna was running 700/450 spring rates with the same initial KBO v1.0. Finally, after several years of development and improving our customer's cars with newer KBO innovations (lighter components and tighter tolerances for faster blow-off valve response), by early 2016 we were ready to update Senna.

Ripple Reducer – developed for large solid-axle vehicles, excellent on all platforms!

In late 2014 we were working with builder to improve the suspensions of their Sprinter-based executive shuttles and coaches. It was clear that the demands of a solid-axle meant the typical monotube design had to be significantly improved otherwise a VERY harsh / choppy ride would result. We took queues from several areas of tuning related to heavy vehicles, including off-road racing, and decided one approach was to focus on the frequency response of the damper on small displacements. Ohlins had already developed a high-frequency piston (at $140 each) which has many small holes drilled in it.



http://store.resuspension.com/product.php?productid=18901&cat=275&page=1

Ohlins High-Frequency piston, available from RE Suspension

You can watch this video I made for a primer on the ideas and execution of our high-frequency modifications. In short, drilling small holes allowing fluid to move easily between both sides of the piston

reduces the initial force ramp as the damper moves into compression. This softens the damper response and gives a small amplitude region that has less resistance vs. a damper only utilizing bleed shims (which force the fluid to go through multiple bends inside the piston before exiting the other side). The holes also effectively 'choke' as the damper velocity increases so you can build sufficient mid and high speed compression force. A standard shock dyno plot will NOT show the Ripple Reducer / high-frequency softening behavior, you have to look at lower speeds and higher frequencies so this is something most (the majority?) of aftermarket and OE tuners are not incorporating in their damper designs except for specific applications such as off-road racing.

How Shocks Work - FCM Ripple Reducer softens the impact of Rough Roads

https://www.youtube.com/watch?v=dUt00J3eMsY

The Ripple Reducer was amazingly effective! We tested it first on our BMW 330i sedan's rear damper (since those were separate from the spring and very easy to remove). The increase in grip AND ride quality was very noticeable – to the point that we immediately had to add Ripple Reducer to the front suspension otherwise the balance would be skewed toward understeer (less front grip than rear).

Ripple Reducer became our more popular and cost-effective technology and we've now gone to a v2.0 Ripple Reducer using even smaller holes and more of them to get even lower 'cracking' force and better ride quality. Like many things in life, this is something you need to feel to believe and from driving Senna around, his ride quality would put many far more expensive 'modern' cars to same. You can read what our recent 2007 Miata customer has to say about his GT setup which is very similar to what Senna is currently tuned with (although Senna has higher ride frequencies since he's geared for track use):

Matthew's FCM Elite KBO and Ripple Reducer review for his 2007 Mazda MX-5 Miata

http://www.fatcatmotorsports.com/FCM_Elite_projects_MatthewM_MX5.htm

As Matthew said, we have indeed learned so much in the past 5 years. His comparison after driving 'modern' cars and being under-whelmed by them validates what I've also felt: there are certain design choices that are required to achieve excellent ride quality and that ride quality can also translate (with additional wise design choices) to great driving control. We have drawn on the best minds, explored crazy ideas that turned out to be very relevant, and been fortunate to experience insights that have put Fat Cat Motorsports on the list of 'the best suspension tuners in the world.' All of these insights and experience have gone into making Senna as refined and fast as he is today, which any future owner would be lucky to enjoy!