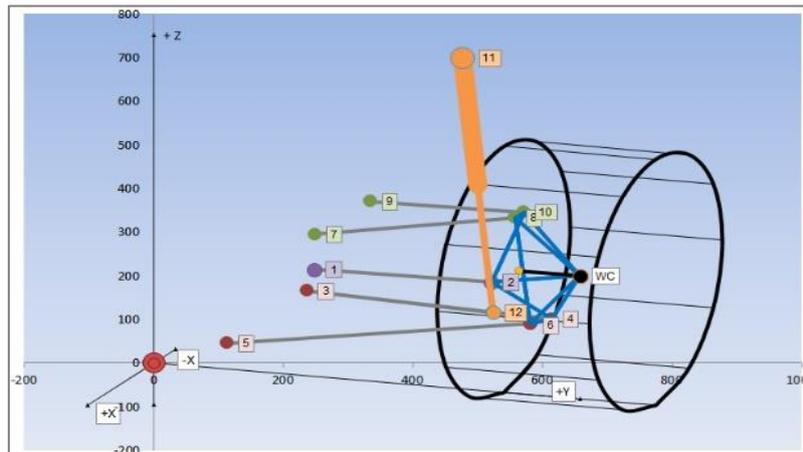




DYNATUNE-XL SIMULATION TOOL SUITE

10 “EASY” STEPS TO HAPPY (ELASTO-) KINEMATICS

A Comprehensive Suspension Design Guide



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The following 10 Step Recipe Guide is describing our Approach & Recommendation for Creating an (Elasto-) Kinematic Suspension Model with subsequent Tuning & Optimizing for maximum Performance. All Analysis will be executed in the **DYNATUNE-XL “Expert” SUSPENSION DESIGN MODULE** using a standard included data set of an Automotive OEM Suspension layout. Although this document is primarily written for the Users of the **DYNATUNE-XL SDM “Expert” MODULE**, it will hopefully give a deeper insight into the particularities of Suspension Design to any interested reader.

SUSPENSION DESIGN GUIDE – 10 “EASY” STEPS

- **STEP 1: UNDERSTANDING THE KINEMATIC WHEEL MOVEMENT**
- **STEP 2: UNDERSTANDING THE SUSPENSION FORCES & MOMENTS**
- **STEP 3: THE MOST IMPORTANT KINEMATIC PARAMETERS**
- **STEP 4: THE MOST IMPORTANT ELASTO-KINEMATIC PARAMETERS**
- **STEP 5: DEFINING SUSPENSION CONFIGURATION / APPLICATION**
- **STEP 6: DEFINING BASE ELASTO-KINEMATIC TARGETS**
- **STEP 7: DEFINE BASE KINEMATIC TARGETS**
- **STEP 8: DEFINE BASE STEERING SYSTEM TARGETS**
- **STEP 9: CREATING BASE SUSPENSION GEOMETRY HARDPOINTS**
- **STEP 10: OPTIMIZING ELASTO-KINEMATIC SUSPENSION STIFFNESS**

Note: The paper does assume good general understanding of Kinematic Suspension Terminology and does build up on the document “[The 5 Fundamentals of Suspension Design](#)”.

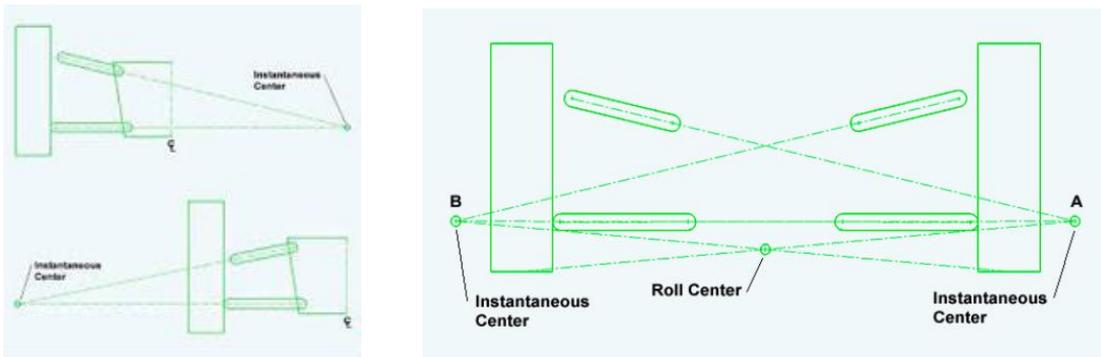
This document will be referring frequently to the **DYNATUNE-XL FAQ** webpage for customers:
<http://www.dynatune-xl.com/support-sdm.html>



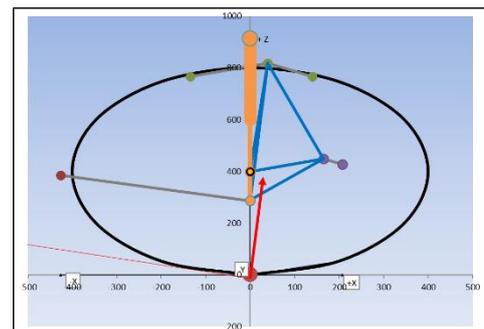
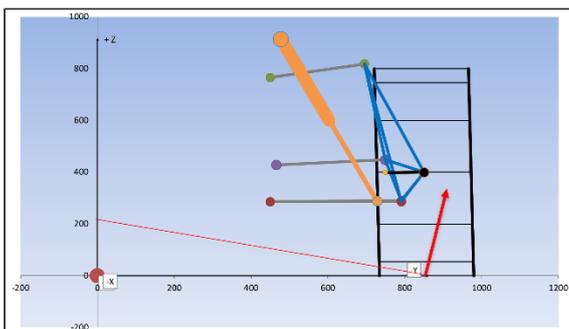
STEP 1: UNDERSTANDING THE WHEEL MOVEMENT

The “Classic” Approach to Suspension Kinematic Analysis is based on using elementary geometric procedures to analyse 2-Dimensional movements of suspension components and as such investigate their influence on the overall suspension system. For Multi-Link Suspension Analysis does serve a completely different approach.

- The most well-known “classic” method to calculate and “visualize” suspension characteristics like Roll Centre Height, Camber Gain, Anti-Lift & Anti-Dive is drawing lines through the link joints and using basic mechanical engineering procedures to calculate instantaneous centres of movement(s).



- As explained in “[The 5 Fundamentals of Suspension Design](#)” this method can only be applied on 2-D Suspension types. 2.5-D & 3-D Suspensions cannot (or only with some more or less severe limitations) be analysed.
- In fact, when trying to Analyse or even Optimise a 3-D Suspension, one must move away from “thinking in wishbone lines” and revert mentally to focus solely on the Upright/Wheel assembly Vector Movement (= How much does the wheel move in each direction per discrete step of vertical travel of the wheel).
- For instance, the rear-view Y-Z “Vector” movement of the Contact Patch does fully address the location of the Instantaneous Centre of Movement & Roll Centre Height. Like-wise does the side-view X-Z “Vector” Movement of the Contact Patch define the Brake Anti-Angle.



- All relevant Suspension Characteristics can be calculated out of the 3-Dimensional “Vector” Movement of either the Wheel Centre or the Contact Patch Point:
 - Contact Patch X-Z Vector Movement = Braking Anti-Angle & Pitch Centre Location
 - Contact Patch Y-Z Vector Movement = Roll Centre Position & Movement
 - Wheel Centre X-Z Vector Movement = Traction Anti-Angle & Pitch Centre Location
 - Wheel Centre Y-Z Vector Movement = Track Width / Track Width Change
 - Wheel Z-Axis Rotation = Toe / Bump Steer
 - Wheel X-Axis Rotation = Camber / Camber Gain
 - Wheel Y-Axis Rotation = Caster Angle / Caster Angle Change



STEP 2: UNDERSTANDING THE SUSPENSION FORCES & MOMENTS.

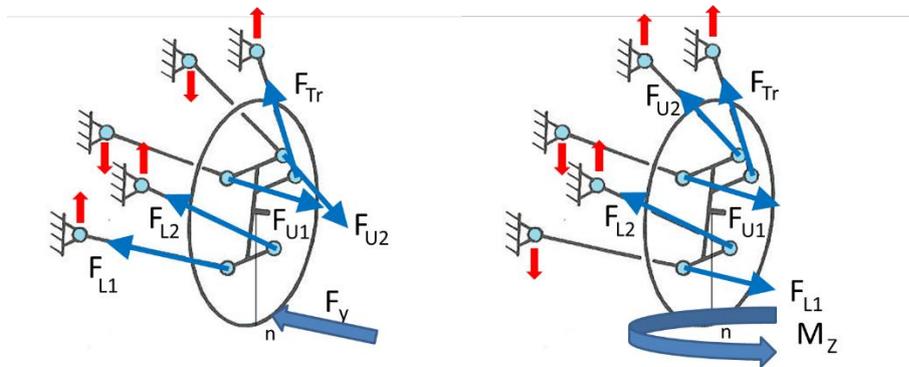
The Kinematic Suspension Analysis Method does typically not consider the effect of Suspension Loads on Geometric Behaviour, as most analysis tools do generally assume that all suspensions components are infinitely stiff (rigid elements) and/or that there are no loads in the suspension links.

As Suspensions do see in real life considerable Forces & Moments and resulting out of that, can see a non-neglectable amount of deformations, the effects of these suspension loads on the behaviour of kinematics must absolutely be considered.

The following 2 dominant effects to consider are:

1) Geometric (Link-) Load Transfer:

- Geometric (Link-) Load Transfer is addressing the part of the Load Transfer caused by the 3-Dimensional Position of the Suspension Links in the Vehicle. It is an effect entirely caused by Geometric Position of the Links.



[Click image\(s\) for more info](#)

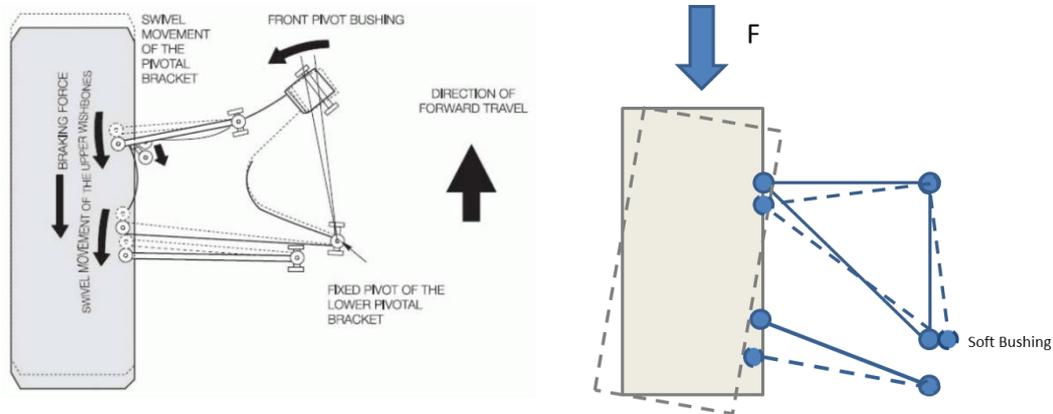
- Any Lateral (or Longitudinal) Force at the Contact Patch will create (in blue) reaction forces in the Suspension Links. Likewise, any Moment acting on the Suspension (Tire Aligning Torque, Overturning Moment or Brake Torque) will do the same (in blue) but can/will create other Link Loads. These Link Forces can from their side create at their respective chassis attachments (in red) Vertical Force components which will influence the amount of load that at the end must be provided by the Springs and Anti-Roll Bars.
- In fact, Geometric Link Load Transfer and Suspension Roll Centres / Pitch Centres are equivalent. The lower the RCH, the lower the Link Load Transfer and vice versa.

2) Suspension Link Stiffness / Compliant Deformation:

- As many Suspensions are equipped with Bushings and even when equipped with very stiff rose joints, any load on a suspension component will cause a deflection of that component. The sum of all deflections and corresponding movements of the suspension hard points will ultimately alter the position/coordinates of all geometric hardpoints and thus also affect the Kinematics.
- Hence, it is inevitable to not-consider these elastic deformations. In Suspension Linguistic this compliant behaviour is being referred to as “Elasto-Kinematics”.
- Elasto-Kinematic Suspension Behaviour can (even to a very high degree) improve, compensate or worsen the Performance of the desired Kinematic Characteristics and thus positively, neutrally or negatively affect the Handling of the vehicle.



- In the scheme below, depending on the Basic Geometry Lay-Out and the Stiffness of the Joint Bushing(s), the Braking Force could cause either Toe-In, Toe-Out or No Toe Change at all.



- Typically, complex (and very expensive) multi-body simulation tools are being used to analyse Elasto-Kinematics. The **DYNATUNE-XL SDM “Expert” MODULE** does provide a very efficient First Order Elasto-Kinematic Compliance Tool. More on this later.

STEP 3: THE MOST IMPORTANT KINEMATIC PARAMETERS

There are many kinematic metrics in Suspension Design. The below table does synthesize the most important “must use” Parameters for a (steerable) Suspension System with or without a racing type Push/Pull Rod driven Spring / Damper layout.

RESULTS @ REFERENCE WHEEL POSITION					0.00	mm in Jounce	
CALCULATION RESULTS - STATIC SUSPENSION SYSTEM PARAMETERS							
Bump Steer [°/m]	Camber Gain [°/m]	Roll Center Height [mm]	Roll Center Height Movement / Wheel Travel Ratio [-]	Spring/Damper Travel / Wheel Travel Ratio [-]	Wheel Center Anti-Angle [°]	Contact Patch Anti-Angle [°]	
2.09	-1.01	2.47	0.986	0.860	-0.52	-4.68	
CALCULATION RESULTS - STATIC STEERING SYSTEM PARAMETERS					Steering Ratio	9.54	
Toe [°]	Camber [°]	Caster [°]	Caster Trail [mm]	KPI [°]	Scrub Radius [mm]	KPI Off. [mm]	Caster Off. [mm]
0.00	0.00	6.79	33.81	8.13	36.43	82.14	-4.29
CALCULATION RESULTS - STATIC PUSH/PULL-ROD, ROCKER & ROLLBAR LINKAGE PARAMETERS							
U-Bar Motion Ratio [-]	T-Bar Motion Ratio [-]	Push-/Pull-Rod Motion Ratio [-]	3rd Spring/Damper Motion Ratio [-]	Rocker Angular Motion Ratio [°/mm]	U-Bar Beam Ang. Motion Ratio [°/mm]	T-Bar Beam Ang. Motion Ratio [°/mm]	
N/A	1.046	0.559	1.046	0.745	N/A	1.089	

[Click image for more info](#)

- The nomenclature and definition of each kinematic parameter is assumed to be known and fully understood by the reader.
- At this point it is worthwhile to mention that the table does not contain values for the commonly used Kinematic Parameters “Percentage” Anti-Lift, Anti-Squat or Anti-Dive. The reasoning behind this, is based on the fact, that these percentage numbers are calculated out of the Wheel-Centre or Contact-Patch Anti-Angles in combination with specific Vehicle Parameters & the Axle Brake Balance Distribution / Power Distribution of the Vehicle. Hence, it is incorrect to refer to them as a “strict” Suspension Parameter. The Anti-Angles are the sole correct metrics.



- In the **DYNATUNE-XL SDM “Expert” MODULE** the User will find a convenient tool for converting Anti-Angles into Anti-Percentages by adding some Vehicle and Powertrain / Brake System Data. More on this later.

STEP 4: THE MOST IMPORTANT ELASTO-KINEMATIC PARAMETERS

Outside of the OEM world, the importance of Elasto-Kinematics is hugely underestimated. In fact, the REAL performance of Suspensions systems is located in the tunability of their Elasto-Kinematics.

The below table does synthesize the most important “Must-Pay-Attention-To” Elasto-Kinematic Parameters/Metrics for a Suspension System.

		SUSPENSION COMPLIANCE TABLE					
		Vertical Load @ CP	Braking Load @ CP	Acceleration Load @ WC	Longitudinal Impact Load @ WC	Lateral Load @ Outside Wheel @ CP WITHOUT Pneumatic Trail	Lateral Load @ Outside Wheel @ CP WITH Pneumatic Trail
	Toe Compliance [°/kN]	-0.016	0.030	0.012	-0.012	0.033	0.024
	Camber Compliance [°/kN]	-0.006	0.009	-0.003	0.003	0.017	0.017
	Caster Compliance [°/kN]	0.008	-0.055	0.009	-0.009	-0.019	-0.017
	Contact Patch X Compliance [mm/kN]	0.071	-0.577	0.193	-0.193	-0.173	-0.161
	Contact Patch Y compliance [mm/kN]	0.092	-0.141	0.029	-0.029	-0.231	-0.221
	Wheel Center X Compliance [mm/kN]	0.016	-0.199	0.132	-0.132	-0.042	-0.046
	Wheel Center Y Compliance [mm/kN]	0.049	-0.081	0.008	-0.008	-0.114	-0.104

[Click image for more info](#)

- As the term Elasto-Kinematics already indicates, the resulting Wheel Movement is caused by a superimposing pure kinematic geometry changes with compliant deflections of suspension components due to acting loads on the links.
- As a rule of thumb in Elasto-Kinematics one should apply the **GOLDEN “TCC” RULE** of Suspension Design: **Toe – Camber – Caster**. These 3 parameters are interacting directly with the Performance of the Tire and are therefore vastly important. In the table above these 3 parameters are for that reason covering the first 3 rows.
- The “Orange” Cells are considered to be the Key “Vehicle Dynamics Metrics” of Elasto-Kinematics and should be tuned properly or, if that is not possible, remain contained to certain values.
- All Elasto-Kinematic **TCC** numbers should be small, as they typically will be multiplied with the acting Suspension Corner load numbers - which can result in rather great Toe & Camber Angles or Wheel Displacements.
- Longitudinal Wheel Movements can be allowed to be larger numbers as they can be required to positively affect Ride-Comfort and/or can be specifically used to tune Toe-Under-Braking / Acceleration Effects.
- At the end of the day, all materials and mechanical systems are compliant. One should always aim to make any deflections of the Suspension into one’s favour.
- One should NEVER Optimize for Kinematics Only, but always consider Elasto-Kinematics.



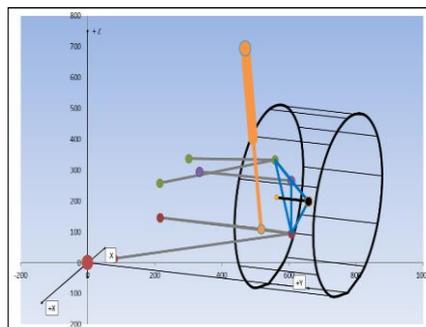
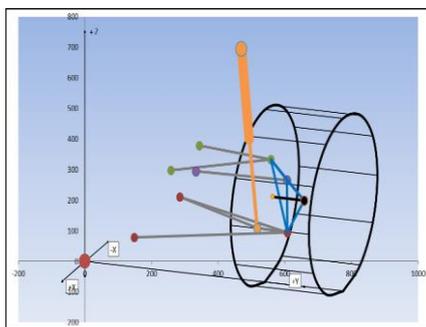
STEP 5: DEFINE THE SUSPENSION CONFIGURATION / APPLICATION

The Mission of the Vehicle on which you do intend to apply your suspension will largely define the boundary conditions for your Suspension Architecture. In order to keep things oversee-able, we will concentrate here solely on Race Car & Road Vehicle Applications.

Generally speaking the consensus is, that Race Car Suspension Links should be “Stiff” and Road Car Suspension Links should be more “Compliant” to provide some more or less degree of Comfort. Typically Race Applications work with Rose Joints and Road Car Application with Bushes.

- For various reasons Race Suspension Architectures are typically derived from 2-D Archetypes and Road Car Suspension Architectures – especially on the rear axle – are now quite commonly based on full 3-D (Multi-Link) Archetypes.

1) Select and A-Arm or L-Arm Concept in your Suspension Architecture:



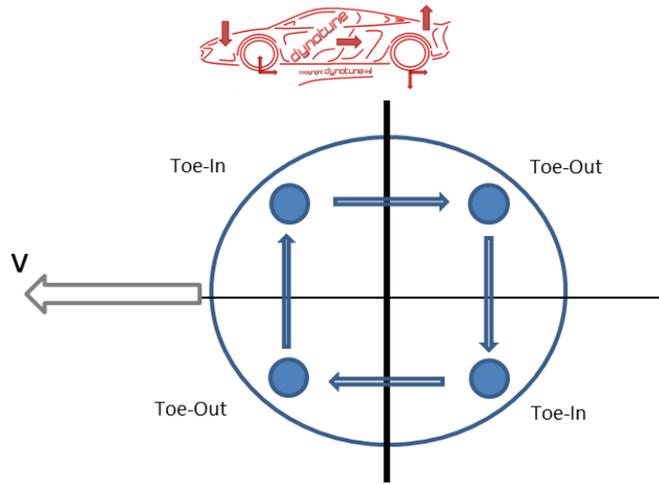
[Click image\(s\) for more info](#)

A-Arm vs. L-Arm Design

- We have learned in “[The 5 Fundamentals of Suspension Design](#)” the fundamental difference between an A-Arm wishbone design and an L-Arm wishbone design. Recapitulating, this does mean that the A-Arm design **DOES NOT** allow a proper decoupling of Longitudinal & Lateral Force Compliance Characteristics whereas the L-Arm design **CAN** allow that. So, if one does need a decoupling one should go for the L-Arm design. If you think that you do not need Elasto-Kinematic Decoupling or if you wish to go for maximum structural stiffness by using an A-Arm Concept, then do – prior to deciding - consider first the following requirement:
- If one does wish to have Adjustability of Suspension Geometry – as is the case on many Racing Cars – then you should opt for the L-Arm Design wishbone. As one leg of the “Wishbone” will be in the plane of the Wheel Centre Line, a different location of the other leg will not affect the Kinematics that define the Lateral Performance of the Suspension Kinematics. In effect the L-Arm design will allow a decoupling between Roll Centre Height & Camber Gain on one side, and the Suspension Anti-Angles on the other side. The A-Arm concept does not allow – at least not without significant effort – to create adjustable Suspension Geometries where only 1 Kinematic Parameter does change. Usually any Geometry Change does affect various performance parameters at once. Typically, 2 or 3 parameters change at once. For instance, changing Lower FWD A-Arm joint will typically affect Anti-Angles, RCH & Camber Gain.

2) Define the Track-Rod Position:

- We have also learned in in “[The 5 Fundamentals of Suspension Design](#)” that at Iso - Kinematic Performance, the position of the Track-Rod either in front or rear of the Wheel Centre Line will affect the Elasto-Kinematic Performance significantly.
- Besides the above, we will learn now that the position of the Track-Rod is actually even more important for the (lateral) compliant behaviour of the Suspension. Taking a Double Wishbone Suspension as a reference, one can – generally - see the following Compliant Lateral Force behaviour depending on the Vertical and Fore/Aft position of the Track-Rod in side view:



- The above schematic does show the “4 Quadrants” for Track-Rod position and is valid for typical conventional Suspension Caster Layouts. Diversions however are very well possible !
- **NOTE:** Creating Toe-Out on a Front Suspension does – in general – improve Vehicle Stability but does also lead to more Understeer / less Oversteer whilst Cornering.
- **NOTE:** Creating Toe-Out on a Rear Suspension does – in general – decrease Vehicle Stability and does also lead to less Understeer / more Oversteer whilst Cornering.

3) Define your Comfort & Anti-Angle Requirements:

- Requirements for Suspension Comfort (=Longitudinal Impact Harshness and not so much Vertical Spring Damper settings) are primarily related to Kinematic and Elasto-Kinematic Wheel Centre Recession. The more the Wheel-Centre can move in X-Direction when excited by road impacts, the better the suspension will perform with respect to Comfort Perception.
- Nowadays modern Road Vehicles do require to perform well at all load conditions. As many vehicles are not yet equipped with ride height control units like air springs, a more or less pronounced progression of various suspension characteristics is required as a function of riding height. Next to the desired Roll Centre Height Control over Ride Height, especially the Anti-Angles progressions are key to modern suspension performance perception.
- Typically, these requirements cannot be fulfilled with the rather straight forward 2-D Suspension Archetypes, especially not on the rear axle. For that exact reason, nowadays already many C-Class cars are equipped with state-of-the-art Multi-Link Suspensions. As more and more of these vehicles are being used for racing the tendency is clear, more and more racing cars will be based on Multi-Link (Rear-) Suspension Concepts and probably cause a lot of headache to those who are used to work with classical 2-D Suspensions up to now.

STEP 6: DEFINING BASE ELASTO-KINEMATIC TARGETS

Usually “traditional Non-OEM” Suspension Design does start with defining the Kinematic Targets. Unfortunately, this approach is sub-optimal. It is of vital importance to define prior to everything else the “Comfort” requirements and “how” Front and Rear Suspension should react under Longitudinal Braking & Traction and more importantly under Lateral Forces. The latter requirement will almost uniquely define – in combination with the selected Suspension Links Architecture - suitable positions of the Track-Rod and all else will be a consequence of that.

Comfort requirements will define whether an A-Arm design or and L-Arm design of any wishbone in the suspension layout is mandatory. Stability requirements will govern the compliant Toe-Characteristics and as such also indirectly dictate where the Track-Rod Inner and Outer coordinates must be located with respect to the Wheel Centre. In the guide below, the focus will be on setting targets for **TCC**.



1a) TCC - Set Target for Toe-Compliance Under Longitudinal Force:

- Typically, under Braking Forces, the Toe-Compliance should be between 0 and 0.025 deg/kN and as a rule of thumb tend towards Understeer. Larger numbers can be tolerated depending on the Cornering Stiffness of the Tire.
- Likewise, for Accelerating the Toe-Compliance should be similar to braking. Especially on RWD cars the tendency should be towards Toe-In (Understeer) whereas FWD cars can live very well with a compliant suspension behaviour towards reducing Understeer.
- Nowadays EV vehicles can regenerate significant amount of Energy which can require specific Elasto-Kinematic behaviour.

1b) TCC - Set Target for Toe-Compliance Under Lateral Force:

- Typically, under Lateral Forces, the Toe-Compliance should be between 0 and 0.025 deg/kN and as a rule of thumb tend towards creating more Understeer.
- Power Steering Systems do add a significant amount of Toe Compliance and must be carefully tuned. On the **DYNATUNE-XL FAQ** Webpage one can find more info on the topic.
- As the Tire does produce Lateral Force by deformation (pneumatic trail), the actual Force application point on the Wheel is not at Centre Line but further back, this will create additional compliant Toe-Out behaviour resp. reduce the compliant Toe-In behaviour.
- The Effect of Tire Aligning Torque - which ALWAYS does create a tendency for more Toe-Out resp. reduced Toe-In – must be also be considered and eventually compensated.

2a) TCC – Set Target for Camber Compliance Under Longitudinal Force:

- Typically, Camber is not really affected by Longitudinal Forces. Assuming a Negative Static Camber Base Setting, a slight reduction of Camber Angle under Braking / Traction Forces would typically increase the Tire Contact Patch and as such improve Longitudinal Grip.

2b) TCC - Set Target for Camber Compliance Under Lateral Force:

- Camber Compliance under Lateral Force should be as small as possible. Typically, when using extremely rigid components and a superb wheel bearing once can achieve less than 0.1 deg/kN. In real life however, a good wheel bearing does by itself “cost” 0.1 deg/kN, meaning that it will be hard to achieve values below 0.2 deg/kN.
- McPherson Strut Suspensions are particularly sensitive to Camber Stiffness due to the bending of the Damper Rod. **DYNATUNE-XL SDM “Expert” MODULE** does come with a specific tool to Analyse the effect of Damper Rod Bending on the Elasto-Kinematics of Strut Suspensions.

3a) TCC – Set Target for Caster Compliance Under Longitudinal Force:

- Generally speaking one would aim – especially at the Front Suspension - for a high Caster Stiffness under Braking in order to reduce the “Wind-Up” of the Suspension and guarantee a sufficient Caster Trail Value for sufficient steering feedback. However, often on OEM vehicles this requirement is in direct conflict with the Comfort Requirements and as such a compromise will have to be achieved. Good Values are 0.1deg/kN or less.

3b) TCC – Set Target for Caster Compliance Under Lateral Force:

- Caster Angle is rather insensitive to Lateral Load and target values should be quite low or close to 0 deg/kN. Full 3-D Multilink Suspensions typically show higher values as there is typically no wishbone which can “lock” a plane properly in the system. Furthermore, one should consider that Caster Angle is typically positive in Front Suspensions but can very well be negative on Rear Suspensions and as such invert the Effect of Aligning Torque created by Lateral Force on the Suspension Links and hence alter their loads.



STEP 7: DEFINING BASE KINEMATIC TARGETS

After having reflected over the Elasto-Kinematic Targets, it is now time to discuss and set the Base Targets for the Kinematic Analysis following the table presented in Step 3. The following targets are good common recommendations but are by no means the holy grail, far more a guidance towards a sound Suspension Layout. Specific (often aerodynamically driven) applications can vastly differ from these.

Static Settings:

1) Toe

- Static Toe Setting is for Suspension Analysis not very relevant. It is recommended to always set the simulation model to 0 deg as it will affect Ackermann Analysis. Typical real world Static Toe Settings range from -0.25 deg to +0.25 deg but can be – depending on the application – also be doubled or even quadrupled, especially when used to create heat in a Slick Tire.

2) Camber

- Significant amounts of static (negative-) Camber should be considered in the Kinematic Analysis as the location of the Contact Patch is directly affected. Static Camber Angle does also influence Bump-Steer, especially when values above -5 degree are applied like in typical race car setups. Common OEM reference values are typically around -0.5 deg to -1.0 deg on the front axle and -1.0 deg to -1.5 deg on the rear axle. As said in racing applications is up to -5 degree no exception.

Suspension Lateral & Longitudinal Performance Kinematics:

1) Bump Steer (Toe Gradient over Wheel Travel)

- Bump Steer is in the OEM World one of the primary suspension tuning parameters and can both be used for tuning the vehicle response on steering inputs, stability and/or limit handling understeer/oversteer balance. Typical OEM values are ranging from maximum -5 deg/m to +5 deg/m. In Racing Applications often a +/- 0 deg/m is targeted. Also due to inherent lesser wheel travel on race cars it is generally more effective to change the Static Toe Settings.

2) Camber Gain (Camber Gradient over Wheel Travel)

- Nowadays Camber Gain seems both in the OEM world as in Racing Applications to have converged to around -20 deg/m on the Front Axle and around -25 deg/m on the Rear Axle. As the amount of achievable Camber Gain is - quite heavily - directly linked to the Roll Centre Heights, but can be slightly tuned by varying the length of the upper link(s) Also here, due to inherent lesser wheel travel on race cars it is generally more effective to change the Static Camber Settings.

3) Roll Centre Height & Roll Centre to Wheel Movement Motion Ratio

- In modern Suspension Design is a clear trend to keep Roll Centres quite low. Although high RCH do support the initial load transfer during cornering – and thus speed up the vehicle response - they do also create jacking forces that do only harm to the performance of the vehicle. Nowadays typical values for RCH are on a Front Axle between 0 mm and 50 mm and on a Rear Axle between 50 mm and 100mm. Typically Racing Applications tend to be located at the lower end of the indicated ranges. As a rule of thumb, one does aim at an Inclination of the Roll-Axis of approximately 1 degree which for most wheelbases comes down to a difference of 50 mm between Front and Rear Axle.
- The Ratio of Vertical Movement of RCH vs Wheel Travel is an often forgotten and underestimated parameter. As the RCH does in effect influence the Lateral Load Transfer Distribution any different RCH/Wheel travel ratio other than 1:1, will ultimately affect the balance of the car at various riding heights. Tuning this parameter does require some expertise. Usually it is specially tuned on Aero Vehicles and in the OEM world used to compensate for Pay-Load changes. Creating a 1:1 ratio can be quite difficult, as specific relationships between link lengths have to be respected. Usually, values range – due to package constraints – between 1.5 to 2.5.



4) Suspension Anti-Angles

- Suspension Anti-Angles define the Instantaneous Pitch Centres of Front & Rear Axle. Braking events are characterized by the Anti-Angles of the Contact Patch Movement and Traction / Regeneration events are covered by the Anti-Angles of the Wheel Centres. As mentioned before, with additional Vehicle, Brake System & Powertrain data these Angles can be transformed in more commonly known Anti-Percentages. Typical values for Front Axle Anti-Angles are in the range of 0 deg to 5 deg, whereas at the Rear Axle the Anti-Angles are typically twice as high, primarily driven by the fact that Rear Axle Brake Forces are typically half of those of the Front Axle.

5) Spring/Damper Motion Ratio

- The Spring Motion Ratio and even more important Damper Motion Ratio – defining Damper Displacement per increment of Vertical Wheel movement - is a Key Parameter for efficient Spring & Damper functioning in the suspension system. Many of you will know that the value of that motion ratio does affect quadratically the performance of those components at the wheel, but fewer will know that due to that same quadratic dependency the resulting link forces can be negatively affected with potential draw backs on Elasto-Kinematics. Typically, as a rule of thumb the motion ratio of Spring/Damper to Wheel Travel should be above 0.7. Quite conveniently the square of 0.7 is 0.49 and thus close to 0.5 which makes hand-calculations quite easy. Ideally would be a 1:1 ratio, but that can usually only be achieved with Push-Rod Suspensions (hence one reason for using them) or McPherson Struts.

STEP 8: DEFINING BASE STEERING SYSTEM TARGETS

The following Suspension Parameters are typically referring to Steerable Suspension Systems and have been historically used to describe the performance of the Steering System with respect to it's many requirements. Of course, many of these metrics are also interesting for Non-Steerable (Rear) Suspensions and should primarily be seen as visualization metrics for Force Application Points and Moment Lever Arms, which as we know, can influence the Elasto-Kinematics significantly.

1) Caster Angle, Caster Trail & Caster Offset

- Caster Angle is typically introduced in a Suspension System in order to create Caster Trail which in effect does add a Geometric Lever Arm for the Side Force and as such does create an Aligning Torque on the Steering System which does give feedback to the Driver about the actual Grip Level on the Front Axle. Typical Caster Angles on modern Suspension Layouts vary from 2.5 deg to 7.5 deg. On Rear Suspensions Caster Angles can sometimes be negative.
- Typical Caster Trail values (on Front Suspensions) are between +20 mm and +40 mm.
- As Caster Angle and Caster Trail are coupled, one does sometimes have to displace the Caster Axis slightly by moving it fore/aft from the Wheel Center (=Caster Offset) in order to match both requirements.
- A Positive Caster Angle (typically on Front Suspensions) does create a positive Caster Trail which does create an Aligning Torque vs. Toe-Out. A Negative Caster Angle does the opposite.
- A Positive Caster Angle does create additional Negative Camber on the Outside Wheel during Steering Events. For a 5 deg Caster Axis the gain is -0.1 deg Camber / 1 deg Wheel Steer Angle.
- A Positive Caster Angle does create additional Roll on the Vehicle during Steering Events, however without additionally deflecting springs or roll bars (ref. Go-Kart).
- A Positive Caster Angle does reduce the effect of the KPI Induced Weight Jacking during Steering Events.



2) King Pin Inclination (KPI), Scrub Radius & KPI Offset

- King Pin Inclination Angle is a direct result of the “Historic” requirement for additional Negative Camber Gain in Wheel Compression Movements, leading to the up to now classic architecture of Shorter Upper links and Longer Lower Links. In Planar 2-D Suspension Architectures the KPI Angle typically varies from 7.5 deg to 15 deg. Lower values are difficult to achieve due to package limitations unless one would go for an AUDI type 3-D Multi Link Front Suspension.
- The Scrub Radius – historically important for Mue-Split Braking Behaviour - does define the Moment Lever Arm of the Braking Force on the Steering System and is nowadays with mandatory ABS Systems recommended to be in the range from -25 mm to 25 mm in order to not disturb the Steering System when ABS is activated.
- The King Pin Offset Value does define the Moment Lever Arm of any Traction / Road Impact / Regen Force on the Steering System and is as such a Key Metric for Evaluating Torque Steer & Road Disturbance Input to the Steering System. Classical 2-D Architectures are able to keep the KPI Offset Value below 80mm. If required on can divert to 3-D Multi Link Front Suspension and reduce that value significantly.
- The King Pin Offset Value does also define the Moment Lever Arm of the Vehicle Corner Weight on the Steering System and is as such – in combination with the KPI Angle - the primary cause for the amount of perceived Weight Jacking during Steering Events. On Non-Power-Steering Vehicles this effect is very much perceivable during manoeuvring at parking speeds.

3) Steering Ratio

- As the Steering Ratio does describe how much Angular Input the driver has to give at the Steering Wheel in order to achieve 1 degree of Wheel Steer Angle, it is a rather important metric to define the responsiveness of the Vehicle. Typical values are ranging from a Steering Ratio of 10 for a Formula 1 car to around 16 for a standard OEM Vehicle.
- The Steering Ratio is a compound value of Rack & Pinion Ratio and the Steer-Arm Length, which is the distance of the Track-Rod to the Steering Axis. Typical numbers for the Steer Arm Length are between 100 mm and 150 mm. When going below 100 mm, one will have to carefully check if the Full-Lock Steering System Joint Angles do not exceed maximum allowed operating angles.
- Steering Ratio can be Non-Linear due to a Non-Linear Rack & Pinion Gear Ratio.

4) Percentage Ackermann Steer

- Ackermann Steer is the key requirement for any Steering System and as such will have to be considered in the Suspension Link Layout. In modern Suspension Design a typical requirement is to achieve approximately 50% Ackermann Steer On-Centre and ideally increase this to higher numbers going to full lock. However, the nowadays almost exclusively used Rack & Pinion Steering Systems do not allow such Kinematic Freedom, which does mean that one has to converge to a compromise.
- One Race Applications (mostly Aerodynamic Cars) it is quite common to run Negative Ackermann which is related to specific characteristics of Slick Racing Tires.
- Percentage Ackermann Curves do massively change with Static Toe-Setting. It is therefore recommended to Analyse Ackermann Curves ALWAYS at 0 Static Toe-Angle.
- When mounting the Track-Rod Low in Front of the Wheel Centre, it is more difficult to achieve the desired Ackermann Steer Percentages. A behind the Wheel Centre located Steering Rack does not pose this limitation and is one of the drivers for that location on many OEM vehicles.



STEP 9: CREATING BASE SUSPENSION GEOMETRY HARDPOINTS

The following recipe will try to create a classical double wishbone front suspension “From Scratch”. In case one does start from an existing base geometry each step of this guide will be useful for checking the quality of the base geometry and potentially provide action points for improvements.

Section 1: Base Geometry (No Steering Analysis)

- 1) As the Track-Rod position will dominate the Lateral Force Compliance Behaviour, we have to define in which of the 4 quadrants the Track-Rod will be located. Let's assume in Front of the Wheel Centre and located just below the Wheel Centre Height is our targeted position.
- 2) Set all Link Stiffness to 10 kN/mm. This is a good reference number when we at a later stage evaluate the Elasto-Kinematics. In **DYNATUNE-XL SDM** one can also set the Link Stiffness to 0 ad de-activate the compliance calculation. More on this later.
- 3) Start always with an Upper & Lower L-Arm placing of each Arm one Link at the Wheel Centre Line. Place the other link 200mm to 300mm for/aft of Wheel Centre Line. By using the L-Arm approach it is easier to initially dial in all requirements. At a later stage one can divert to A-Arm or Multi-Link. Define the location of the Wheel Centre.
- 4) Ensure that both L-Arm Links are parallel to ground. The RCH will be at 0mm and the Lower Arm(s) should respect the requested ground clearance. The Upper Arms should be as high as possible whilst respecting package space at the wheel and chassis.
- 5) Create Outboard Joints that do give 0 deg Caster and 0 deg KPI. Put the outer joints as far out as possible (but do leave about 10mm to 25 mm playroom). Typically, the Brake Disc Rotor is the boundary for their location. Once a base geometry has been created, fine tuning will sort it.
- 6) Do place the Track-Rod in the same plane as one of the L-Arms and make it equally long as one of the arms. Place the Track-Rod approximately 150mm from the Wheel Centre.
- 7) Place a Spring Damper Unit on the Lower Link at 75% of the Link Length in Wheel Centre Line vertically. This will give a good Motion Ratio.
- 8) Static Toe and Camber are set to 0 deg.

At this point the Suspension Layout does look like this:

SELECT SUSPENSION TYPE	Load Generic 5-Link Template	Load McPherson Template	Load Integral Link Template	SELECT COORDINATE SYSTEM			Enter Project Name / ID
	GENERIC 5-LINK			DSDM			GENERIC 5-LINK
Link ID Nr.	LINK DESCRIPTION			X [mm]	Y [mm]	Z [mm]	Link Stiffness [N/mm] Subselected Link Length [mm]
1	Track Rod @ Chassis Joint			100.000	230.000	185.000	10000
2	Track Rod @ Wheel Joint			125.000	650.000	185.000	420.743
3	Spring Link @ Chassis Joint			0.000	230.000	185.000	10000
4	Spring Link @ Wheel Joint			0.000	650.000	185.000	420.000
5	Lower Link 2 (or 2nd A-Arm Leg) @ Chassis Joint			300.000	230.000	185.000	10000
6	Lower Link 2 @ Wheel Joint			0.000	650.000	185.000	516.140
7	Upper Link 1 @ Chassis Joint			200.000	230.000	425.000	10000
8	Upper Link 1 @ Wheel Joint			0.000	650.000	425.000	465.188
9	Upper Link 2 (or 2nd A-Arm Leg) @ Chassis Joint			0.000	230.000	425.000	10000
10	Upper Link 2 @ Wheel Joint			0.000	650.000	425.000	420.000
11	Spring/Damper @ Chassis Joint			0.000	550.000	800.000	
12	Spring/Damper @ Spring Link Joint			0.000	550.000	185.000	615.000
WC	Wheel Center Point			0.000	700.000	300.000	
WC ALIGN	Calculated Wheel Center Alignment Point			0.000	600.000	300.000	100.000
CP	Calculated Contact Patch			0.000	700.000	0.000	

And Initial Tabular Results will be looking this:

CALCULATION RESULTS - STATIC SUSPENSION SYSTEM PARAMETERS						
Bump Steer [°/m]	Camber Gain [°/m]	Roll Center Height [mm]	Roll Center Height Movement / Wheel Travel Ratio [-]	Spring/Damper Travel / Wheel Travel Ratio [-]	Wheel Center Anti-Angle [°]	Contact Patch Anti-Angle [°]
0.00	0.00	N/A	N/A	0.759	0.00	0.00

This document will be referring frequently to the **DYNATUNE-XL FAQ** webpage for customers:
<http://www.dynatune-xl.com/support-sdm.html>



As we have learned that Elasto-Kinematics are (very) important, one should at each of the following steps carefully look if the table with the Elasto-Kinematic does change significantly. If this does happen one should investigate specifically why the change has occurred.

Our starting point will by this table:

		SUSPENSION COMPLIANCE TABLE						Execute a Jounce Motion ONLY Calculation for correct Compliance numbers		
		Vertical Load @ CP	Braking Load @ CP	Acceleration Load @ WC	Longitudinal Impact Load @ WC	Lateral Load @ Outside Wheel @ CP WITHOUT Pneumatic Trail	Lateral Load @ Outside Wheel @ CP WITH Pneumatic Trail	Pneumatic Trail	Toe Aligned Torque Stiffness	
		Toe Compliance [°/N]	0.010	-0.178	0.081	-0.081	-0.088	-0.108	25.0 mm	0.802 %/Nm
		Camber Compliance [°/N]	-0.010	0.108	-0.004	0.004	0.061	0.066	AT Stiffness Definition iso SAE (+) AT creating Toe-Out	
		Caster Compliance [°/N]	0.017	-0.405	-0.035	0.035	-0.098	-0.106	Track Rod Link Stiffness	10000.0 N/mm
		Contact Patch X Compliance [mm/N]	0.094	-2.401	0.281	-0.281	-0.641	-0.718	Spring Link Stiffness	10000.0 N/mm
		Contact Patch Y compliance [mm/N]	0.053	-0.641	0.128	-0.128	-0.373	-0.411	Lower Link 2 (or 2nd A-Arm leg) Stiffness	10000.0 N/mm
		Wheel Center X Compliance [mm/N]	0.003	-0.281	0.464	-0.464	-0.128	-0.163	Upper Link 1 Stiffness	10000.0 N/mm
		Wheel Center Y Compliance [mm/N]	0.001	-0.074	0.109	-0.109	-0.055	-0.067	Upper Link 2 (or 2nd A-Arm Leg) Stiffness	10000.0 N/mm

Step 1 – Designing / Tuning in the Front View Plane:

Our primary interest will be creating RCH and Camber Gain. However, prior to doing so we must do some preparation work on the steering axis location. We will concentrate on getting the static numbers in design reference position right, at a later stage we will look into wheel travel graphs.

- As the Scrub Radius is effectively the Lever Arm of Braking Forces on the Steering Axis it will also influence the Elasto-Kinematics. Aiming for < 5 mm Scrub Radius, we have to move the upper outboard joint 70mm more inboard in order to let us achieve that target. By doing so the KPI has become 14 deg and KPI Offset 79mm. Scrub Radius and KPI are on a 2-D Suspension interconnected. Only a 3-D Suspension with virtual steering axis does allow to tune them independently.

KPI [°]	Scrub Radius [mm]	KPI Off. [mm]
14.04	3.75	78.75

- With parallel horizontal links the RCH is at 0mm. Next, we set/tune the RCH. Let's say we aim for approximately 50mm. We start doing so by raising the outboard upper link joint – by moving it along the KPI axis - by 40mm up and 10mm more inboard which does get us close:

RESULTS @ REFERENCE WHEEL POSITION		0.00	mm in Jounce			
CALCULATION RESULTS - STATIC SUSPENSION SYSTEM PARAMETERS						
Bump Steer [°/m]	Camber Gain [°/m]	Roll Center Height [mm]	Roll Center Height Movement / Wheel Travel Ratio [-]	Spring/Damper Travel / Wheel Travel Ratio [-]	Wheel Center Anti-Angle [°]	Contact Patch Anti-Angle [°]
0.00	-22.29	50.39	1.451	0.747	0.00	0.00

SELECT SUSPENSION TYPE	Load Generic 5-Link Template	Load McPherson Template	Load Integral Link Template	SELECT COORDINATE SYSTEM	Enter Project Name / ID	
	GENERIC 5-LINK			DSDM	GENERIC 5-LINK	
Link ID Nr.	LINK DESCRIPTION	X [mm]	Y [mm]	Z [mm]	Link Stiffness [N/mm] Undescribed	Link Length [mm]
1	Track Rod @ Chassis Joint	100.000	230.000	185.000	10000	10000
2	Track Rod @ Wheel Joint	125.000	650.000	185.000	420.743	420.743
3	Spring Link @ Chassis Joint	0.000	230.000	185.000	10000	10000
4	Spring Link @ Wheel Joint	0.000	650.000	185.000	420.000	420.000
5	Lower Link 2 (or 2nd A-Arm Leg) @ Chassis Joint	300.000	230.000	185.000	10000	10000
6	Lower Link 2 @ Wheel Joint	0.000	650.000	185.000	516.140	516.140
7	Upper Link 1 @ Chassis Joint	200.000	230.000	425.000	10000	10000
8	Upper Link 1 @ Wheel Joint	0.000	580.000	465.000	405.053	405.053
9	Upper Link 2 (or 2nd A-Arm Leg) @ Chassis Joint	0.000	230.000	425.000	10000	10000
10	Upper Link 2 @ Wheel Joint	0.000	580.000	465.000	352.278	352.278
11	Spring/Damper @ Chassis Joint	0.000	550.000	800.000	615.000	615.000
12	Spring/Damper @ Wheel Joint	0.000	550.000	185.000	615.000	615.000
WC	Wheel Center Point	0.000	700.000	300.000		
WC ALIGN	Calculated Wheel Center Alignment Point	0.000	620.000	300.000	100.000	100.000
CP	Calculated Contact Patch	0.000	700.000	0.000		



11) By the above steps we have created a geometry that does already provide -21.8 deg/m Camber Gain. As it happens to be in the recommended target range we can leave it as it is. Typically, on a Vehicle there is less package space for the Upper Link(s). Let's assume we must move the upper inboard joints 100 mm out for clearing the bodywork. If we do not want to change the RCH we must move along the link centre line which does mean, that the Z-coordinate of the inboard joints must go up by approximately 11 mm.

RESULTS @ REFERENCE WHEEL POSITION				0.00	mm in Jounce	
CALCULATION RESULTS - STATIC SUSPENSION SYSTEM PARAMETERS						
Bump Steer [°/m]	Camber Gain [°/m]	Roll Center Height [mm]	Roll Center Height Movement / Wheel Travel Ratio [-]	Spring/Damper Travel / Wheel Travel Ratio [-]	Wheel Center Anti-Angle [°]	Contact Patch Anti-Angle [°]
0.00	-22.61	51.11	0.988	0.747	0.00	0.00

As one can see the effect of shortening the upper link has had no real significant effect on camber gain. It did though quite drastically affect the RCH Ratio to Wheel Travel from 1.475 to 0.99.

Our Suspension does now look like this:

SELECT SUSPENSION TYPE	Load Generic S-Link Template	Load McPherson Template	Load Integral Link Template	SELECT COORDINATE SYSTEM	Enter Project Name / ID
	GENERIC 5-LINK			DSDM	GENERIC 5-LINK
Link ID Nr.	LINK DESCRIPTION	X [mm]	Y [mm]	Z [mm]	Link Stiffness [N/mm] 0=deactivated Link Length [mm]
1	Track Rod @ Chassis Joint	100.000	230.000	185.000	10000
2	Track Rod @ Wheel Joint	125.000	650.000	185.000	420.743
3	Spring Link @ Chassis Joint	0.000	230.000	185.000	10000
4	Spring Link @ Wheel Joint	0.000	650.000	185.000	420.000
5	Lower Link 2 (or 2nd A-Arm Leg) @ Chassis Joint	300.000	230.000	185.000	10000
6	Lower Link 2 @ Wheel Joint	0.000	650.000	185.000	516.140
7	Upper Link 1 @ Chassis Joint	200.000	330.000	436.000	10000
8	Upper Link 1 @ Wheel Joint	0.000	590.000	465.000	329.304
9	Upper Link 2 (or 2nd A-Arm Leg) @ Chassis Joint	0.000	330.000	436.000	10000
10	Upper Link 2 @ Wheel Joint	0.000	590.000	465.000	287.612
11	Spring/Damper @ Chassis Joint	0.000	550.000	800.000	615.000
12	Spring/Damper @ Spring Link Joint	0.000	550.000	185.000	615.000
WC	Wheel Center Point	0.000	700.000	300.000	
WC ALIGN	Calculated Wheel Center Alignment Point	0.000	600.000	300.000	100.000
CP	Calculated Contact Patch	0.000	700.000	0.000	

Step 2 – Designing / Tuning in the Side View Plane:

Like we did earlier in the “Front View Plane” by first defining the KPI Angle and RCH, we do start in the “Side View Plane” with defining the Caster Angle followed by Traction & Braking Anti-Angles.

12) Introducing Caster Angle will cause Caster Trail, and as it is the Moment Lever Am of the Lateral Force on the Steering Axis - and thus does affect the Compliance Characteristics too – we will start there. In order to create a Caster Angle of around 5 deg and a Caster Trail of approximately 30mm we will have to move the upper outboard joint 12.5 mm rearward and the lower outboard joint 12.5 mm forward. These displacements should hardly affect the “Front View” Results:

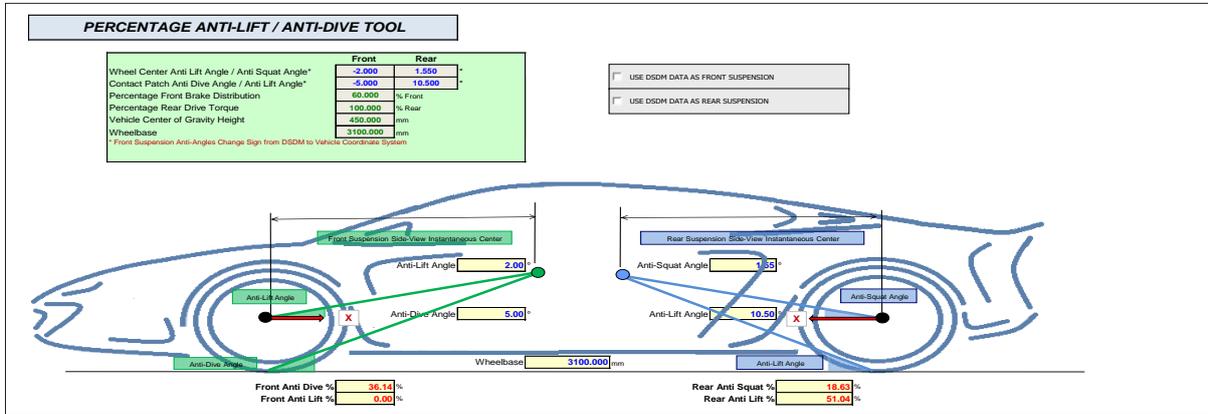
Caster [°]	Caster Trail [mm]	Caster Off. [mm]
5.10	29.02	2.23

Our Suspension will look like this:

SELECT SUSPENSION TYPE	Load Generic S-Link Template	Load McPherson Template	Load Integral Link Template	SELECT COORDINATE SYSTEM	Enter Project Name / ID
	GENERIC 5-LINK			DSDM	GENERIC 5-LINK
Link ID Nr.	LINK DESCRIPTION	X [mm]	Y [mm]	Z [mm]	Link Stiffness [N/mm] 0=deactivated Link Length [mm]
1	Track Rod @ Chassis Joint	100.000	230.000	185.000	10000
2	Track Rod @ Wheel Joint	125.000	650.000	185.000	420.743
3	Spring Link @ Chassis Joint	0.000	230.000	185.000	10000
4	Spring Link @ Wheel Joint	12.500	650.000	185.000	420.186
5	Lower Link 2 (or 2nd A-Arm Leg) @ Chassis Joint	300.000	230.000	185.000	10000
6	Lower Link 2 @ Wheel Joint	12.500	650.000	185.000	508.976
7	Upper Link 1 @ Chassis Joint	200.000	330.000	436.000	10000
8	Upper Link 1 @ Wheel Joint	-12.500	590.000	465.000	329.389
9	Upper Link 2 (or 2nd A-Arm Leg) @ Chassis Joint	0.000	330.000	436.000	10000
10	Upper Link 2 @ Wheel Joint	-12.500	590.000	465.000	281.987
11	Spring/Damper @ Chassis Joint	0.000	550.000	800.000	615.000
12	Spring/Damper @ Spring Link Joint	0.000	550.000	185.000	615.000
WC	Wheel Center Point	0.000	700.000	300.000	
WC ALIGN	Calculated Wheel Center Alignment Point	0.000	600.000	300.000	100.000
CP	Calculated Contact Patch	0.000	700.000	0.000	



The next characteristics to put in place are the Anti-Angles. As an example – and considering that we are designing a front suspension – we will implement some Anti-Dive Angle. All **DYNATUNE-XL SDM MODULES** do provide a convenient Suspension Anti-Dive Angle to Vehicle Anti-Dive Percentage Tool:



13) Let's assume we would like to achieve approximately 35% anti-dive for our vehicle. Using the tool with indicated vehicle data we would need to achieve an Anti-Dive Angle of approximately -5 deg. We can achieve this value by moving lower forward pick up point of the L-arm down by 17 mm. Changing lower link(s) does typically affect the "Braking" Anti-Angles and hardly the "Traction" Anti-Angles as can be seen. Vice versa is also valid however to a far lesser extent.

CALCULATION RESULTS - STATIC SUSPENSION SYSTEM PARAMETERS						
Bump Steer [°/m]	Camber Gain [°/m]	Roll Center Height [mm]	Roll Center Height Movement / Wheel Travel Ratio [-]	Spring/Damper Travel / Wheel Travel Ratio [-]	Wheel Center Anti-Angle [°]	Contact Patch Anti-Angle [°]
0.84	-22.31	49.38	0.999	0.749	-1.95	-5.29

SELECT SUSPENSION TYPE	Load Generic 5-Link Template			SELECT COORDINATE SYSTEM			Enter Project Name / ID
	Load McPherson Template	Load Integral Link Template	DSDM	X [mm]	Y [mm]	Z [mm]	
	GENERIC 5-LINK						GENERIC 5-LINK
Link ID Nr.	LINK DESCRIPTION			X [mm]	Y [mm]	Z [mm]	Link Stiffness [N/mm] (Selected/Not)
1	Track Rod @ Chassis Joint			100.000	230.000	185.000	10000
2	Track Rod @ Wheel Joint			125.000	650.000	185.000	420.743
3	Spring Link @ Chassis Joint			0.000	230.000	185.000	10000
4	Spring Link @ Wheel Joint			12.500	650.000	185.000	420.186
5	Lower Link 2 (or 2nd A-Arm Leg) @ Chassis Joint			300.000	230.000	168.000	10000
6	Lower Link 2 @ Wheel Joint			12.500	650.000	185.000	509.260
7	Upper Link 1 @ Chassis Joint			200.000	330.000	436.000	10000
8	Upper Link 1 @ Wheel Joint			-12.500	580.000	465.000	329.389
9	Upper Link 2 (or 2nd A-Arm Leg) @ Chassis Joint			0.000	330.000	436.000	10000
10	Upper Link 2 @ Wheel Joint			-12.500	580.000	465.000	251.987
11	Spring/Damper @ Chassis Joint			0.000	550.000	800.000	
12	Spring/Damper @ Spring Link Joint			0.000	550.000	185.000	615.000
WC	Wheel Center Point			0.000	700.000	300.000	
WC ALIGN	Calculated Wheel Center Alignment Point			0.000	650.000	300.000	100.000
CP	Calculated Contact Patch			0.000	700.000	0.000	

At this stage, it is worthwhile mentioning, that Bump-Steer has now started to change. By putting suspension links "Out of Planes", the interactions start to become (more) noticeable and will from here onwards become increasingly more complex.

If one would want or have to create a Suspension based on A-Arm designs, one would typically at this stage start to create the equivalent A-Arm Lay-Out by moving the inboard suspension points accordingly by moving them along the action of rotation and verify the base Kinematics. One should though be fully aware that the Elasto-Kinematics will also change accordingly and execute all the necessary verifications.



Step 3 Design / Optimize the Position of the Track-Rod

14) The next and final step of the Base Suspension Geometry Lay-out is positioning the Steering Rack / Track-Rod as required or desired. In this exercise we will locate the Steering Rack / Track-Rod about 65 mm above the Lower Outer Ball-Joint and adjust the Geometry where necessary.

SELECT SUSPENSION TYPE	Load Generic 5-Link Template	Load McPherson Template	Load Integral Link Template	SELECT COORDINATE SYSTEM			Enter Project Name / ID
	GENERIC 5-LINK			DSDM			GENERIC 5-LINK
Link ID Nr.	LINK DESCRIPTION			X [mm]	Y [mm]	Z [mm]	Link Stiffness [N/mm] 6:Unspecified Link Length [mm]
1	Track Rod @ Chassis Joint			100.000	230.000	250.000	10000
2	Track Rod @ Wheel Joint			125.000	550.000	250.000	420.743
3	Spring Link @ Chassis Joint			0.000	230.000	185.000	10000
4	Spring Link @ Wheel Joint			12.500	650.000	185.000	420.196
5	Lower Link 2 (or 2nd A-Arm Lag) @ Chassis Joint			300.000	230.000	168.000	10000
6	Lower Link 2 @ Wheel Joint			12.500	650.000	185.000	509.260
7	Upper Link 1 @ Chassis Joint			200.000	330.000	436.000	10000
8	Upper Link 1 @ Wheel Joint			-12.500	580.000	465.000	329.389
9	Upper Link 2 (or 2nd A-Arm Leg) @ Chassis Joint			0.000	330.000	436.000	10000
10	Upper Link 2 @ Wheel Joint			-12.500	580.000	465.000	251.987
11	Spring/Damper @ Chassis Joint			0.000	550.000	800.000	
12	Spring/Damper @ Spring Link Joint			0.000	550.000	185.000	615.000
WC	Wheel Center Point			0.000	700.000	300.000	
WC ALIGN	Calculated Wheel Center Alignment Point			0.000	800.000	300.000	100.000
CP	Calculated Contact Patch			0.000	700.000	0.000	

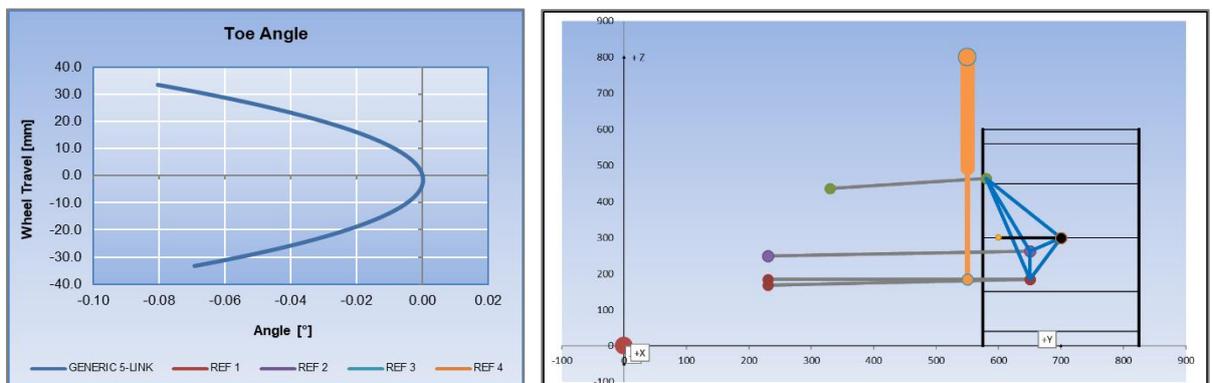
In the tabular results we can see immediately that this modification did change the bump-steer gradient massively:

CALCULATION RESULTS - STATIC SUSPENSION SYSTEM PARAMETERS						
Bump Steer [°/m]	Camber Gain [°/m]	Roll Center Height [mm]	Roll Center Height Movement / Wheel Travel Ratio [-]	Spring/Damper Travel / Wheel Travel Ratio [-]	Wheel Center Anti-Angle [°]	Contact Patch Anti-Angle [°]
-11.90	-21.21	44.95	1.051	0.750	-0.95	-5.25

A very helpful rule of thumb is that one does need to move the inner or outer joints vertically by just 1mm to change the bump steer gradient by 1 deg/m. In this case, it does mean that one of the joints does need to be relocated 12 mm higher or lower to bring -12 deg/m to 0 deg/m. Moving the outboard Track-Rod Joint up (bringing the front view angle more in-line with the upper link) does do the job:

CALCULATION RESULTS - STATIC SUSPENSION SYSTEM PARAMETERS						
Bump Steer [°/m]	Camber Gain [°/m]	Roll Center Height [mm]	Roll Center Height Movement / Wheel Travel Ratio [-]	Spring/Damper Travel / Wheel Travel Ratio [-]	Wheel Center Anti-Angle [°]	Contact Patch Anti-Angle [°]
-0.20	-22.22	49.02	1.061	0.749	-1.86	-5.29

Having solved this initial problem, it is time to evaluating the bump steer graph:

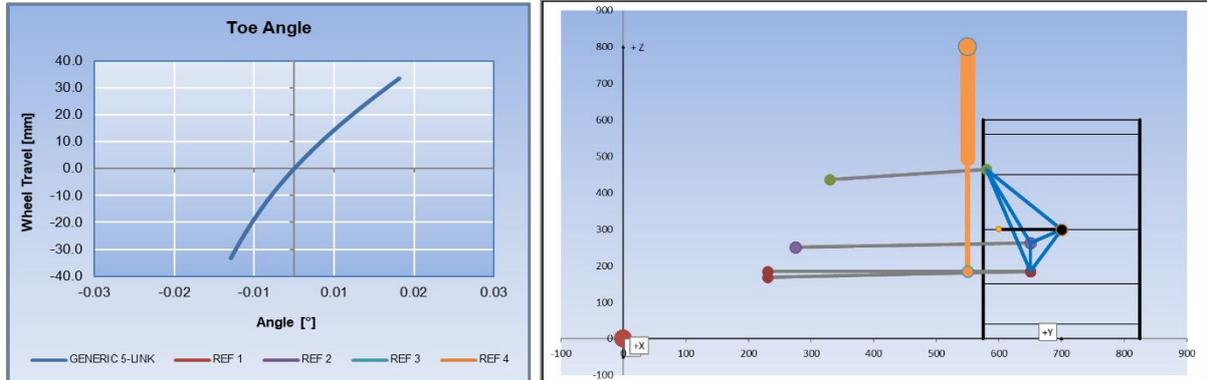


The Bump-Steer Curve Shape on the left is a typical indication for a “too-long” Track-Rod. If the Track-Rod would be too short the curve would be mirrored over the Vertical Axis. In fact, one can also visually see in the suspension model that the Track-Rod is somewhat long compared to the Upper Link(s).

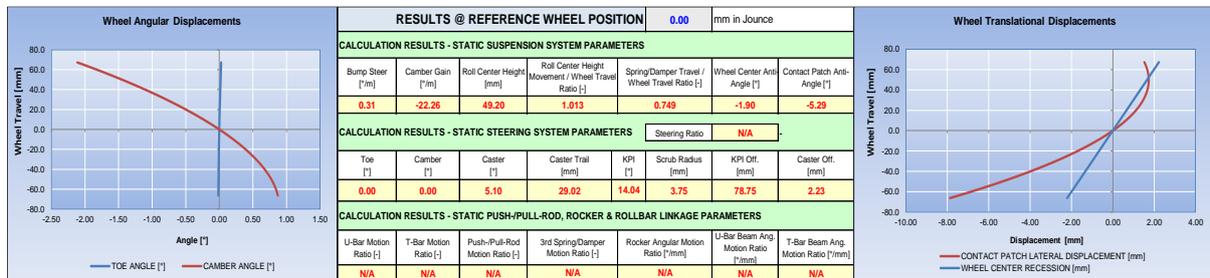
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Shortening the Track-Rod by 50 mm along its centreline (and moving the inboard point up by 1mm) does make it all work and we do have our basic geometry ☺.



All tabular results and most important overview graphs:

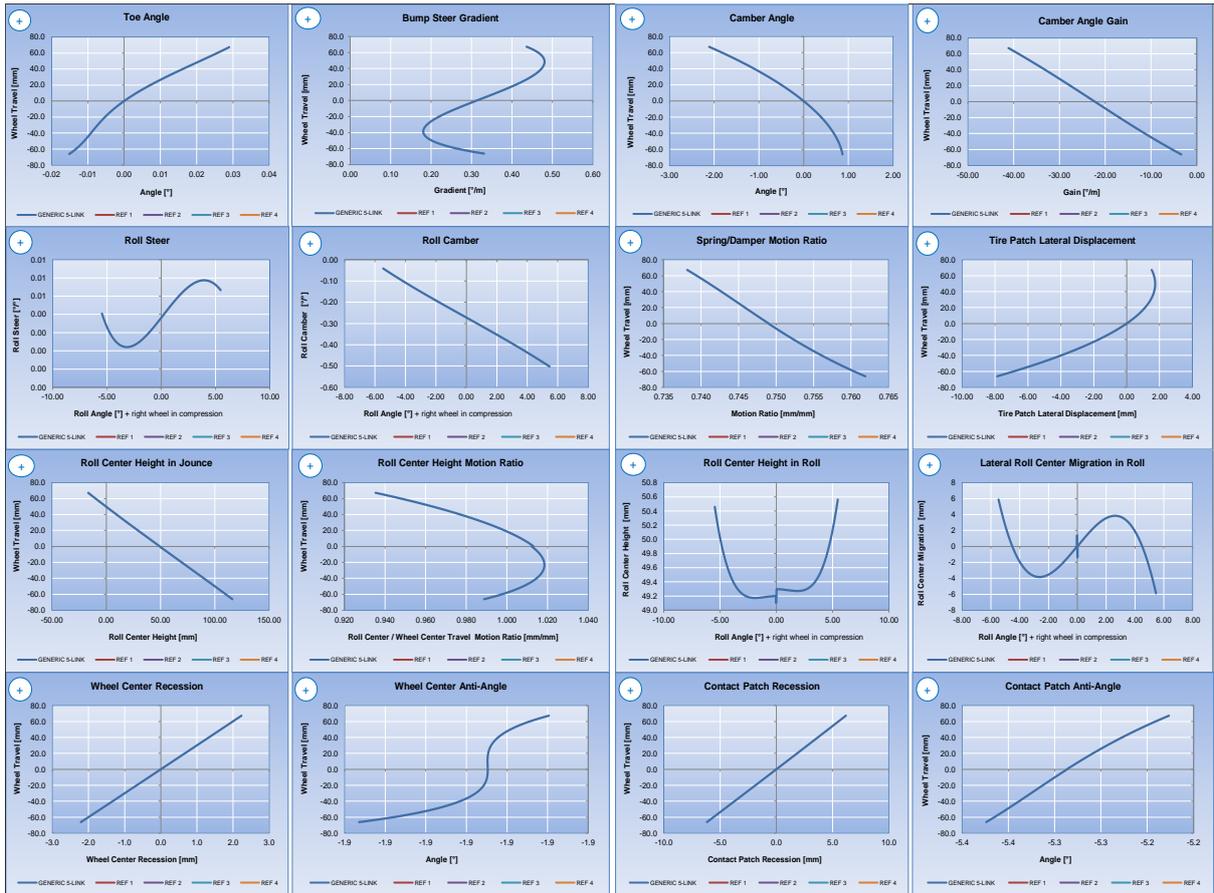


And the table of hardpoint coordinates:

SELECT SUSPENSION TYPE	Load Generic 5-Link Template			Load McPherson Template			Load Integral Link Template			SELECT COORDINATE SYSTEM			Enter Project Name / ID
	GENERIC 5-LINK									DSDM			GENERIC 5-LINK
Link ID Nr.	LINK DESCRIPTION									X [mm]	Y [mm]	Z [mm]	Link Stiffness [N/mm] 0=deactivated
													Link Length [mm]
1	Track Rod @ Chassis Joint									100.000	275.000	251.000	10000
2	Track Rod @ Wheel Joint									125.000	650.000	262.000	375.993
3	Spring Link @ Chassis Joint									0.000	230.000	185.000	10000
4	Spring Link @ Wheel Joint									12.500	650.000	185.000	420.186
5	Lower Link 2 (or 2nd A-Arm Leg) @ Chassis Joint									300.000	230.000	168.000	10000
6	Lower Link 2 @ Wheel Joint									12.500	650.000	185.000	509.260
7	Upper Link 1 @ Chassis Joint									200.000	330.000	436.000	10000
8	Upper Link 1 @ Wheel Joint									-12.500	580.000	465.000	329.389
9	Upper Link 2 (or 2nd A-Arm Leg) @ Chassis Joint									0.000	330.000	436.000	10000
10	Upper Link 2 @ Wheel Joint									-12.500	580.000	465.000	251.987
11	Spring/Damper @ Chassis Joint									0.000	550.000	800.000	
12	Spring/Damper @ Spring Link Joint									0.000	550.000	185.000	615.000
WC	Wheel Center Point									0.000	700.000	300.000	
WC ALIGN	Calculated Wheel Center Alignment Point									0.000	600.000	300.000	100.000
CP	Calculated Contact Patch									0.000	700.000	0.000	

Having created a Base Geometry, it is now time to look at wheel travel graphs and if those are to specification / target. Clearly this is a specialist exercise but looking at the results the first shot geometry is confirming that nothing is really out of the order. At the same time, it is fair to say that this exercise is providing a typical baseline setup and there are many more detailed different solutions possible.

This document will be referring frequently to the **DYNATUNE-XL FAQ** webpage for customers: <http://www.dynatune-xl.com/support-sdm.html>



As indicated at the beginning of the Design Process, one should always look at each step how the Elasto-Kinematic performance is being affected. Below one can see the tables for comparison:

Start:

	SUSPENSION COMPLIANCE TABLE						Execute a Jounce Motion ONLY Calculation for correct Compliance numbers
	Vertical Load @ CP	Braking Load @ CP	Acceleration Load @ WC	Longitudinal Impact Load @ WC	Lateral Load @ Outside Wheel @ CP WITHOUT Pneumatic Trail	Lateral Load @ Outside Wheel @ CP WITH Pneumatic Trail	
 Toe Compliance [°/N]	0.010	-0.178	0.081	-0.081	-0.088	-0.108	Pneumatic Trail: 25.0 mm
Camber Compliance [°/N]	-0.010	0.108	-0.004	0.004	0.061	0.066	Toe Aligning Torque Stiffness: 0.692 %/Nm
Caster Compliance [°/N]	0.017	-0.405	-0.035	0.035	-0.098	-0.106	AT Stiffness Definition (iso SAE, +) AT creating Toe-Out
Contact Patch X Compliance [mm/N]	0.094	-2.401	0.281	-0.281	-0.641	-0.718	Track Rod Link Stiffness: 10000.0 N/mm
Contact Patch Y Compliance [mm/N]	0.053	-0.641	0.128	-0.128	-0.373	-0.411	Spring Link Stiffness: 10000.0 N/mm
Wheel Center X Compliance [mm/N]	0.003	-0.281	0.464	-0.464	-0.128	-0.163	Lower Link 2 (or 2nd A-Arm Leg) Stiffness: 10000.0 N/mm
Wheel Center Y Compliance [mm/N]	0.001	-0.074	0.109	-0.109	-0.055	-0.067	Upper Link 1 Stiffness: 10000.0 N/mm
							Upper Link 2 (or 2nd A-Arm Leg) Stiffness: 10000.0 N/mm

End:

	SUSPENSION COMPLIANCE TABLE						Execute a Jounce Motion ONLY Calculation for correct Compliance numbers
	Vertical Load @ CP	Braking Load @ CP	Acceleration Load @ WC	Longitudinal Impact Load @ WC	Lateral Load @ Outside Wheel @ CP WITHOUT Pneumatic Trail	Lateral Load @ Outside Wheel @ CP WITH Pneumatic Trail	
 Toe Compliance [°/N]	0.007	-0.088	0.098	-0.098	-0.070	-0.087	Pneumatic Trail: 25.0 mm
Camber Compliance [°/N]	-0.006	0.067	-0.017	0.017	0.052	0.056	Toe Aligning Torque Stiffness: 0.697 %/Nm
Caster Compliance [°/N]	0.000	-0.201	0.009	-0.009	-0.047	-0.046	AT Stiffness Definition (iso SAE, +) AT creating Toe-Out
Contact Patch X Compliance [mm/N]	0.015	-1.535	0.480	-0.480	-0.446	-0.484	Track Rod Link Stiffness: 10000.0 N/mm
Contact Patch Y Compliance [mm/N]	0.035	-0.446	0.200	-0.200	-0.353	-0.383	Spring Link Stiffness: 10000.0 N/mm
Wheel Center X Compliance [mm/N]	0.013	-0.480	0.434	-0.434	-0.200	-0.242	Lower Link 2 (or 2nd A-Arm Leg) Stiffness: 10000.0 N/mm
Wheel Center Y Compliance [mm/N]	0.005	-0.096	0.112	-0.112	-0.079	-0.092	Upper Link 1 Stiffness: 10000.0 N/mm
							Upper Link 2 (or 2nd A-Arm Leg) Stiffness: 10000.0 N/mm

Concentrating only on the Metrics in the Orange Cells, one can see that the Toe-behaviour under Braking has been altered by 50% and that Toe-behaviour under Lateral Force and Aligning Torque Stiffness have seen changes up to 15%. All of these changes are caused purely by the geometry changes as the link stiffness values have not been altered. This exercise demonstrates how important Elasto-Kinematics are and moreover how "misleading" Pure Kinematic Suspension Design & Optimization can be.

This document will be referring frequently to the DYNATUNE-XL FAQ webpage for customers: <http://www.dynatune-xl.com/support-sdm.html>

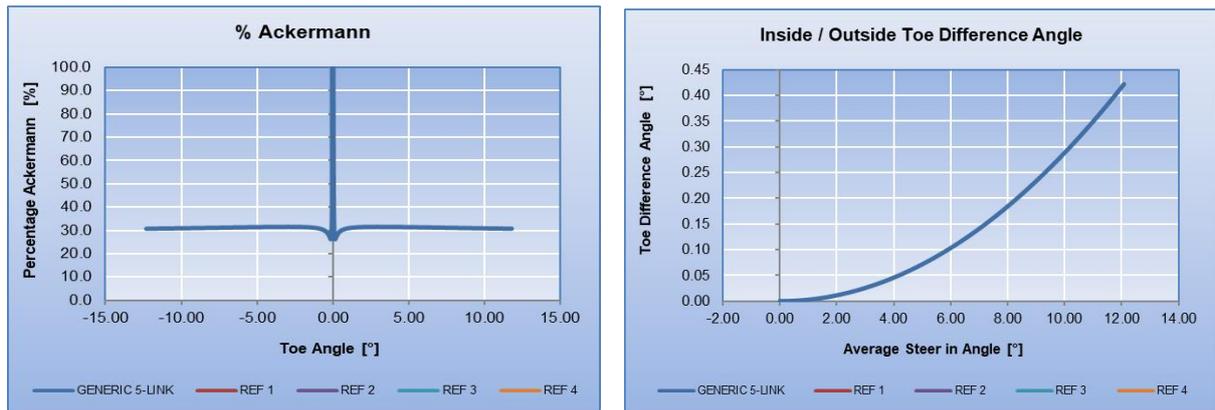


Section 2: Steering Geometry / Kinematics

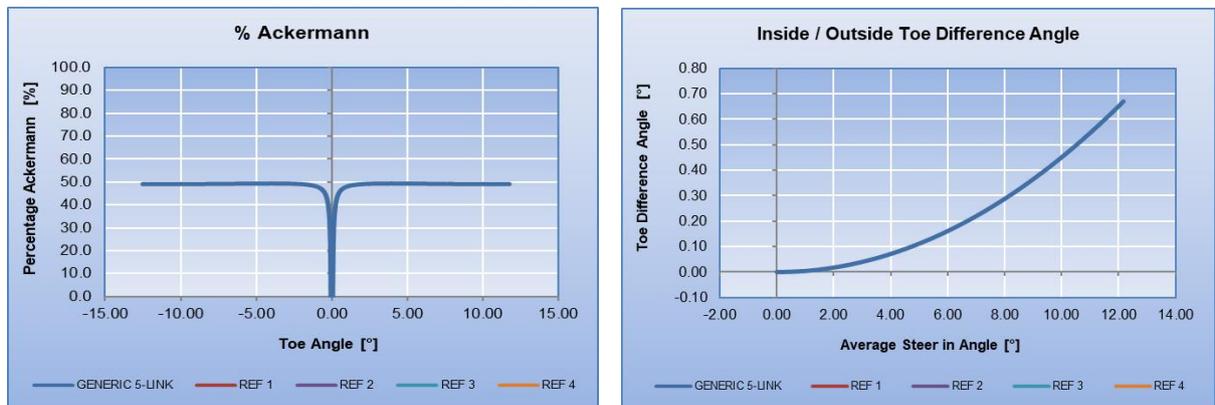
Having finalized Section 1, the remaining geometric work to do is to make sure that the Steering System is working properly. At this point the reader is supposed to fully understand the principle of Ackermann Steer as is described extensively in automotive literature.

The main parameters to look into are “Overall Steering Ratio” and “Percentage Ackermann Steer”. Considering that Ackermann is the more complex one we will start with that.

- 15) Executing a Steering Analysis on our base geometry does provide the following graphical results for Ackermann Steer:



Our target for Ackermann is achieving 50%. Changing % Percentage Ackermann Steer is almost exclusively done by changing the Y-Coordinate of the Outer Track-Rod. One can also – however to a much lesser extend – change it by either changing the X-Coordinate of the Outer Track-Rod or the Steering Rack Location. The latter solution is typically used for controlling the allowable Full-Lock joint Angles. Moving the Outboard Track-Rod Joint further out by 12.5 mm does allow us to achieve the target:



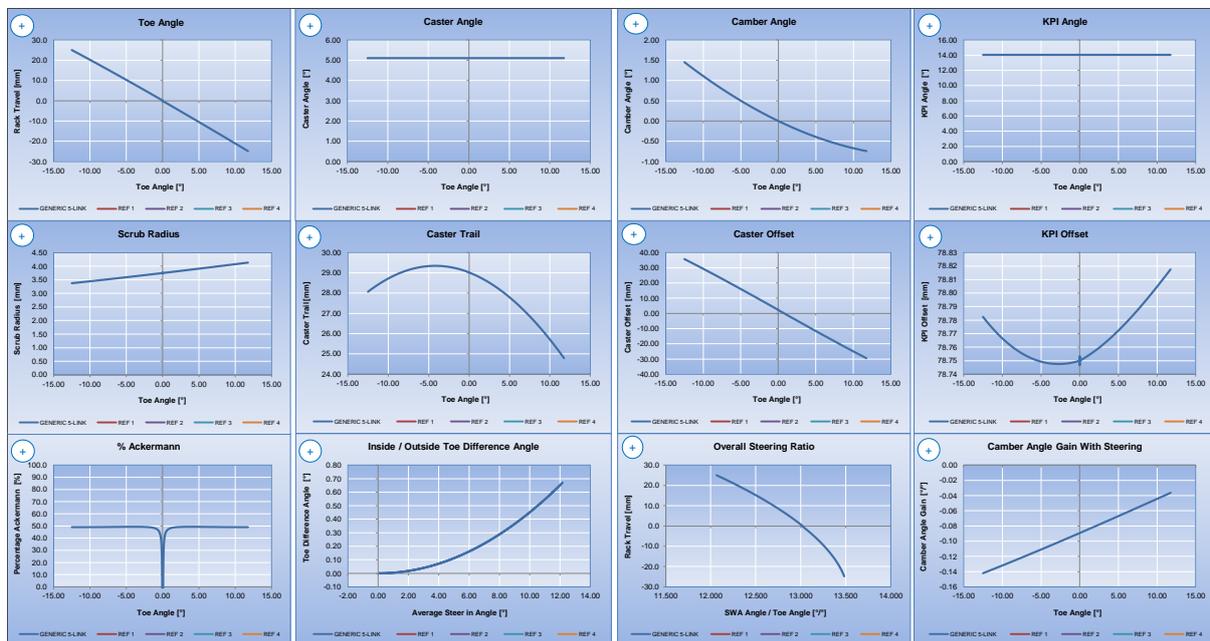
- 16) The Overall Steering Ratio is calculated with help of the rack ratio and the distance of the Outer Track-Rod Joint to the Steering Axis. If we do use a 57 mm/rev Rack Ratio our overall Steering Ratio in the model does become close to 13, a good value for sporty steering response.

CALCULATION RESULTS - STATIC STEERING SYSTEM PARAMETERS					Steering Ratio	-		
Toe [°]	Camber [°]	Caster [°]	Caster Trail [mm]	KPI [°]	Scrub Radius [mm]	KPI Off. [mm]	Caster Off. [mm]	
0.00	0.00	5.10	29.02	14.04	3.75	78.75	2.23	



With these final modifications the creation and first optimization loop of a suitable Base Geometry has been realized. The final geometry hardpoint table and steering kinematic graphs are shown below:

SELECT SUSPENSION TYPE	Load Generic 5-Link Template	Load McPherson Template	Load Integral Link Template	SELECT COORDINATE SYSTEM			Enter Project Name / ID
	GENERIC 5-LINK				DSDM		GENERIC 5-LINK
Link ID Nr.	LINK DESCRIPTION			X [mm]	Y [mm]	Z [mm]	Link Stiffness [N/mm] 0=deactivated Link Length [mm]
1	Track Rod @ Chassis Joint			100.000	275.000	251.000	10000
2	Track Rod @ Wheel Joint			125.000	662.500	262.000	388.461
3	Spring Link @ Chassis Joint			0.000	230.000	185.000	10000
4	Spring Link @ Wheel Joint			12.500	650.000	185.000	420.186
5	Lower Link 2 (or 2nd A-Arm Leg) @ Chassis Joint			300.000	230.000	168.000	10000
6	Lower Link 2 @ Wheel Joint			12.500	650.000	185.000	509.260
7	Upper Link 1 @ Chassis Joint			200.000	330.000	436.000	10000
8	Upper Link 1 @ Wheel Joint			-12.500	580.000	465.000	329.389
9	Upper Link 2 (or 2nd A-Arm Leg) @ Chassis Joint			0.000	330.000	436.000	10000
10	Upper Link 2 @ Wheel Joint			-12.500	580.000	465.000	251.987
11	Spring/Damper @ Chassis Joint			0.000	550.000	800.000	
12	Spring/Damper @ Spring Link Joint			0.000	550.000	185.000	615.000
WC	Wheel Center Point			0.000	700.000	300.000	
WC ALIGN	Calculated Wheel Center Alignment Point			0.000	600.000	300.000	100.000
CP	Calculated Contact Patch			0.000	700.000	0.000	



At this point, one must decide whether the achieved Kinematic Results are satisfactory and if not, the corresponding steps should be revisited & repeated. Applying the explained recipe on existing suspension geometries will give a good first impression on the sensitivity of all the important parameters to changes and moreover should provide a robust roadmap to feasible solutions without – or at least with significantly reduced – number of iterations.

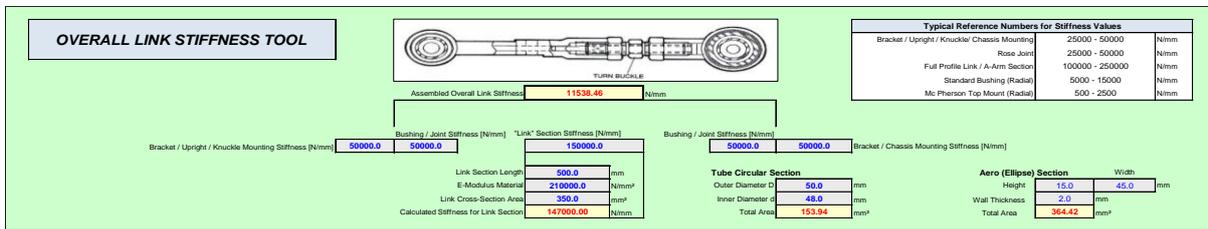


STEP 10: OPTIMIZING ELASTO-KINEMATIC STIFFNESS

Typically, in OEM Suspensions one does find Elastic “Bushings” which are primarily used for noise insulation. The elasticity (=stiffness) of these components can vary vastly and on top of that can also be more or less non-linear. Combining that with the fact that the various directional stiffnesses of the bushings can also create numerous “somewhat-over-constrained” individual links, does make optimizing Elasto-Kinematics a hugely complex and (CPU-) time consuming exercise.

The **DYNATUNE-XL SDM Compliance Feature** does aim to give some insight to the user in this particular field and to indicate areas/hardpoints in the Suspension Layout that should receive special attention in order to extract maximum performance out of the system.

As all materials are more or less flexible, the **DYNATUNE-XL SDM “Expert” MODULE** does provide the opportunity to analyse these first order effects by using flexible links. In the Module the user can find a helpful tool which enables to calculate the resulting stiffness of one link depending on the link material and the type of fixture to the wheel carrier or chassis.



Establishing a straight forward Recipe/Procedure is quite difficult. The general recommendation to make here, is to “pick out” one specific Elasto-Kinematic Performance and investigate the effect of each Link and its Stiffness on that performance. We will do one full iteration example here:

If one for instance would like to reduce the Toe-Change under Braking (Red Circle in the Table):

	SUSPENSION COMPLIANCE TABLE						Execute a Jounce Motion ONLY Calculation for correct Compliance numbers	
	Vertical Load @ CP	Braking Load @ CP	Acceleration Load @ WC	Longitudinal Impact Load @ WC	Lateral Load @ Outside Wheel @ CP WITHOUT Pneumatic Trail	Lateral Load @ Outside Wheel @ CP WITH Pneumatic Trail	Pneumatic Trail	Toe Aligning Torque Stiffness
Toe Compliance [°/kN]	0.00	-0.068	-0.058	-0.098	-0.079	-0.087	25.0	0.627
Camber Compliance [°/kN]	-0.006	0.067	-0.017	0.017	0.052	-0.056	AT Stiffness Definition (so SAE: (+) AT creating Toe-Out	
Caster Compliance [°/kN]	0.000	-0.201	0.009	-0.009	-0.047	-0.046	Track Rod Link Stiffness	10000.0
Contact Patch X Compliance [mm/kN]	0.015	-1.535	0.480	-0.480	-0.446	-0.484	Spring Link Stiffness	10000.0
Contact Patch Y Compliance [mm/kN]	0.035	-0.446	0.200	-0.200	-0.353	-0.383	Lower Link 2 (or 2nd A-Arm leg) Stiffness	10000.0
Wheel Center X Compliance [mm/kN]	0.013	-0.480	0.434	-0.434	-0.200	-0.242	Upper Link 1 Stiffness	10000.0
Wheel Center Y Compliance [mm/kN]	0.005	-0.096	0.112	-0.112	-0.079	-0.092	Upper Link 2 (or 2nd A-Arm Leg) Stiffness	10000.0

- 1) One does start the investigation with how much the effect of doubling the link stiffness of the Lower Forward Link will have. As one can see the influence is little with a 6% reduction:

	SUSPENSION COMPLIANCE TABLE						Execute a Jounce Motion ONLY Calculation for correct Compliance numbers	
	Vertical Load @ CP	Braking Load @ CP	Acceleration Load @ WC	Longitudinal Impact Load @ WC	Lateral Load @ Outside Wheel @ CP WITHOUT Pneumatic Trail	Lateral Load @ Outside Wheel @ CP WITH Pneumatic Trail	Pneumatic Trail	Toe Aligning Torque Stiffness
Toe Compliance [°/kN]	0.00	-0.063	-0.057	-0.097	-0.071	-0.088	25.0	0.704
Camber Compliance [°/kN]	-0.006	0.065	-0.017	0.017	0.052	-0.056	AT Stiffness Definition (so SAE: (+) AT creating Toe-Out	
Caster Compliance [°/kN]	0.002	-0.153	-0.009	0.009	-0.048	-0.047	Track Rod Link Stiffness	10000.0
Contact Patch X Compliance [mm/kN]	0.026	-1.137	0.333	-0.333	-0.457	-0.493	Spring Link Stiffness	10000.0
Contact Patch Y Compliance [mm/kN]	0.035	-0.457	0.204	-0.204	-0.353	-0.384	Lower Link 2 (or 2nd A-Arm leg) Stiffness	20000.0
Wheel Center X Compliance [mm/kN]	0.017	-0.333	0.381	-0.381	-0.204	-0.247	Upper Link 1 Stiffness	10000.0
Wheel Center Y Compliance [mm/kN]	0.005	-0.099	0.113	-0.113	-0.079	-0.092	Upper Link 2 (or 2nd A-Arm Leg) Stiffness	10000.0

As a good practice – especially when stiffening up the system does not show big changes - one should also investigate what a reduction of Link Stiffness will do. Halving the Link Stiffness does contribute to 11% more change, so in fact the system is almost double as sensitive when going softer:

	SUSPENSION COMPLIANCE TABLE						Execute a Jounce Motion ONLY Calculation for correct Compliance numbers	
	Vertical Load @ CP	Braking Load @ CP	Acceleration Load @ WC	Longitudinal Impact Load @ WC	Lateral Load @ Outside Wheel @ CP WITHOUT Pneumatic Trail	Lateral Load @ Outside Wheel @ CP WITH Pneumatic Trail	Pneumatic Trail	Toe Aligning Torque Stiffness
Toe Compliance [°/kN]	0.00	-0.055	-0.102	-0.102	-0.078	-0.098	25.0	0.707
Camber Compliance [°/kN]	-0.006	0.054	-0.016	0.016	0.052	-0.056	AT Stiffness Definition (so SAE: (+) AT creating Toe-Out	
Caster Compliance [°/kN]	-0.003	-0.099	0.044	-0.044	-0.044	-0.044	Track Rod Link Stiffness	10000.0
Contact Patch X Compliance [mm/kN]	-0.009	-2.331	0.775	-0.775	-0.424	-0.466	Spring Link Stiffness	10000.0
Contact Patch Y Compliance [mm/kN]	0.036	-0.424	0.192	-0.192	-0.354	-0.384	Lower Link 2 (or 2nd A-Arm leg) Stiffness	5000.0
Wheel Center X Compliance [mm/kN]	0.004	-0.775	0.544	-0.544	-0.192	-0.237	Upper Link 1 Stiffness	10000.0
Wheel Center Y Compliance [mm/kN]	0.005	-0.090	0.110	-0.110	-0.080	-0.093	Upper Link 2 (or 2nd A-Arm Leg) Stiffness	10000.0

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From this first exercise one can see that making the forward lower link stiffer does help reducing the Toe-Out under Braking. However, one can also see that one is already on the path of diminishing returns. Next to evaluating Toe, one should also keep an eye on the other “orange” indicators in the table. The interactions are numerous and even for experts not always at first glance predictable.

2) If we in a next step investigate the sensitivity of the Rear Lower Link Stiffness we do see that doubling the stiffness of that link does:

- reduce the Toe-Out under Braking significantly by 50%
- reduce Toe-Out under Lateral Force significantly by 50%

SUSPENSION COMPLIANCE TABLE							Execute a Jounce Motion ONLY Calculation for correct Compliance numbers	
	Vertical Load @ CP	Braking Load @ CP	Acceleration Load @ WC	Longitudinal Impact Load @ WC	Lateral Load @ Outside Wheel @ CP WITHOUT Pneumatic Trail	Lateral Load @ Outside Wheel @ CP WITH Pneumatic Trail	Pneumatic Trail	Toe Aligning Torque Stiffness
Toe Compliance [*°/N]	0.00	-0.043	0.073	-0.073	-0.037	-0.051	25.0	0.577
Camber Compliance [*°/N]	-0.004	0.041	-0.002	0.002	0.033	0.034		
Caster Compliance [*°/N]	-0.001	-0.179	-0.004	0.004	-0.030	-0.028		
Contact Patch X Compliance [mm/N]	-0.003	-1.258	0.322	-0.322	-0.239	-0.258		
Contact Patch Y Compliance [mm/N]	0.022	-0.239	0.082	-0.082	-0.198	-0.215		
Wheel Center X Compliance [mm/N]	0.003	-0.322	0.344	-0.344	-0.082	-0.113		
Wheel Center Y Compliance [mm/N]	0.000	-0.026	0.072	-0.072	-0.027	-0.035		

Execute a Jounce Motion ONLY Calculation for correct Compliance numbers

Pneumatic Trail: 25.0 mm

Toe Aligning Torque Stiffness: 0.577 N/m

AT Stiffness Definition iso SAE: (+) AT creating Toe-Out

Track Rod Link Stiffness: 10000.0 N/mm

Spring Link Stiffness: 20000.0 N/mm

Lower Link 2 (or 2nd A-Arm leg) Stiffness: 10000.0 N/mm

Upper Link 1 Stiffness: 10000.0 N/mm

Upper Link 2 (or 2nd A-Arm Leg) Stiffness: 10000.0 N/mm

All Compliance Data refer to Design Position

Input Parameters for Dynatune Ride & Handling Tool

In theory one would have to evaluate also the effect of a softer rear lower link but as the amount of Toe-Change is almost linearly related to the rate of change in stiffness this step is not necessary and could be skipped to save time. Results are nonetheless presented showing the expected changes:

SUSPENSION COMPLIANCE TABLE							Execute a Jounce Motion ONLY Calculation for correct Compliance numbers	
	Vertical Load @ CP	Braking Load @ CP	Acceleration Load @ WC	Longitudinal Impact Load @ WC	Lateral Load @ Outside Wheel @ CP WITHOUT Pneumatic Trail	Lateral Load @ Outside Wheel @ CP WITH Pneumatic Trail	Pneumatic Trail	Toe Aligning Torque Stiffness
Toe Compliance [*°/N]	-0.01	-0.178	0.150	-0.150	-0.138	-0.162	25.0	0.961
Camber Compliance [*°/N]	-0.009	0.119	-0.047	0.047	0.091	-0.098		
Caster Compliance [*°/N]	0.003	-0.246	0.034	-0.034	-0.061	-0.063		
Contact Patch X Compliance [mm/N]	0.050	-2.088	0.798	-0.798	-0.860	-0.937		
Contact Patch Y Compliance [mm/N]	0.062	-0.860	0.438	-0.438	-0.663	-0.723		
Wheel Center X Compliance [mm/N]	0.033	-0.798	0.618	-0.618	-0.438	-0.504		
Wheel Center Y Compliance [mm/N]	0.014	-0.236	0.193	-0.193	-0.184	-0.207		

Execute a Jounce Motion ONLY Calculation for correct Compliance numbers

Pneumatic Trail: 25.0 mm

Toe Aligning Torque Stiffness: 0.961 N/m

AT Stiffness Definition iso SAE: (+) AT creating Toe-Out

Track Rod Link Stiffness: 10000.0 N/mm

Spring Link Stiffness: 5000.0 N/mm

Lower Link 2 (or 2nd A-Arm leg) Stiffness: 10000.0 N/mm

Upper Link 1 Stiffness: 10000.0 N/mm

Upper Link 2 (or 2nd A-Arm Leg) Stiffness: 10000.0 N/mm

All Compliance Data refer to Design Position

Input Parameters for Dynatune Ride & Handling Tool

3) Next in Line is the Track-Rod Stiffness. Doubling the value does hardly affect the Toe-Behaviour under Braking. It does though (as expected) affect the Aligning Torque Stiffness:

SUSPENSION COMPLIANCE TABLE							Execute a Jounce Motion ONLY Calculation for correct Compliance numbers	
	Vertical Load @ CP	Braking Load @ CP	Acceleration Load @ WC	Longitudinal Impact Load @ WC	Lateral Load @ Outside Wheel @ CP WITHOUT Pneumatic Trail	Lateral Load @ Outside Wheel @ CP WITH Pneumatic Trail	Pneumatic Trail	Toe Aligning Torque Stiffness
Toe Compliance [*°/N]	0.006	-0.087	0.082	-0.082	-0.064	-0.077	25.0	0.499
Camber Compliance [*°/N]	-0.006	0.067	-0.015	0.015	0.052	0.055		
Caster Compliance [*°/N]	0.001	-0.202	0.013	-0.013	-0.048	-0.049		
Contact Patch X Compliance [mm/N]	0.014	-1.535	0.479	-0.479	-0.446	-0.484		
Contact Patch Y Compliance [mm/N]	0.035	-0.446	0.192	-0.192	-0.350	-0.378		
Wheel Center X Compliance [mm/N]	0.011	-0.479	0.413	-0.413	-0.192	-0.228		
Wheel Center Y Compliance [mm/N]	0.005	-0.096	0.111	-0.111	-0.079	-0.092		

Execute a Jounce Motion ONLY Calculation for correct Compliance numbers

Pneumatic Trail: 25.0 mm

Toe Aligning Torque Stiffness: 0.499 N/m

AT Stiffness Definition iso SAE: (+) AT creating Toe-Out

Track Rod Link Stiffness: 20000.0 N/mm

Spring Link Stiffness: 10000.0 N/mm

Lower Link 2 (or 2nd A-Arm leg) Stiffness: 10000.0 N/mm

Upper Link 1 Stiffness: 10000.0 N/mm

Upper Link 2 (or 2nd A-Arm Leg) Stiffness: 10000.0 N/mm

All Compliance Data refer to Design Position

Input Parameters for Dynatune Ride & Handling Tool

Again here, as good practice, one should also investigate what reducing Track-Rod Stiffness will do. Halving the Link Stiffness does hardly change the Toe-Behaviour under Braking and does almost exclusively affect the Aligning Torque Stiffness:

SUSPENSION COMPLIANCE TABLE							Execute a Jounce Motion ONLY Calculation for correct Compliance numbers	
	Vertical Load @ CP	Braking Load @ CP	Acceleration Load @ WC	Longitudinal Impact Load @ WC	Lateral Load @ Outside Wheel @ CP WITHOUT Pneumatic Trail	Lateral Load @ Outside Wheel @ CP WITH Pneumatic Trail	Pneumatic Trail	Toe Aligning Torque Stiffness
Toe Compliance [*°/N]	0.000	-0.089	0.131	-0.131	-0.082	-0.110	25.0	1.118
Camber Compliance [*°/N]	-0.006	0.067	-0.020	0.020	0.053	0.058		
Caster Compliance [*°/N]	0.000	-0.201	0.001	-0.001	-0.044	-0.040		
Contact Patch X Compliance [mm/N]	0.015	-1.535	0.483	-0.483	-0.447	-0.496		
Contact Patch Y Compliance [mm/N]	0.037	-0.447	0.217	-0.217	-0.359	-0.395		
Wheel Center X Compliance [mm/N]	0.017	-0.483	0.480	-0.480	-0.217	-0.274		
Wheel Center Y Compliance [mm/N]	0.005	-0.096	0.113	-0.113	-0.080	-0.093		

Execute a Jounce Motion ONLY Calculation for correct Compliance numbers

Pneumatic Trail: 25.0 mm

Toe Aligning Torque Stiffness: 1.118 N/m

AT Stiffness Definition iso SAE: (+) AT creating Toe-Out

Track Rod Link Stiffness: 5000.0 N/mm

Spring Link Stiffness: 10000.0 N/mm

Lower Link 2 (or 2nd A-Arm leg) Stiffness: 10000.0 N/mm

Upper Link 1 Stiffness: 10000.0 N/mm

Upper Link 2 (or 2nd A-Arm Leg) Stiffness: 10000.0 N/mm

All Compliance Data refer to Design Position

Input Parameters for Dynatune Ride & Handling Tool



4) Moving to the Upper Plane in the acceleration Suspension we do analyse the effect of doubling the stiffness of the Forward Upper Link. Doubling the value does hardly affect the Toe-Behaviour under Braking:

SUSPENSION COMPLIANCE TABLE							Execute a Jounce Motion ONLY Calculation for correct Compliance numbers	
	Vertical Load @ CP	Braking Load @ CP	Acceleration Load @ WC	Longitudinal Impact Load @ WC	Lateral Load @ Outside Wheel @ CP WITHOUT Pneumatic Trail	Lateral Load @ Outside Wheel @ CP WITH Pneumatic Trail	Pneumatic Trail	mm
Toe Compliance [*AN]	0.017	-0.099	0.099	-0.099	-0.071	-0.099	25.0	
Camber Compliance [*AN]	-0.006	0.065	-0.017	0.017	0.052	0.056	0.709	*N/m
Caster Compliance [*AN]	0.001	-0.183	0.020	-0.020	-0.046	-0.046	AT Stiffness Definition iso SAE: (+) AT creating Toe-Out	
Contact Patch X Compliance [mm/N]	0.018	-1.476	0.518	-0.518	-0.444	-0.444	Track Rod Link Stiffness	10000.0
Contact Patch Y Compliance [mm/N]	0.036	-0.444	0.202	-0.202	-0.353	-0.384	Spring Link Stiffness	10000.0
Wheel Center X Compliance [mm/N]	0.011	-0.518	0.411	-0.411	-0.202	-0.244	Lower Link 2 (or 2nd A-Arm leg) Stiffness	10000.0
Wheel Center Y Compliance [mm/N]	0.005	-0.097	0.111	-0.111	-0.080	-0.093	Upper Link 1 Stiffness	20000.0
							Upper Link 2 (or 2nd A-Arm Leg) Stiffness	10000.0

Likewise, does halving the Link Stiffness have little effect on Toe-Change under Braking and/or side effects on the other “orange” indicators:

SUSPENSION COMPLIANCE TABLE							Execute a Jounce Motion ONLY Calculation for correct Compliance numbers	
	Vertical Load @ CP	Braking Load @ CP	Acceleration Load @ WC	Longitudinal Impact Load @ WC	Lateral Load @ Outside Wheel @ CP WITHOUT Pneumatic Trail	Lateral Load @ Outside Wheel @ CP WITH Pneumatic Trail	Pneumatic Trail	mm
Toe Compliance [*AN]	0.017	-0.099	0.099	-0.099	-0.070	-0.099	25.0	
Camber Compliance [*AN]	-0.006	0.065	-0.016	0.016	0.052	0.056	0.706	*N/m
Caster Compliance [*AN]	-0.002	-0.238	-0.015	0.015	-0.048	-0.047	AT Stiffness Definition iso SAE: (+) AT creating Toe-Out	
Contact Patch X Compliance [mm/N]	0.008	-1.653	0.405	-0.405	-0.450	-0.488	Track Rod Link Stiffness	10000.0
Contact Patch Y Compliance [mm/N]	0.035	-0.450	0.198	-0.198	-0.353	-0.384	Spring Link Stiffness	10000.0
Wheel Center X Compliance [mm/N]	0.017	-0.405	0.484	-0.484	-0.198	-0.241	Lower Link 2 (or 2nd A-Arm leg) Stiffness	10000.0
Wheel Center Y Compliance [mm/N]	0.005	-0.093	0.114	-0.114	-0.079	-0.092	Upper Link 1 Stiffness	5000.0
							Upper Link 2 (or 2nd A-Arm Leg) Stiffness	10000.0

5) Finally, we do analyse the effect of doubling the stiffness of the Rearward Upper Link. Also here, doubling the value does hardly affect the Toe-Behaviour under Braking.

SUSPENSION COMPLIANCE TABLE							Execute a Jounce Motion ONLY Calculation for correct Compliance numbers	
	Vertical Load @ CP	Braking Load @ CP	Acceleration Load @ WC	Longitudinal Impact Load @ WC	Lateral Load @ Outside Wheel @ CP WITHOUT Pneumatic Trail	Lateral Load @ Outside Wheel @ CP WITH Pneumatic Trail	Pneumatic Trail	mm
Toe Compliance [*AN]	0.018	-0.093	0.094	-0.094	-0.075	-0.092	25.0	
Camber Compliance [*AN]	-0.006	0.059	-0.024	0.024	0.046	0.050	0.698	*N/m
Caster Compliance [*AN]	-0.001	-0.189	0.019	-0.019	-0.038	-0.038	AT Stiffness Definition iso SAE: (+) AT creating Toe-Out	
Contact Patch X Compliance [mm/N]	0.010	-1.501	0.510	-0.510	-0.421	-0.462	Track Rod Link Stiffness	10000.0
Contact Patch Y Compliance [mm/N]	0.032	-0.421	0.222	-0.222	-0.335	-0.367	Spring Link Stiffness	10000.0
Wheel Center X Compliance [mm/N]	0.017	-0.510	0.410	-0.410	-0.222	-0.263	Lower Link 2 (or 2nd A-Arm leg) Stiffness	10000.0
Wheel Center Y Compliance [mm/N]	0.007	-0.114	0.097	-0.097	-0.093	-0.104	Upper Link 1 Stiffness	20000.0
							Upper Link 2 (or 2nd A-Arm Leg) Stiffness	10000.0

Likewise, does halving the Link Stiffness have little effect on Toe-Change under Braking. A side effect on the other “orange” indicators can be seen on the Camber Stiffness which is starting to suffer:

SUSPENSION COMPLIANCE TABLE							Execute a Jounce Motion ONLY Calculation for correct Compliance numbers	
	Vertical Load @ CP	Braking Load @ CP	Acceleration Load @ WC	Longitudinal Impact Load @ WC	Lateral Load @ Outside Wheel @ CP WITHOUT Pneumatic Trail	Lateral Load @ Outside Wheel @ CP WITH Pneumatic Trail	Pneumatic Trail	mm
Toe Compliance [*AN]	0.016	-0.076	0.109	-0.109	-0.062	-0.080	25.0	
Camber Compliance [*AN]	-0.008	0.083	-0.003	0.003	0.064	0.066	0.740	*N/m
Caster Compliance [*AN]	0.003	-0.225	-0.012	0.012	-0.065	-0.062	AT Stiffness Definition iso SAE: (+) AT creating Toe-Out	
Contact Patch X Compliance [mm/N]	0.024	-1.603	0.422	-0.422	-0.496	-0.529	Track Rod Link Stiffness	10000.0
Contact Patch Y Compliance [mm/N]	0.042	-0.496	0.157	-0.157	-0.390	-0.417	Spring Link Stiffness	10000.0
Wheel Center X Compliance [mm/N]	0.005	-0.422	0.486	-0.486	-0.157	-0.205	Lower Link 2 (or 2nd A-Arm leg) Stiffness	10000.0
Wheel Center Y Compliance [mm/N]	0.000	-0.061	0.142	-0.142	-0.053	-0.069	Upper Link 1 Stiffness	10000.0
							Upper Link 2 (or 2nd A-Arm Leg) Stiffness	5000.0

Conclusion:

Having completed the whole loop of links, we can conclude out of this exercise that Toe-Change under Braking is primarily sensitive to the stiffness of the #2 lower links. Interestingly, stiffening up the Rear Lower Leg of the Suspension is far more efficient than the Forward Leg, which was not to be expected as that Rear Leg does primarily govern the Lateral Stiffness of the Suspension (as can be seen in the effects on Camber Stiffness). Typically, one would expect that the Lower Forward leg would be more influential. This would normally be the starting point of another Deep-Dive Elasto-Kinematic analysis.

This study will hopefully have raised awareness about the fact that Elasto-Kinematics are creating a whole new dimension above and beyond “simple” Kinematics. It is indeed of vital importance to understand that one optimization cannot be executed without considering the other and vice versa.

After all:

The REAL performance of Suspensions systems is located in their tunability of the Elasto-Kinematics.

This document will be referring frequently to the **DYNATUNE-XL FAQ** webpage for customers:
<http://www.dynatune-xl.com/support-sdm.html>



DYNATUNE – XL

DYNATUNE-XL is the registered name of a suite of core skill **MS EXCEL** ® based Engineering and Simulation Tools.

The **DYNATUNE-XL** Tool Suite does provide Professional Engineering Tools covering the most Important Aspects of Vehicle Dynamics. All Tools aim to achieve a Maximum of Results with a Minimum of Input Data allowing quick Setup Checks or - if wanted - more complex Generic Parameter Studies. Being a fully **MS EXCEL** ® based Tool does significantly reduce the application threshold for many engineers and technicians. MS Excel is available on most computers as part of **MS OFFICE** ® and widely supported in business applications.

SOFTWARE REQUIREMENTS & LICENSE MANAGEMENT

Software requirements for **RELEASE 8.0** are **Full** Versions (incl. latest updates) of **MS EXCEL** ® **2007, 2010, 2013, 2016** or **2019** or **Office/365** with a **MS Windows** ® **XP, Windows Vista, Windows 7 Starter, Windows 7, Windows 8** or **10 Operating System**.

All Modules of **DYNATUNE-XL** come as a compiled executable (*.exe) binary file which will call **MS EXCEL**® as a separate stand-alone instance. Source code is copyright protected and safe data handling is guaranteed through secure binary files.

Standard Customer Licenses are typically valid for the use of the workbooks (and ALL user-saved variants) on 1 computer and for 1 user only without a timing constraint. Portable Licenses can be made available upon request.

The protection software does offer to the customer next to the security of encoded binary data handling also - by means of a unique License Key Verification Procedure - a state-of-the-art data protection.

License support is available for the latest releases only and as there is no annual maintenance fee existing clients with older product releases can acquire "upgrading" licenses to the latest version release at special client rates.

Recommended minimum hardware configuration for the **DYNATUNE-XL** Tools are Intel Core i5/i7 CPU (or similar) with 4GB Ram.

All Units in **DYNATUNE-XL** are SI.

DYNATUNE-XL DEMO VERSIONS

DEMO Versions of the following **DYNATUNE-XL** Modules can be downloaded here:

- DYNATUNE Ride & Handling Module: <http://www.dynatune-xl.com/download-demo-rh.html>
- DYNATUNE Suspension Design Module: <http://www.dynatune-xl.com/download-demo-sdm.html>
- DYNATUNE Suspension Tuning Module: <http://www.dynatune-xl.com/download-demo-stm.html>

DYNATUNE-XL STORE

B2C customers can acquire the various **DYNATUNE-XL** Modules online in our webstore:

http://www.dynatune-xl.com/store/c1/Featured_Products.html

B2B customers are kindly requested to contact us directly.

DYNATUNE-XL CONTACT

Website: www.dynatune-xl.com

Email: info@dynatune-xl.com

This document will be referring frequently to the **DYNATUNE-XL FAQ** webpage for customers:
<http://www.dynatune-xl.com/support-sdm.html>