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Using K&C Measurements for Practical Suspension Tuning and Development

Phillip Morse
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ABSTRACT

In recent decades suspension kinematics and compliance (K&C) testing has become a support-testing standard in the vehicle industry, providing invaluable data for suspension design and vehicle dynamics simulations. But in practical ride and handling tuning/development work, many readily available K&C test measurements have yet to achieve the empirical significance of traditional derived parameters such as roll center heights and roll stiffness distributions. In an attempt to emphasize the practical usefulness of K&C test data, this paper presents several methods by which this data can directly assist with chassis tuning and development. Traditional K&C data interpretation methods are discussed and new concepts such as "yaw efficiency" are developed and presented.

INTRODUCTION

An unprecedented amount of detailed vehicle information is available to today's chassis engineers. This is the inevitable result of progress within the automotive industry as a whole, but it is also due in no small part to the increased informational demands of computer design and simulation tools. Detailed modeling requirements have even driven, to some extent, the development of test standards in recent years [1, 2].

Within the suspension development area alone, an extremely large array of specialized support test protocols and test machines now exist for almost every suspension component and sub-system. Behind every successful vehicle test program lie machines such as damper dynamometers, tire force and moment measurement machines, hydraulic shakers, component endurance testers, suspension kinematics and compliance (K&C) test rigs, and vehicle inertia swings - to name just a few.

Collectively, all this support testing equipment has the capability of producing an enormous amount of measurement data. Paradoxically, this can be both helpful and obstructive to chassis tuning and development work. In support of modeling efforts, more available data is typically better (assuming it can be efficiently fed into the appropriate design and simulation tools). However the sheer volume of available test data can quickly become unmanageable for on-vehicle tuning and record keeping.

For example, consider a standard suspension K&C test, which can easily produce a 300+ page report documenting hundreds of measured parameters. What good is all this information to a suspension development engineer or track-side tuner if key results are buried and/or difficult to extract? Real performance development advantages come about when available information can be efficiently converted into *useful* information. So the question becomes: How does one translate detailed measurement data into manageable and, most importantly, useful suspension tuning guidelines? In the context of suspension K&C testing, this paper explores several possible approaches.

BACKGROUND

The first order of business is defining the "K" and the "C" in suspension K&C testing. In brief, they are as follows [3]:

KINEMATICS ("K") = Motion without reference to force or mass. A term which refers to the controlled orientation of road wheels by the suspension linkages.

COMPLIANCE ("C") = Deflection due to application of force (the inverse of stiffness). A term which refers to the controlled movement of road wheels by the springs, bushings, and component deflections.

K&C parameters are truly present in each of the primary functions of any vehicle's suspension, which can be stated as follows [4]:

- Isolate the vehicle chassis from road roughness by allowing the road wheels to move (independent of the chassis) and follow road irregularities. (This is *Compliance*.)
- Maintain the road wheels in the proper steer and camber attitudes to the road surface. (This is *Kinematics* and *Compliance*.)

- React to vehicle control forces produced by the tires. (Control forces being longitudinal forces and torques produced by braking and accelerating, and lateral forces and torques produced by cornering.) (This is *Kinematics* and *Compliance*.)

- Resist chassis roll when the vehicle is cornering, and resist chassis pitch when the vehicle is accelerating or braking. (This is *Kinematics* and *Compliance*.)

- Keep the tires in contact with the road surface, with minimal load variations. (This is *Compliance*.)

Controlling wheel motions and positions has always been a recognized way to influence a vehicle's road manners, and suspension design, even if limited to empirical work, has always included consideration of "K&C" characteristics. However, Michelin's introduction of the radial ply tire (with its inherent sensitivity to load and orientation) in the late 1940's created a new need for precision wheel control.

Out of necessity, and in order to design motor cars that could effectively use radial ply tires, early K&C work began in earnest by French automobile manufacturers in conjunction with Michelin in the 1950s. In subsequent decades this work was followed by automobile and tire manufacturers around the globe. Of particular note is the pioneering K&C work done at General Motors in the 1960s and 1970s [3,5].

Today, most automobile and tire manufacturers have some measure of in-house suspension K&C testing capability. And today's K&C test machines take many forms - from "home-built" custom designs, to commercially available purpose-built K&C test rigs.

K&C TESTING AND ITS APPLICATIONS

Laboratory testing, because it is repeatable and takes place in a controlled environment, provides the necessary measurement accuracy for proper suspension K&C development work. Typically, K&C lab work is used as a precursor or as a supplement to road/track testing. As a precursor, K&C measurements can be used to confirm designs and suggest changes before road testing even begins, thus reducing overall test hours and expenses. As a supplement, K&C measurements can be used in an iterative manner with road/track test matrices (and simulation models) to quickly identify and document suspension component changes and their influences on driving performance.

In order to effectively supplement road testing, K&C testing must be efficient – i.e. acquiring measurements and converting them into some useful format must happen quickly. This is where purpose-built K&C rigs have a significant advantage over home-built K&C measurement equipment and adapted machines (machines originally designed for other purposes). What may take a week to measure using the latter, may only take a few hours on a purpose-built K&C rig, such as the SPMM by Anthony Best Dynamics, Ltd. [3]. (See Figure1.)

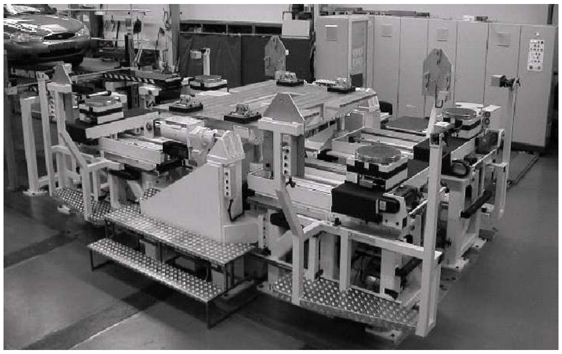

Figure 1 – SPMM by Anthony Best Dynamics, Ltd.

By precisely exercising a vehicle and its suspension, K&C machines can efficiently extract data which is otherwise very difficult to obtain. Typical measurements include, but are not limited to:

- Suspension rates and hysteresis
- Bump/Roll steer & camber
- Roll stiffness distribution
- Instant Center locations (roll centers, anti- ratios, etc)
- Longitudinal/Lateral compliance steer
- Aligning moment compliances
- Camber stiffness
- Steering system characteristics

As mentioned above, there is no shortage to the amount of data which can be produced during a standard K&C test. As a result, some practicality is required when making K&C measurements and processing results. Cross-plots of irrelevant data do nothing but add clutter, yet one does not wish to overlook valuable data. And equally important to properly extracting vehicle design and simulation inputs, is the perspective to step back and make qualitative sense of K&C measurement results. Even with highly developed simulation capability in place, there is no question that efficient suspension tuning and set-up work requires at-a-glance knowledge of key suspension parameters, and how changes in these parameters may affect vehicle performance.

K&C DATA INTERPRETATION

K&C measurement data at its minimum is a collection of cross-plots for a particular vehicle in a particular state of tune. K&C measurement data at its pinnacle is an entirely different way to look at a suspension; it is a way to see the suspension as a system, and to glimpse its real contribution to overall vehicle performance.

Measurable vehicle performance (be it an understeer gradient, a ride frequency, or a lap time, etc.) depends entirely on system-level parameters, *not* individual component specifications. This admittedly seems like a rather odd statement, when it is known that changing a front sway bar diameter can indeed alter a lap time. For the statement to make sense, a bit of a paradigm shift is required: From the vehicle's perspective, its lap time does not change as a result of a component change (like a front sway bar), but rather as a result of a change in a system parameter (like a roll stiffness distribution or, perhaps more appropriately, a tire load distribution).

All standard suspension K&C measurements, by their very nature, are system measurements. Toe curves, camber compliances, anti-dive coefficients and the like are all measurements that describe how a number of components work together. And again from a vehicle's perspective: A vehicle does not care what components are needed to create its toe curves; it only cares that its wheels move in a prescribed and predictable path, and its relevant performance is determined by those wheel paths. Understanding this fact is actually the key to properly managing K&C data, and to successfully using K&C results to assist with practical suspension tuning and development. Below are some of the primary types of K&C data studies, which in effect are methods by which K&C results can be repackaged to maximize the benefit to the suspension tuner.

BASIC PARAMETER TRACKING

Typically, K&C test results are post-processed and viewed graphically as cross-plots of measurement channels (See Figure 2). Basic parameter tracking is nothing more than a direct look at these K&C graphical results, without too much further processing. This can be quite helpful, but it represents only the starting point for K&C data studies. (Most purpose-built K&C rigs offer an array of calculated channels in addition to true measurement channels. For example, "Camber" as shown in Figure 2 may actually be a calculated result from a number of K&C rig transducers.)

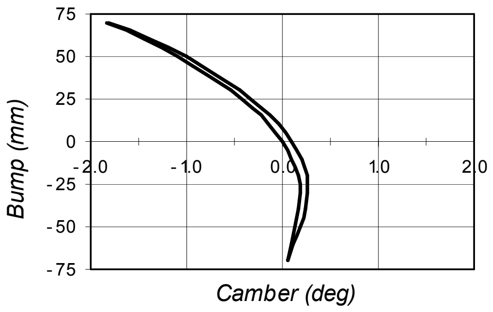

Figure 2 – Bump Camber

In brief, the following can be gained from basic K&C parameter tracking:

- Ensure suspension behavior matches design intent
- Quickly locate build errors (incorrect design, incorrect part application, loose bolts, etc.)
- Calculate gradients over range(s) of interest (or apply curve fits as needed)
- Assess individual parameter specifications, acceptable values, etc.
- Evaluate symmetries/asymmetries
- Directly feed vehicle simulations

Although there is almost unlimited flexibility in the test modes and data extraction from a K&C rig, there is some benefit to standardizing the post-processed results.

Standardization avoidance is usually related to the assumption that valuable data will be "lost" if reported data sets are somehow limited. But if done thoughtfully over a period of time, results standardization will end up capturing a majority of useful measurements while significantly limiting the clutter of superfluous cross-plots. And if properly referenced and saved, no raw measurement data is really lost, regardless of post-processing preferences. In fact, having access to the raw data from K&C tests is always very useful – be it for data import/export, or for diving in and having a more detailed look at a particular measurement.

As mentioned above, K&C measurement data at its minimum is a collection of cross-plots. So "basic parameter tracking" is really just the starting point for extracting real benefit from K&C tests, and as such it may only be of limited benefit to the suspension tuner. However, although this represents a very basic review of K&C data, basic parameter tracking is a necessary precursor to the other data studies described below.

BENCHMARKING

In the classic sense, K&C benchmarking is the comparison of test results from multiple vehicles within a large database of known results. In the automotive industry, for example, benchmark studies are often summarized by a series of average-with-tolerance maps for different vehicle classes (saloon, sport, economy, etc.). (See Figure 3).

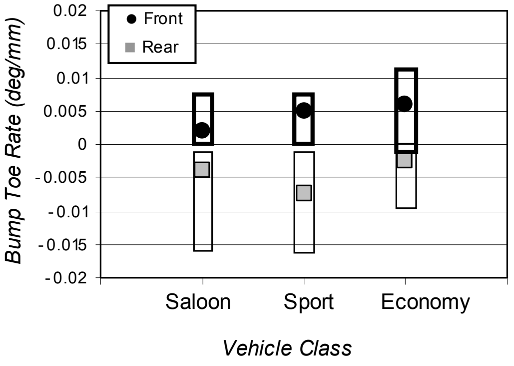

Figure 3 – Benchmarking by Vehicle Class

These maps are particularly useful during the design of new vehicles, where placement into existing performance sectors is scrutinized. A map such as Figure 3 is created by linearizing toe over a particular bump range, say ±20 mm, and comparing the results for as many vehicles as possible. Over time, as a K&C measurement database grows, trends begin to emerge. *Qualitative* knowledge of the relationship between suspension system performance and overall vehicle performance is all that is really needed to successfully use benchmark maps in the early stages of suspension design for a new vehicle. For example, collective K&C benchmark parameters for sporty vehicles may be decidedly different from economy-class vehicles, and it may be inferred that certain parameter shifts, if properly applied, might be used to enhance the sporting feeling of an otherwise mundane economy car.

In addition to multi-vehicle comparisons, K&C benchmarking can also be applied to a single vehicle to study multiple part changes. Compared to "parameter envelope" studies (discussed below), single-vehicle benchmarking can be thought of as a broader look at K&C results – often an at-a-glance review of gradients or reduced data. For a race vehicle, for example, one purpose of such benchmarking might be to identify where suspension set-ups for a particular venue are placed relative to a larger tuning window.

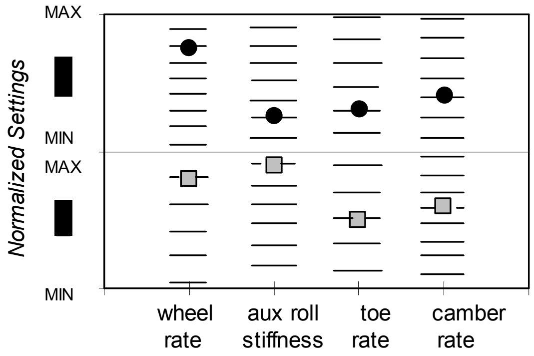

Figure 4 – Benchmarking Single Vehicle Settings

A map such a Figure 4 is created by normalizing the tuning/adjustment limits for the front and rear suspension, and recording the actual parameter set-ups used on race day. K&C measurements are used here to calculate the relative placement of the set-up marks within the adjustment windows (in Figure 4, this is based on preparatory K&C measurements of wheel rate, roll stiffness, toe rate, and camber rate for various part changes). Information such as this can be used to supplement "part sheets" or "spec-sheets" to help indicate alternative tuning changes (or even future design changes – indicated when acceptable vehicle performance consistently requires that parameters are pushed to their tuning limits).

MIGRATION STUDIES & PARAMETER ENVELOPES

Migration studies, to some extent, are related to the single-vehicle benchmark studies described above. However, rather than looking at a broad collection of reduced results, migration studies delve into the details of a particular suspension change.

Because laboratory K&C testing is so repeatable and controlled, it presents an ideal forum for efficiently investigating component changes (and the resulting migrations of key suspension parameters) on a single vehicle. Running "part sweeps" is perhaps one of the most common and practical utilizations of suspension K&C testing capability. Subtle changes in suspension parameter measurements can be detected when a test is repeated after various hardware bits are changed, and a large number of such hardware changes can be explored through K&C testing (as in Figure 5) in a relatively short period of time.

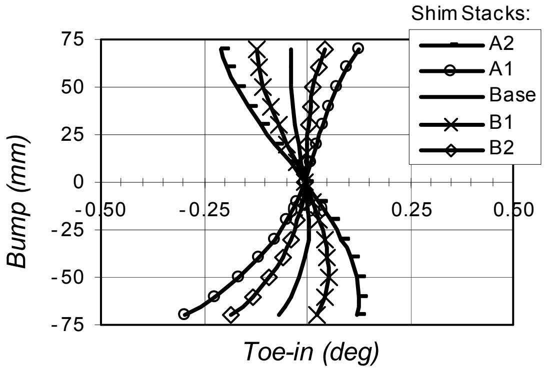

Figure 5 – Toe Migration

From a practical suspension tuning perspective, however, one must be able to *efficiently* extract key suspension information from these K&C part sweep test sessions, and have some method to associate measured suspension system-level parameters (toe gains, camber gains, roll stiffnesses, etc.) with actual tuning changes. For example, rather than only tracking physical adjustments to front and rear sway bars (diameter changes, drop-link or blade adjustments, etc.), a track-side spec-sheet can include a roll stiffness coefficient or a roll distribution balance – some additional system-level indicator based on K&C part sweep testing. In addition to effectively raising the level at which component changes are viewed, these system-level indicators can truly serve as beacons to help guide suspension tuning choices.

Parameter envelope studies, a subset of migration studies, are a way to take the classic engineering approach – i.e. explore the limits of a particular question in order to gain insight. In this case, envelopes offering a useful view of suspension behavior can be established by measuring suspension K&C performance when parts and/or adjustments are maximized and minimized.

A suspension's physical tuning limits can be determined by the suspension design, its physical constraints, parts availability, and, of course, motorsports sanctioning rules. And the limits for specific K&C parameters are very important, as are the relationships between the limits of tunable groups (i.e. Understeer adjustments can be maximized by overlapping envelopes of multiple part adjustments affecting, say, bump steer) Figure 6 shows the bump steer envelope created by max/min adjustments to a tie rod shim stack. Any actual settings, as seen previously in Figure 5, will necessarily fall within this envelope.

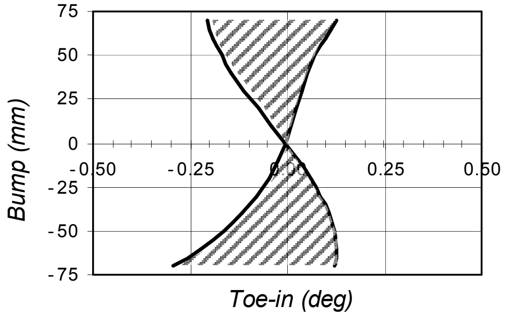

Figure 6 – Toe Adjustment Envelope

Although less comprehensive than a full migration study, more detail is available from such envelopes than from single-value linearized rates or gains. And knowing the suspension characteristics at just the limits of adjustability *can* be quite useful – particularly in simulation work. Ideally, actual on-vehicle set-ups do not require limit tuning of key parameters, but in a simulation environment such limits can be quickly explored to determine overall vehicle performance envelopes.

In addition, envelope studies represent an economical method of K&C testing, as all available parts/adjustments do not need to be tested, only the maximums and minimums. Thoughtful set-up of a single K&C envelope test session can lead to an efficient gathering of most, if not all, suspension tuning effects.

In a practical tuning sense, information such as the bump steer envelope in Figure 6 provides several key insights. For example, when combined with other measurements (K&C measurements of bump steer resulting from other part changes, lateral steer compliances, roll steer characteristics, etc.) this parameter envelope provides supplemental information needed to map the understeer trim and stability gradients of a vehicle for various cornering conditions. Without K&C measurements, this would be quite difficult to accomplish. And collectively, this information can be an excellent guide to track-side tuning adjustments (i.e. Much like a vernier dial, small tuning changes within one window will produce large changes in vehicle response, while others will have subtler influences – and these parameter envelopes can provide a excellent quick reference to "dialing in" a vehicle's handling behavior, so to speak.)

BUDGET STUDIES

Budget studies provide a unique way to look at the interplay between multiple suspension parameters. A "budget" is merely a description of how individual suspension parameters contribute to a defined total. As a simple example, a vehicle's roll stiffness budget might be expressed as follows:

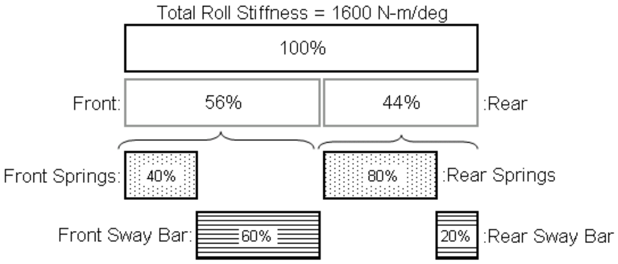

Figure 7 – Roll Stiffness Budget Example

Although this is a basic example, capturing only a single suspension set-up, a budget like Figure 7 can nonetheless provide a quick view of a vehicle's roll stiffness makeup – in this case, the limited tuning potential of the rear sway bar is readily evident. A more insightful budget example, expressed in a slightly different way, is presented in Figure 8.

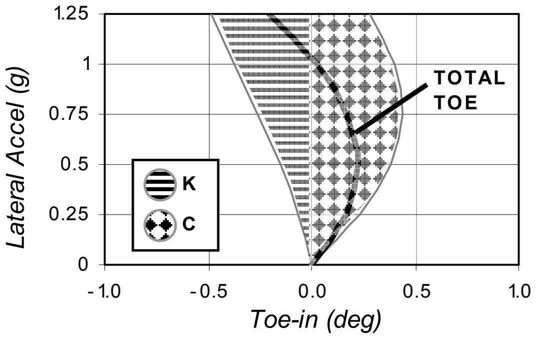

Figure 8 – Roll Steer Budget Example

Although Figure 8 depicts only a front right suspension, roll steer budgets for each corner of a vehicle can readily be constructed from standard K&C test measurements (and some supplemental information such as overall vehicle roll per "g", and general tire force characteristics). In this roll steer budget, kinematic steer and compliance steer are brought together as a function of a vehicle lateral acceleration, but, if desired, they could just as easily be expressed relative to lateral contact patch loads (or in whatever format might be necessary to promote suspension tuning insight).

A quick glance at Figure 8 shows that in a 1-g corner, total front right steer is nearly zero. This in itself is helpful, as it tells us a part of the steady-state trim condition and understeer level. But, perhaps even more insight is gained by readily observing the *way* in which this toe level is achieved (i.e. the K-budget and the C–budget). In this case, toe deflections are in fact occurring at significant levels, but the kinematics and compliances happen to be opposed and nearly equal, effectively counteracting each other.

The K&C roll steer budget has a strong impact on handling; Compliances can create a direct turn-in feeling (as only the unsprung mass is required to react, and can thus do so quickly), whereas kinematic steer requires chassis roll (which takes some amount of time to develop). Therefore, the way in which a vehicle "takes a set" upon corner entry is highly influenced by this particular parameter set. And even in cases where the total magnitude of both "K" and "C" remains small (in a race vehicle, for example), the kinematic and compliance steer *balance* is still quite important to responsiveness, stability, and driver feeling. As such, K/C budgets and proportionality ratios are yet another good candidate for supplemental tracking on suspension tuning spec-sheets.

WORK-ENERGY STUDIES

Although meaningful as stand-alone parameters, suspension compliances (and/or stiffnesses) are perhaps most meaningful when viewed relative to other suspension parameters, as in the roll steer budget discussed above. In addition to simply providing insight into understeer trim (i.e. wheel orientations under load), compliances are also key to understanding a vehicle's response characteristics from an energy perspective.

In a traditional approach, a vehicle's steady-state yaw rate gain (i.e. the amount a vehicle will turn for a given steer input) can be expressed as follows [6]:

$$YS = \frac{U_x}{\ell + \frac{U_x}{g} K_{us}} \tag{1}$$

In this expression the understeer coefficient, K_{us}, can be as simple or as complex as one desires. In its simplest and most commonly expressed form, the understeer coefficient is defined by the lateral slip angles of the front and rear tires as follows:

$$K_{us} = \frac{W_f}{C_{\alpha f}} - \frac{W_r}{C_{\alpha r}} \tag{2}$$

But K_{us} can also be easily expanded upon to include standard suspension K&C parameters [4]:

$$K_{us} = \underbrace{\left[\frac{W_f}{C_{\alpha f}} - \frac{W_r}{C_{\alpha r}}\right]}_{\textit{Tires}} + \underbrace{\frac{\partial \phi}{\partial a_y}\left(\mathrm{E}_f - \mathrm{E}_r\right)}_{\textit{Roll Steer}} +$$

$$\underbrace{\left[\frac{W_f}{K_f} - \frac{W_r}{K_r}\right]}_{\textit{Lateral Toe}} - \underbrace{\left[\frac{W_f}{H_f} + \frac{W_r}{H_r}\right]}_{\textit{Chassis}} + \underbrace{\cdots}_{\textit{Etc…}} \tag{3}$$

Through an expression such as (3) it possible to explore numerical relationships between suspension K&C parameters and defined vehicle handling metrics such as understeer gradient and yaw rate gain. Interesting qualitative relationships can be readily observed as well. For example, it can be seen (and rightly so) that a *decrease* in front or rear chassis stiffness actually *improves* vehicle turning ability (as measured by steady-state yaw rate gain).

Paradoxically, however, this traditional approach to K&C parameter inclusion in vehicle modeling can underplay the role of suspension compliance parameters (i.e. The sheer magnitude of suspension and chassis stiffness values necessarily results in small contributions to K_{us} as expressed above). And although physical changes in suspension/chassis compliances are known to significantly influence vehicle handling feeling, it can be hard to get after these changes in a quantitative sense; Diminutive changes in measured (or simulated) vehicle metrics do not always correspond to the control and response gains perceived by a driver. One possible method for resolving these discrepancies is to quantify, in energy terms, the various suspension system compliances.

The traditional approach is one of Force/Deflection: Changes in understeer in equation (3) are driven by changes in the effective lateral slip ratio, which, in turn, is based upon estimates of effective steer angles at the front and rear of the vehicle. However, a stiffness change that is very noticeable to a driver (for instance, a chassis stiffness change) may be nearly negligible when viewed in terms of such an "effective steer angle change."

An energy approach requires yet another paradigm shift – one in which a vehicle is viewed as a collection of springs (or potential energy storage devices). During cornering a portion of the driver's handwheel input, intended to produce lateral acceleration, is actually "used-up" in potential energy storage (suspension, tire, and chassis deflections, etc.) Putting energy into storage takes time during corner entry, and it takes time to recover that energy during a corner exit or directional change (and under-damped energy storage devices, nearly all the energy-holders in the suspension, will overshoot upon release as well!).

In order to quantify this stored energy for the chassis and suspension components, the potential energy during cornering might be expressed as follows:

$$\textit{Yaw Energy Storage} = \sum PE_{sus+chassis} =$$

$$\underbrace{\frac{1}{2}R_\phi \phi^2\bigg|_{F+R}}_{\textit{Roll}} + \underbrace{\frac{1}{2}N_\theta \theta^2\bigg|_{F+R}}_{\textit{Lateral Sus.}} + \underbrace{\frac{1}{2}T_\theta \theta_c^2\bigg|_{F+R}}_{\textit{Chassis}} + \underbrace{\cdots}_{\textit{Etc.}} \tag{4}$$

As was the case with K_{us}, "yaw energy storage" can be as simple or complex as one desires. (Note that the tire is *not* included in this expression because lateral slip deflection is a necessary precursor to lateral force generation. That said, *other* tire deflections not contributing to lateral slip generation could certainly be included as needed.)

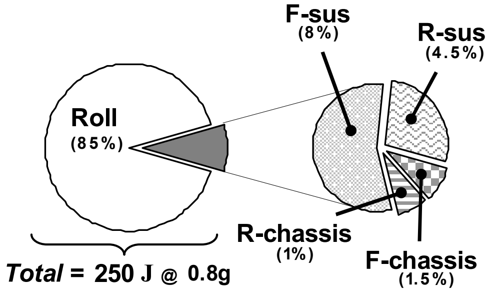

Fig 9 – Yaw Energy Storage Contributions

An energy storage expression such as equation (4) can be used on its own to assess the relative energy storage of various parameters, as in Figure 9. And these relationships (in the form of energy ratios, etc.) could again be added to a suspension spec-sheet to form tuning targets and provide a driver communication tool.

Yaw energy storage can also be used as a basis for additional expressions, such as that for "yaw efficiency" (i.e. The percentage of vehicle input energy that is converted to lateral vehicle motion):

$$\text{Yaw Efficiency} = \frac{\sum KE_{yaw} - \sum PE_{sus+chassis}}{\sum KE_{yaw}} \tag{5}$$

$$\text{where,} \quad \sum KE_{yaw} = \frac{1}{2} m U_y^2 \tag{6}$$

In viewing an expression like equation (5), it is temping to assume that ideal vehicle performance would be achieved when zero energy is given up to potential energy storage (i.e. 100% yaw efficiency). But this, in fact, is not the case. Some compliance is absolutely necessary for a human driver to physically control a vehicle. Control issues aside, it feels natural for a vehicle to take some amount of time (however small) to "take a set" during cornering as various deflections align themselves with a driver's intentions. Too much compliance, of course, results in a loss of response "directness." So practical yaw efficiency targets lie somewhere south of 100%, but not *too* far south. By way of example, contributions as represented in Figure 9 produce a yaw efficiency of ~95% for a medium-sized vehicle.

Suspension and chassis compliances can often be more readily tuned to match energy contribution targets than traditional Force/Deflection targets. The structure of the potential energy expressions (squared deflection terms) can allow more reasonable system comparisons due to favorable relative magnitudes amongst terms, and can even eliminate the bit of confusion regarding understeer/oversteer sign conventions present in traditional expressions such as equation (3). Also, the energy magnitudes typically match well with intuition (i.e. large relative deflections result in large relative energy terms), making correlation with qualitative driver impressions somewhat easier.

TUNING WITH K&C DATA

The goal of any suspension set-up session or suspension development program is to arrive at a state of tune that allows a vehicle to perform at the true limit of its capabilities. This ideal, of course, is rarely achieved as it is often compromised by both intentional (and unintentional) trade-offs. In addition, certain fundamental physical constraints are typically in place, and there is no real way to tune around them. For example, a suspension tuner who wishes to optimize vehicle handling, more often than not, must work with a fixed vehicle mass, a fixed weight distribution and overall c.g. height, and a fixed wheelbase and track width at the front and rear. (From the very start, total lateral weight transfer is a known and inescapable quantity!)

There are many approaches to vehicle handling set-up, and the approach offered here is not intended to supplant any existing methodology, nor is it intended to represent the tuning philosophy of anyone other than the author. The approach below is only presented to provide an example of how one might actually apply some of the above suspension K&C data interpretation concepts. And although this discussion will deal exclusively with the set-up of a race vehicle, similar concepts can be applied to production vehicle suspension tuning.

At its heart, suspension set-up can be broken down into two separate, sequenced stages:

1. Maximize the mechanical grip at each vehicle corner. This can only be achieved if front/rear suspension balance is thoroughly understood. K&C testing and mathematical modeling is required here.

2. Meet feeling/control requirements of the driver. This can be achieved through suspension trim adjustments *overlaid upon* a solid mechanical grip foundation. K&C testing is necessary to support proper trim mapping.

Although these steps seem straightforward enough, the two can easily become jumbled during any suspension tuning session. For example, one might unintentionally unbalance a vehicle's grip capability with suspension adjustments intended to correct, say, unwanted understeer. Although stiffening or softening one axle in roll does change the front/rear lateral weight transfer distribution, it is usually at the expense of one of the axle's mechanical grip. Ideally, each axle should transfer weight in roll without limiting the roll displacement at the other end. Set-ups that deviate from this ideal will reduce a vehicle's overall lateral grip capability (and unduly punish the tires).

K&C TESTS AND MECHANICAL GRIP

Running and documenting "part-sweep" K&C tests as described above is perhaps the most efficient way to investigate front/rear suspension balance and create tuning guides to maximize mechanical grip. In addition to standard recorded tuning spec-sheet numbers (spring rate, sway bar size/settings, static corner weights, static toe/camber, etc.) a few additional K&C-derived tracers should be regularly tracked as well: Namely roll moment arms, suspension roll stiffnesses, (or roll stiffness coefficient), and auxiliary roll stiffnesses. Including these tracers on spec-sheets brings them into the realm of the "familiar" as they should well be – these system-level parameters change along with suspension component changes, and they are necessary to calculate lateral weight transfer and axle roll displacements, and ultimately mechanical grip.

Having access to proper K&C machine-measured (as opposed to calculated) values is very important. For example, it is perhaps more wise to use actual measured force roll centers (or jacking ratios) when calculating roll moment arms, than to rely on geometrically constructed roll centers from a computer model; and actual roll stiffness measurements made on a K&C machine (with its ability to detect chassis/tire contributions and compensate for lateral scrub) are superior to calculated values as well.

Armed with K&C part-sweep measurements it is possible to document various front and rear suspension set-ups, and determine if they are complimentary in terms of maximizing mechanical grip. Each axle set-up will have its own measured suspension parameters contributing to a unique weight transfer and roll displacement when subjected to lateral loads, calculated as follows [7]:

$$WT\Big|_{\substack{per\,axle\\ per\,g}} = \underbrace{\frac{(UW \cdot H_{UCG})}{T}}_{\textit{un-sprung WT}} + \underbrace{\frac{(SW \cdot H_{RC})}{T}}_{\textit{WT via RC}} + \underbrace{\frac{(SW \cdot LM)}{T}}_{\textit{WT via SM}} \quad (7)$$

$$\phi\Big|_{\substack{per\,axle\\ per\,g}} = \frac{(SW \cdot LM)}{R_{\phi}} \quad (8)$$

But ultimately, the front and rear must work together to maintain the best possible mechanical grip at all four corners. So how can unwanted front/rear balance trade-offs be avoided? Several methods have been proposed for combining front and rear suspensions in a single vehicle model and a number of commercial vehicle dynamics software codes are available for detailed investigations [5,7]. These methods are completely valid, but require computer resources and a fair amount of time, and thus remain somewhat elusive for hands-on suspension tuners (4-wheeled vehicles are statically indeterminate; solving for all the vertical and lateral loads while cornering is not an easy task). One method, proposed by Bolles [8], which is perhaps more accessible to hands-on suspension tuners, involves "matching" front and rear suspension roll angles - i.e. independently calculating the front and rear roll angles that *would be* achieved for a given lateral acceleration, and making actual suspension tuning changes such that the calculated angles closely match (as they must in reality). This method can be used to arrive at nicely distributed vertical tire loads, and since vertical tire loads ultimately control lateral load capability, this does lead to well-balanced suspension set-ups that maximize mechanical grip for a given initial weight distribution.

This grip-maximizing methodology can be expedited with suspension K&C testing, by running multiple part-sweep tests and finding matched front/rear set-ups in the lab. It is a very quick way to predict good suspension set-ups in advance of on-track testing sessions, and it also allows for session tuning changes to be re-evaluated quickly to ensure grip potential has not been compromised by session tuning (although tire temperatures will quickly call attention to this as well!).

In brief, front and rear suspension set-ups are considered independently (See Figure 10), and equations (7) and (8) can be used calculate axle roll angles and vertical tire loads for each measured suspension set-up during cornering. K&C measurement matrices can then be revisited and evaluated for good front/rear pairings based on calculated axle roll angles, which will then lead to the best combination of tire vertical loads (and thus total grip). Typically multiple front/rear combinations are possible, with the final choice(s) being dictated by other preferences (total roll displacement targets, aero considerations, etc.).

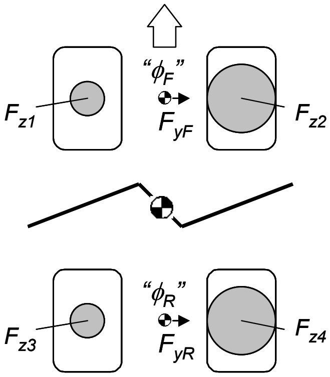

Figure 10 - Front/Rear Grip Map

K&C TESTS AND CONTROL REQUIREMENTS

Once satisfactory overall grip levels have been secured, additional suspension tuning is usually required to satisfy driver preferences and truly refine a vehicle's handling characteristics. The orientation of the wheels and the energy stored in various suspension/chassis components *will* change during directional transitions and throttle/brake applications. A driver receives feedback from these changes and is either comfortable with them, or is forced to provide corrections and compensations in order to extract desired performance levels from the vehicle. Improper suspension set-ups can be felt during corner entry and/or corner exit, when directional control forces are changing direction or magnitude.

As discussed above, tuning changes to load-transfer components can inadvertently lead to mechanical grip level reductions. For this reason, it is important to attempt to satisfy driver and control requirements directly with suspension kinematics and compliance tuning (assuming, of course, overall grip performance is already satisfactory). Not surprisingly, suspension K&C testing and data tracking is essential to this work.

One solid approach to suspension "K&C tuning" is to supplement standard spec-sheets and driver notes with additional K&C tracers and recorded segment times (a sub-set of a full lap time where a key corner on a race track is timed - capturing corner entry, mid-corner, and exit). As shown in Figure 11, a simple spec-sheet can be developed (an evolution of Figure 10) to record a K&C trim set-up and link it to recorded on-track performance.

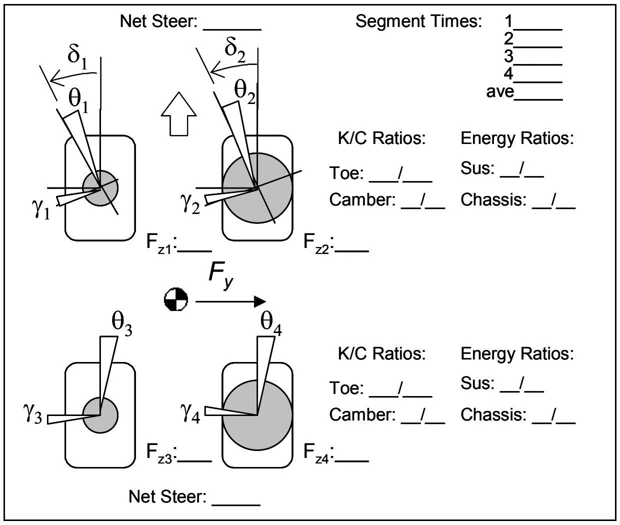

Figure 11 – Example K&C Spec-Sheet

This example serves as a quick visual reference to critical loads, orientations, and energy storage. It is meant to serve as a snap-shot of vehicle loading and trim during mid-corner quasi-steady-state g-loading. In the handling regime, events occur slowly (sub-1.5 Hz), making such quasi-steady snap-shots, and K&C analysis in general, applicable.

Suspension K&C measurements for toe and camber corresponding to a desired lateral load condition (typically mid-corner) can be used to directly fill in such a spec-sheet. Tire vertical loads, K/C ratios (budgets), and energy ratios are all calculated as described above.

As with anything else, a spec-sheet such as this can be as simple or as detailed as one desires. It can be expanded to include other key tracers, linked with other standard recorded specs (like tire temperatures, static alignments, etc.), combined with traction/braking forces to capture corner exit/entry events, or even reduced to capture only mid-corner net steer at the axles.

The goal, of course, is to develop an additional spec-sheet that provides another tuning reference – specifically for supplementing driver feedback and guiding suspension K&C adjustments, and geared toward dialing-in a vehicle for improved segment times. Successfully integrating K&C-tracking into actual test sessions can lead to big performance payoffs, however, special considerations and provisions are often required. For example, changes to camber gain to improve tire wear/temperature can actually wrap-around and reduce lateral grip (due to roll center shifts). Also, special preparations are often required to properly explore compliance shifts (since compliances are typically not readily tune-able parameters).

Actual target levels for suspension trim levels can vary significantly among drivers, vehicles, and tracks, and this paper cannot presume to propose such targets. However, it can be said that with continued use, additional K&C tracers and K&C-based supplemental spec-sheets can become invaluable tools to suspension tuners. Over time, set-up trends and preferences emerge, and documenting these trends in terms of system-level tuning parameters allows suspension tuning to be approached from new directions – a valuable option when pre-race track testing time is limited.

CONCLUSION

Although as-measured K&C parameters are useful for suspension design and development work, some K&C data repackaging is often required to maximize the benefit to the suspension tuner. The end goal of this repackaging is to efficiently add a few more valuable system-level "tracers" to suspension tuning worksheets, spec-sheets, and logs. This paper presents several methods by which standard K&C measurements can be converted into more manageable, track-able, and descriptive parameters.

By stepping beyond basic parameter tracking, and even migration studies, it is possible to create a larger, more encompassing view of suspension performance – a view where the interplay and balance between various suspension parameters becomes more apparent, and where suspension tuning and set-up work is directly related to making the most of these balances. As shown, key suspension parameter balances can be conveniently expressed and tracked through slight K&C data reformulations such as budgets and energy ratios.

K&C measurements are really system-level descriptions of a suspension, and as such they describe the accumulated contribution of multiple components. Having a useable reference (based on K&C measurements) that connects component changes or tuning adjustments with suspension sub-system performance essentially allows the suspension tuner to approach a tuning session from two different directions. Hopefully this can help reduce trial-and-error part swaps and provide some intermediate points of reference to help translate subjective feeling feedback into real tuning guidelines.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

a_y: lateral acceleration of vehicle cg

C_α: effective axle cornering stiffness

E: average roll steer gradient

F,f: indicator, subscript denoting front suspension

g: gravitational constant

H: effective lateral chassis stiffness

H_{RC}: roll center height

H_{UCG}: unsprung mass c.g. height

KE: kinetic energy

K: effective lateral toe stiffness

K_{us}: understeer coefficient

ℓ: wheelbase

LM: roll moment arm

m: total vehicle mass

N_θ: suspension lateral torque toe stiffness

PE: potential energy

R,r: indicator, subscript denoting rear suspension

R_ϕ: roll stiffness

SW: sprung weight

T: track width

T_θ: lateral chassis stiffness

UW: forward velocity of vehicle cg

U_x: unsprung weight

U_y: lateral velocity of vehicle cg

W: axle weight

WT: weight transfer

YS: steady-state yaw rate gain

δ: steer angle

γ: camber angle

ϕ: roll angle

θ: toe angle

θ_c: effective lateral chassis angle wrt vehicle center-line