



Over the course of the last one hundred years, the design of the diamond frame road racing bicycle has evolved surprisingly little. Nonetheless, many riders complain about not feeling comfortable on their bicycles but do not always understand why that is the case. Few complain that their bicycles do not handle as they would wish, silently accepting that a new bicycle does not feel as intuitive as the bicycles of their youth. They usually ascribe the difference to their rose colored backward looking glasses.

In fact, while correct bicycle design and engineering requires a thorough understanding in order to produce a very high performing bicycle, it is not impossible to achieve. In the following pages, we will attempt to outline our thoughts on the subject.

Motion Devices SA  
P.O. Box 235  
109 Route d'Arlon  
L-2012 Luxembourg  
[www.rolobikes.com](http://www.rolobikes.com)  
[info@rolobikes.com](mailto:info@rolobikes.com)

## Contents

A quick look at frame building	2
What has custom meant?	3
When is a monocoque a monocoque?	4
A quick background on carbon fiber	5
Why a custom lay-up?	6
It turns out that geometry is not as easy as it looks	7
The rule of thirds	8
Stack and reach explained	8
The importance of being consistent	8
Top tube length	9
Stem length	10
Handlebar reach	10
Handlebar drop	10
Seat tube length	11
Seat tube angle	11
Bottom bracket drop	11
Wheelbase	12
Chainstay length	12
Seatstays	12
Center of gravity	13
Front-end geometry	13
Head angle and wheel flop	13
Fork offset or fork rake	14
Geometric trail	14
Crosswind	16

The most elementary and fundamental aspect of the bicycle is frame geometry. It determines fit, handling and comfort, the enjoyment derived from riding being directly dependent on those three basic parameters.

In terms of importance, we order these three basic design parameters as follows:

1. Fit
2. Handling
3. Ride

Basic comfort and handling need to be addressed through frame geometry rather than through special component choices at a later stage. Once the basic geometry has been established to drive both the fit and the handling, and only then, can we tackle the ride aspects of the bike's design, namely the structural engineering challenges.

The Motion Devices process hierarchy of design parameters then flows in the order to the right.

The parameters that affect a bike's fit are more or less well-understood, albeit not always that well implemented. On the other hand, the parameters that affect handling characteristics remain poorly understood. The interaction of these different parameters is complex to the point where still today, some fail to understand why the bicycle remains stable and upright when moving.

Although most of today's bicycle nomenclature stems from the time when bicycles were almost exclusively made with tube to tube metal construction, our bikes use a full monocoque composite construction. The fundamental elements and geometry of the bicycle frame however remain the same.

## A quick look at frame building

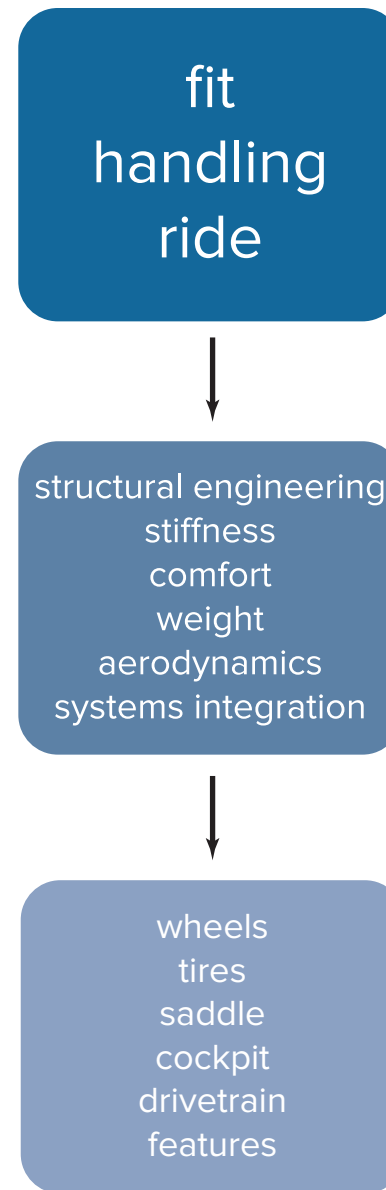
As metal frames evolved and the industry grew, a number of small fabricators emerged who offered a custom service. They purchased steel and later aluminum tubing from Reynolds or Columbus and then welded the tubes together to fit their customers.

The 'ready-to-wear' segment generally did not fully grasp frame geometry leading to bikes with poor fit, handling and comfort characteristics, so the small fabricators developed a niche in which they offered better fit for customers who could afford the service.

The industry metal of choice changed over time from steel, to aluminum and titanium. Although aluminum and titanium require more skill to manipulate and weld, the techniques were effectively the same. And since metals are isotropic materials, the engineering skill required was within reach for virtually all of these fabricators.

When carbon became the material of choice in fabricating frames in the late 1990s, new challenges arose. Because carbon is an anisotropic material, the engineering skill required suddenly moved out of reach for many fabricators. But there was a potential solution: they would continue to use essentially the same manufacturing techniques as they had before and would rely on carbon tubing which they would 'weld' using carbon in a wet lay-up process.

While metal tubing could have varying wall thicknesses, meaning the walls could be thinner at the middle of the tube and thicker at the ends, it required complex and very expensive engineering, tooling, and methodology, such as hydro forming. But it was more difficult to achieve. The manufacturers now had to choose between trial and error or engineering design, which for the most part required finite element analysis (FEA). FEA suddenly



required much more computing power than was within the reach of all but a handful of manufacturers. To move forward, the smaller fabricators who lacked the resources for the advanced engineering and capital investment for tooling had to find another solution. Essentially, to this day they have to rely on the tube manufacturers for the mechanical properties of the tubes they source. Of course, they are also limited to a choice of whatever the tube manufacturer sells. Usually that means a choice between two or three tube set options.

The alternative approach was to manufacture monocoques. The fabricators who had the engineering expertise and access to the computing power could now design any shape of frame imaginable, choose the materials, and dial in the mechanical properties desired at any given point on the frame. The flexibility means that any weight or stiffness is achievable within the range of physical property limits of the carbon itself. But each frame size requires its own mold, its own templates for the carbon and its own engineering specification for the prototypes as well as production, which only intensifies the need to get it right the first time. The initial investment was and remains very significant because the molds are costly to develop and make, sourcing the carbon is not always straightforward, and the manufacturing process involves considerable manual labor and stringent quality control, particularly for low volume production. These issues help explain why virtually all of the ‘monocoque’ fabricators moved their production to low cost environments.

## What has custom meant?

In the past, and even still today, a custom frame means custom geometry using tube to tube construction. A customer calls one of the custom fabricators and begins a process of designing the frame. Together they discuss head tube and seat tube angle, and adjust the length of the top tube. After what is usually a long discussion, they agree to the geometry and the customer can then choose between two, or at most three, sets of tubing which will determine the overall

stiffness, and by extension weight, of the frame. The customer will feel that he is getting his own bespoke frame to fit just him, different from any other on the market. And, in a certain sense, that is true.

While nothing can replace the feeling of having a product made just for you, there are a few important points about this idea of custom geometry. Let’s start by looking at human physiology.

## Human physiology

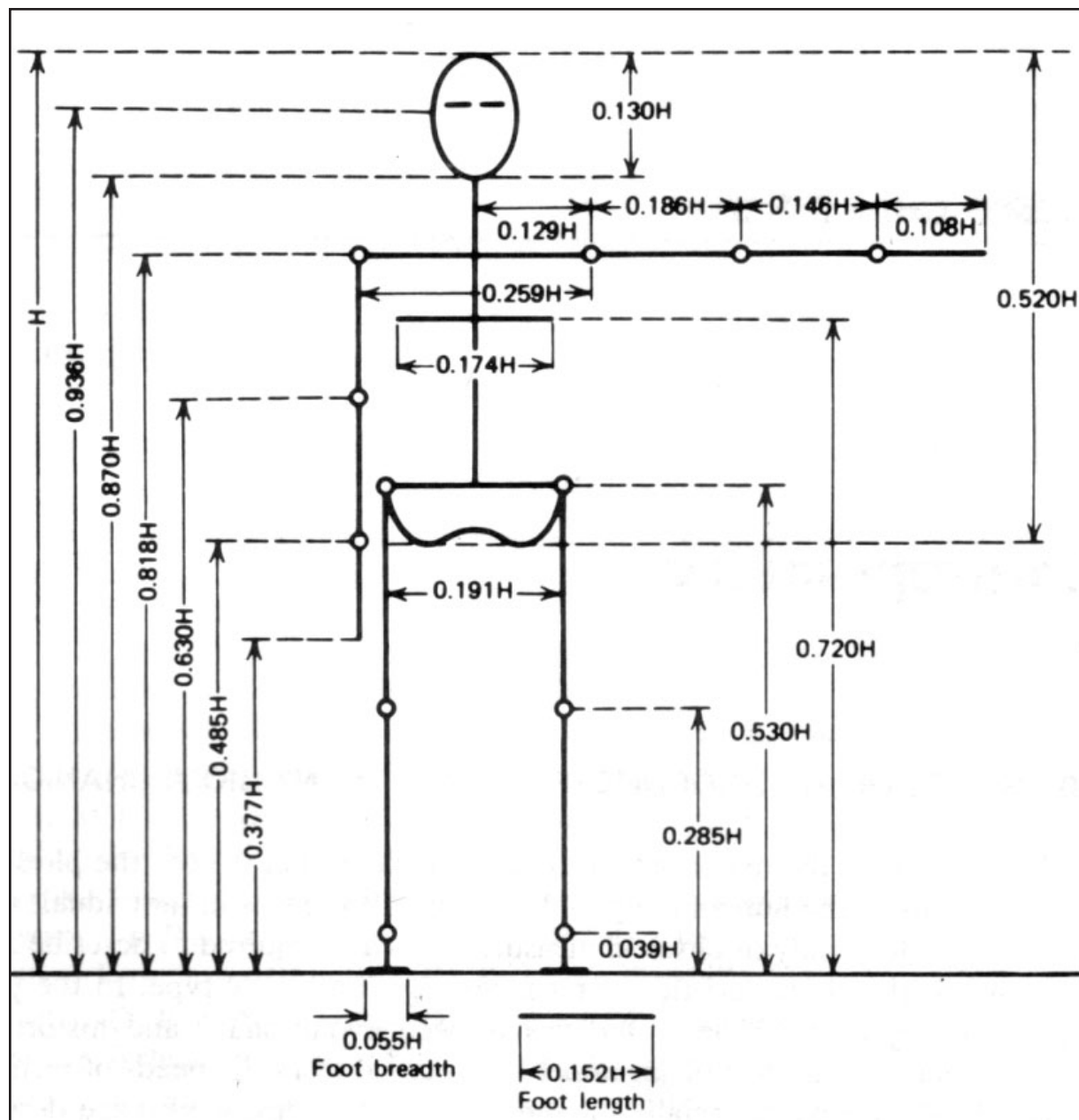
Leonardo da Vinci’s Vitruvian Man illustrates human proportions rather clearly. While taller people obviously have longer limbs than shorter people, the proportions remain essentially the same regardless of how tall someone may be. Put another way, have you ever noticed that a chair’s seat is almost always the same height, and you are uncomfortable if it is either too low or too high? Desks, dining tables, and kitchen counters too? We notice differences as small as 1cm, although we may not always realize it.

Most of us are physically proportioned in a tight statistical band but for some, custom geometry is the only solution, if for no other reason than stock frames are not made in all sizes. Take Shaquille O’Neal as an example. He is 216cm (7’1”) tall and weighs roughly 150kgs (330lbs). There is no manufacturer today who makes a standard frame large enough and strong enough to accommodate him - his only option is a custom tube to tube bike.

Some of us also have somewhat above mean asymmetries between our right and left sides such as between our left and right limbs, or our right and left foot. A bike frame however is a symmetrical structure so these types of variations from the mean usually cannot be properly addressed even through custom frame geometry.

But for most of us, if we start out with a correctly designed basic geometry, we can easily fit very comfortably on a bike and make small adjustments through various components. Let’s take a quick look at what we mean.





Source: See David Winter's *Biomechanics and Motor Control of Human Movement*, 4th Edition, published by John Wiley & Sons Inc, 2010

## The contact points

The way you fit on a bike is determined by three sets of contact points: the handlebars, the saddle and the pedals. As long as you sit correctly relative to those three sets of points, you will be comfortable on the bike and achieve optimum performance.

The rails on most saddles allow for up to 20mm of adjustment range.

Seatposts can range from no setback to up to 25mm of setback. Stems can range from 60mm to 140mm, although more typical sizes are 110mm to 130mm. Handlebars can have as much as 20mm difference in reach. Altogether, the range then adds to more than 100mm of adjustable range. And that does not address the range of adjustment achievable through spacers under the stem. Looking at typical frame sizes, a 100mm range in reach alone would represent roughly the difference between a size 50 and a size 60 frame. Could it be that the better question would be why there are no custom stems?

So if humans do not have that much variation in physical proportions, what are the factors that do vary most? Rider flexibility, weight and power output. Those characteristics need to be addressed through the actual tube geometry and carbon lay-up.

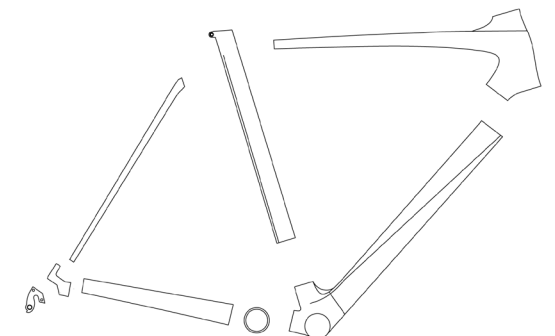
In order to understand the relevance of tube geometry, let's first consider manufacturing techniques and consider a few widely used terms.

## When is a monocoque a monocoque?

A few paragraphs above, we referred to 'monocoque' fabricators. In reality, there are no true monocoque bicycle frames manufactured, although one comes close.

A true monocoque would be a bicycle frame manufactured as one piece. Given the geometry of the rear triangle, making a mold for a pure monocoque would be very complicated since it would have to have a number of pieces that would have to fit together perfectly.

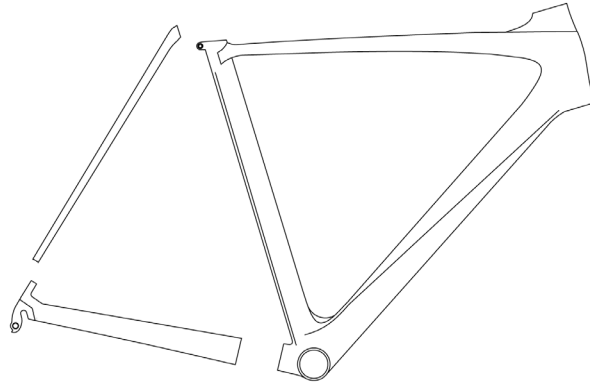
In fact, while many manufacturers refer to their frames as monocoques, they are not. They are actually an assembly of a number of pieces



bonded together, not unlike a tube to tube structure. Rather than using tubes which they then 'weld' through lugs or wet lay-up, these pieces are preformed and then bonded at critical junctures. This method allows a manufacturer to limit the number of molds necessary while still being able to achieve a range of geometries.

The drawback is that every bond creates a discontinuity in the carbon thereby reducing the full capability offered by the use of the material - as we will discuss shortly. But each joint also introduces a further potential for inconsistency in manufacturing as well as a break in load paths, and adds weight.

Our frames are stressed skin structures manufactured in three parts. (Monocoques are a specific subset of stressed skin structures.) By having the key stress areas, specifically the head tube, bottom bracket and seat tube to seat post interface, part of the same structure we are able to control the stiffness and compliance very carefully as well as control the load paths and frequency dispersion.



### A quick background on carbon fiber

Carbon fiber is an anisotropic material meaning that, like wood, it is strong along the length of the fibers and weaker the closer one gets to the perpendicular. (Metals are isotropic materials, meaning that they display the same strength characteristics in all directions.) It is essentially a fabric, and can be used either as a unidirectional product - all the strands are in the same direction - or as a woven twill. Just like any textile, it is weak under compression but strong under tension.

One of the great advantages of working with carbon composites is that the material presents a wide range of capabilities but with some important trade-offs. To begin with unidirectional carbon fiber

is typically used in multiple layers at different angles laid on top of one another in order to achieve specific strength and stiffness characteristics. Twill is stronger in many directions simultaneously but is also heavier. As a result, many structures, such as the wings on the Boeing 787 and our bicycle frames, use many layers of unidirectional fibers sandwiched between outermost and innermost layer of twill. The twill is highly durable and strong, and has different resonant properties from the unidirectional fiber. (The generally accepted alternative to twill is to use two layers of ud, overlaid at  $-45^{\circ}/45^{\circ}$  orientations in order to achieve the same idea as twill.)

While it might appear at first that in order to make a stiffer frame it would be better to use stiffer (higher modulus) carbon only, in fact that is not the case. While it may be lighter in some instances, higher modulus carbon is more brittle and provides far less durability. The key is identifying the correct and desired properties for any given section of tubing and then selecting the appropriate material to achieve those specific characteristics. Finite element analysis, also known as FEA, which requires huge computing power and engineering skill, is the process that optimizes the properties.

While many documents will discuss carbon fiber, they typically do not mention the resin. In fact, the resin is a critical part of the equation. Not only does the resin represent a significant percentage of the weight of the carbon fiber, anywhere from 25 - 40%, it is also critical to choose the resin system that best achieves the desired engineering properties. Choosing resin systems requires a thorough understanding of carbon composite engineering and construction, and an in-depth knowledge of the available resin systems. A carbon frame without resin would be as stiff as a wool sock.

There are a number of methods of fabricating structures using carbon composites, but we will only address two: rtm and pre-preg. Pre-preg, or pre-impregnated carbon, means that the carbon fiber has been impregnated with the resin system by a supplier and then shipped to the fabrication location. The carbon needs to remain

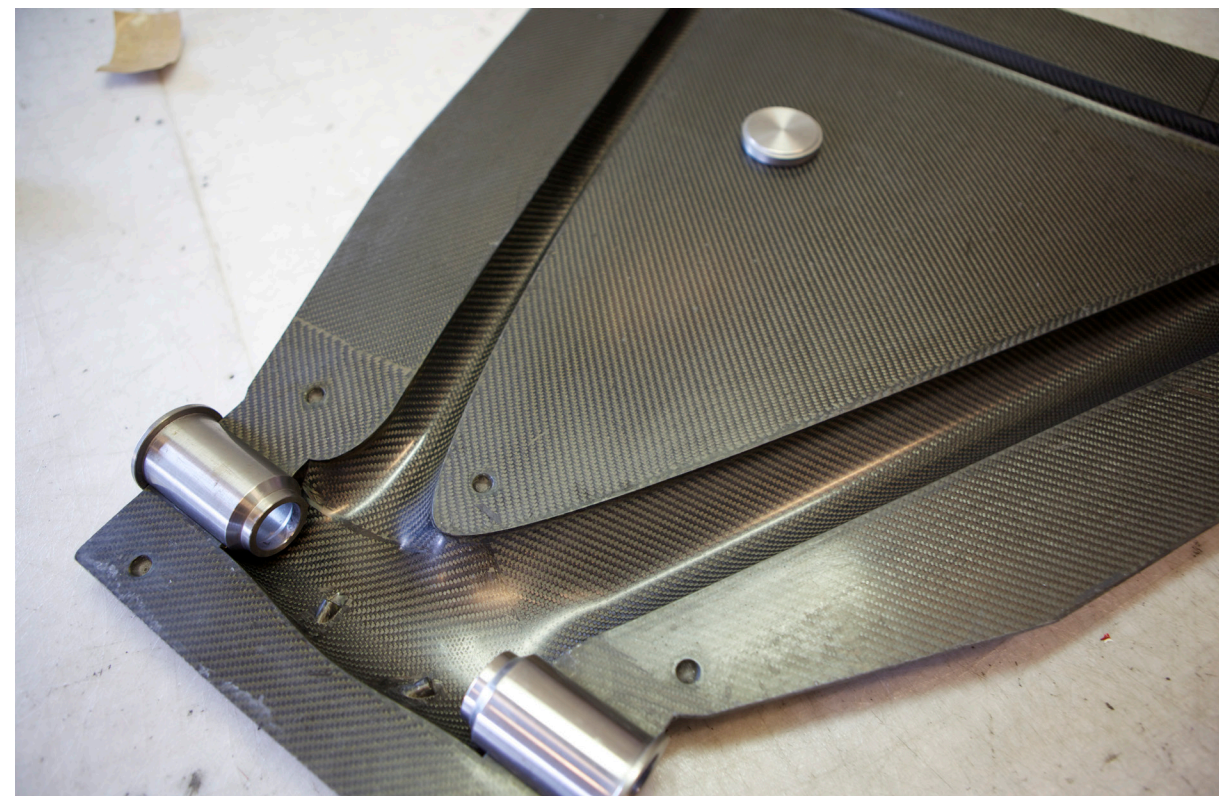


cold because the resin becomes a bit sticky as it reaches room temperature and then essentially becomes unusable if it stays warm too long. To fabricate with prepreg, the carbon is cut to the specific pieces and then laid into the mold piece by piece. An inflatable bag or removable core is placed in the hollow section of the structure and the carbon can be laid around it.

There are two main ways to produce tooling for a monocoque. The basic design is always a clamshell configuration meaning matched halves with a center line joint. For lower volume production and prototypes, master 'male' plugs are normally produced using high density foam, one for each side of the clamshell. From these, 'female' carbon tools are produced using specific tooling carbon pre-impregnated fabric. The main alternative, normally reserved for high volume production, is metallic tooling, either aluminum or steel.

Once fully laid up, the mold is closed and sealed using vacuum before being placed in the autoclave where the inner bag or core is slowly exposed to 4 - 4.5 Bar pressure as the tool is heated to temperatures between 110 - 150C, depending on resin system used. Cure time again depends on the resin system - higher volume production can use higher cure temperatures which have lower cure times. We use a 110C system that cures for 110 minutes. This fabrication method allows for superb finishes and very precise structures but is more expensive because of the higher raw material cost as well as the labor involved in laying up the fiber in the mold.

The rtm process, or resin transfer molding, is largely similar except that the carbon is not impregnated with resin, rather the carbon is laid up in the mold dry and the resin is then forced into the mold under pressure. While this process is much less expensive to perform (the molds are far more costly though) and lends itself far better to higher volume projects because a robot can perform the actual lay-up, in the past the process has proven harder to minimize the amount of resin used to ensure no voids. Since some materials



One of our early prototype main triangle tools. The tool is made of carbon fiber and has aluminum inserts to form the head tube bearing seats.

can shift when the resin is injected, the surface finish has not always been optimal. A number of recent developments may be changing some of the parameters.

### Why a custom lay-up?

If we assume for a moment that the geometry of a frame has been correctly designed (we will get back to this point below, because it turns out that this is a huge assumption), then it becomes possible to design monocoque frames. The frame then is usually manufactured in three parts: the main triangle, the seat stays and the chain stays. Each part is manufactured in a separate mold in which the carbon is laid up, layer by layer - each layer is typically about .1mm thick - and then cured in an autoclave under pressure at a pre-determined temperature for a specific amount of time. The reason the frame is typically molded in three parts is that it is extremely difficult to make a mold that would accommodate the shape of the rear triangle as one piece.

A monocoque presents a different set of challenges, and opportunities, than a classic tube to tube frame. As a starting point, the actual tube cross sections can be made in any shape, the wall thickness can vary at any point along the tube length, and even the carbon layers can change at any point. So what are the advantages?

To begin with, any tube can take on any shape at any point which means that each section of tubing on the bike can be optimized to its purpose for force and frequency dispersion so it is a vastly more efficient and precise structure than tube to tube. By playing with tube wall thickness and the actual lay-up of each individual layer of carbon as it goes into the mold, as well as the type of carbon itself, a monocoque frame can be engineered to achieve almost any performance target for stiffness and weight. As a quick illustration, a well engineered monocoque frame could easily be 40% lighter than a tube to tube for a given stiffness. From an aerodynamic point of view, a monocoque can be also be optimized over round tubes which are not very aerodynamic.

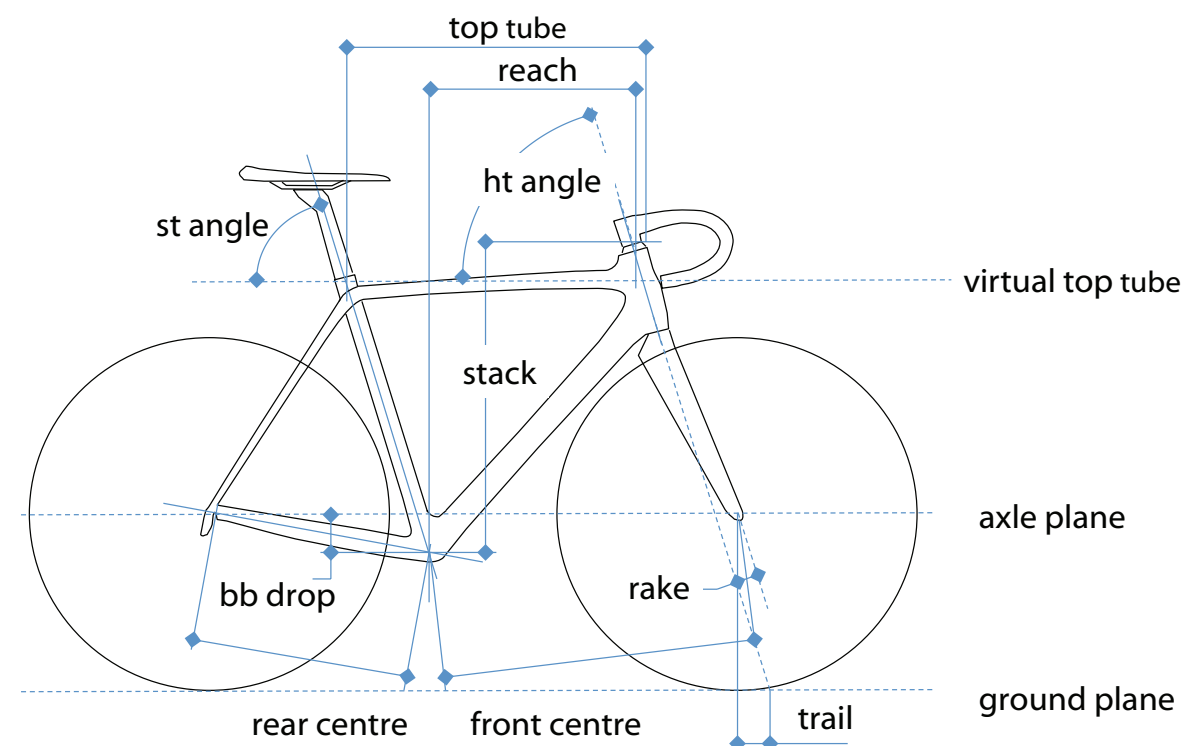
From a manufacturer's point of view, there are a few challenges. For starters, the engineering is hardly straightforward. Since carbon is an anisotropic material, modeling the interaction of each layer of carbon with every other while taking into account the mechanical properties of the carbon itself requires years of experience and access to some fairly fancy computer power. The same holds for the aerodynamic optimization. And then comes the performance characteristics of the bike itself... On the other hand, the big advantage of producing monocoques is that it is much easier to achieve a high level of consistency from one frame to the next, and production costs sink.

Sadly though, until now no manufacturer has offered to customize the lay-up. In fact, many manufacturers use the same lay-up for every size. Imagine for a moment that Levi Strauss used the same amount of material for every pair of jeans, regardless of size. The effect in terms of performance is that the smaller frames are much

stiffer than the larger ones. But usually, larger riders produce more power so their frames should be stiffer, right? Isn't that why many tall and strong pro riders choose small frames and then adjust the size with very long seatposts and stems? Well, you get the picture.

### It turns out that geometry is not as easy as it looks

Remember above where we made the bold assertion about correctly designed frame geometry? Well, it turns out that in fact that is much harder to achieve than it might appear at first. Phil White and Gerard Vroomen set the industry on its head by showing that sizing, and therefore comfort, were paramount and they set about devising a highly effective and consistent way of establishing fit on a bike. Their contribution was to identify and explain stack and reach. At the same time, they were showing that the traditional approach and nomenclature to sizing that was and remains prevalent in the industry was not accurate or consistent.





Let's start by reviewing general geometry issues, then look at stack and reach before we start to alter individual aspects of the geometry.

## The rule of thirds

The main point to keep in mind when designing a road bike, and one that will meet the geometry certification requirements for racing, is that it must generally comply with the rule of thirds. Leaving the rules aside for the moment, if the length gets too short, the distance that will shrink will obviously be that between the wheels, then not only will the rider experience unacceptable and dangerous toe overlap problems, the bike itself will become unstable and difficult to ride. If, conversely, the distance between the wheels grows too large then the bike will become increasingly sluggish and difficult to turn. It will behave more like a cruiser.

## Stack and reach explained

Stack and Reach (s&r) measures the rider's relationship to the handlebars with respect to the bottom bracket - irrespective of saddle height. The relationship between stack and reach shows the postural attitude of the bicycle. To serve all sizes of riders this relationship should remain constant through the frame size range: the ratio of stack to reach should be a constant across all sizes. With the bottom bracket (bb) being the established datum point for the bicycle frame, stack is the vertical dimension between the bb and the center-top of the head tube. Reach is the horizontal dimension between the bb to the center-top of the head tube. Stack and reach are both obviously a function of top tube length, seat tube length and angle, head tube length and angle as measured relative to the bottom bracket.

The advantage of the stack and reach metric is that it essentially incorporates many of the other key variables such as seat tube and top length and angle since it addresses the relationship between the three contact points. By adding in the stem length and angle

and the handlebar and brifter reach, we can then calculate the actual stack and reach for any given bicycle set-up.

## The importance of being consistent

So do all frames from the same manufacturer have the same stack to reach ratio? Does it matter? Let's look at the second question first. The short is yes, and in a big way. Take a rider whose fit is between two sizes from a given frame maker. If the ratio is not consistent, then the rider will have to choose between a more aggressive fit - a lower ratio - and a more relaxed fit - a higher ratio. If a jeans manufacturer only produces in even size combinations (30/30, 32/32, and so on), what do you do if you have an odd size combination such as 35/33?

We realize that the analogy might seem to validate the argument for custom geometry. After all, if a customer can design his frame regardless of his size, then he can always ensure that the stack to reach ratio of his bike is optimal for him. He would then obviate the uncomfortable trade-off. But in fact there is a much more simple answer.

Time and again, data collected about frame geometry indicates the same thing: without even knowing it, the overwhelming majority of riders consider a stack to reach ratio of almost exactly 1.5:1 to be optimal because they are the most comfortable and achieve the highest performance. Of course, some riders - especially pros - will want to have a more aggressive fit, and others will want a more relaxed fit, but overall the 1.5:1 ratio seems to be the best trade-off by far.

At first glance, it might then seem self-evident that manufacturers would produce frames with consistent stack to reach geometries across sizes. But in reality, that does not happen as the graph reflects.

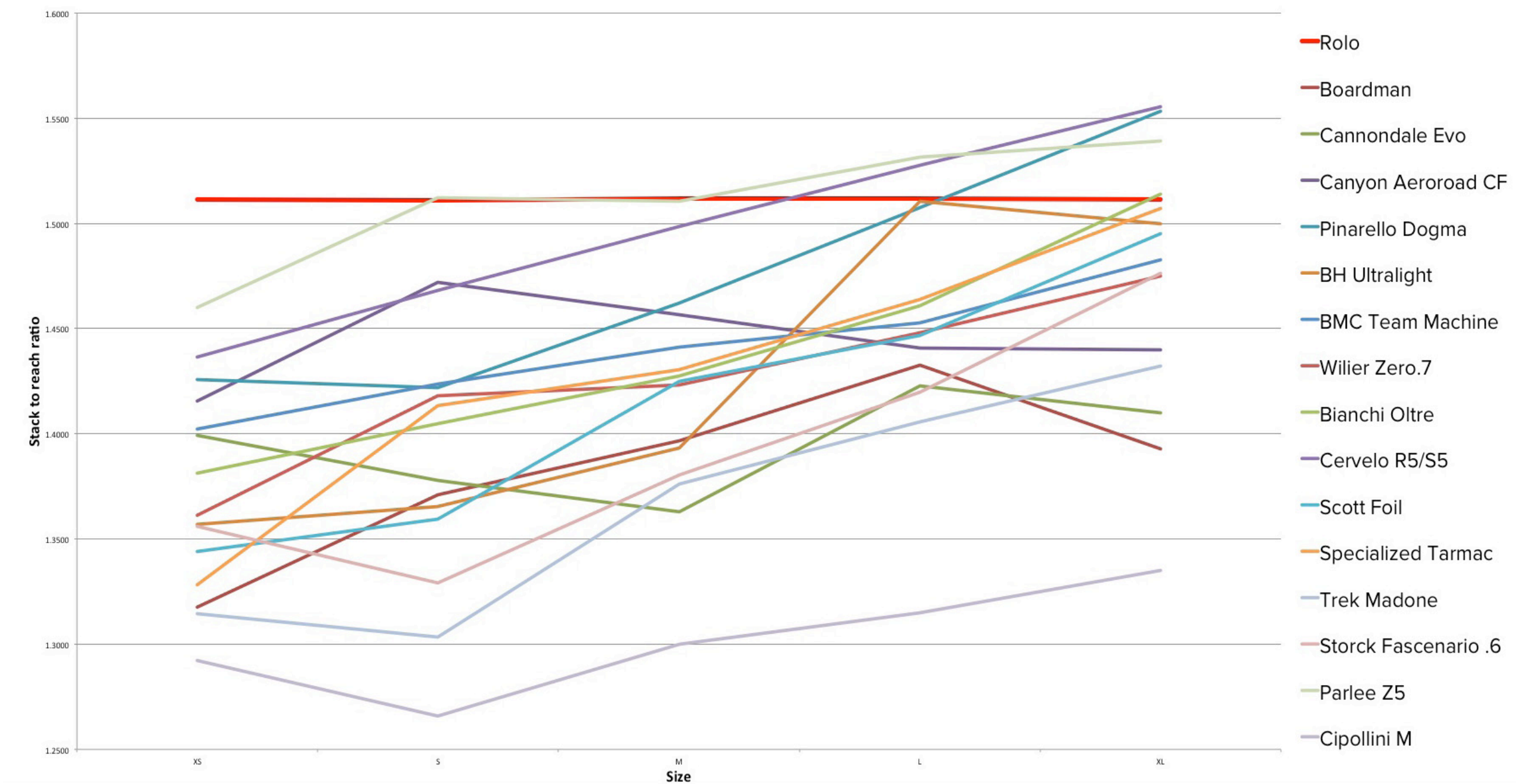
As the graph shows, basically all of the frame geometries trend up but

they get closer to the 1.5 ratio in a size L, which usually corresponds roughly to a size 56 top tube. There are three important takeaways: the first is that while the size L, and to a lesser extent the size M, are in the sweetspot in terms of geometry, the XL gets to be more relaxed. Conversely, the small sizes are extremely aggressive. The third and final point is that for most of the manufacturers there is no consistency and the lines are not even close to linear - actually, only Cervelo appears to be linear in the graph but ranging from 1.43:1 to 1.55:1.

So now let's look in depth at frame geometry.

Top tube length

The top tube is the horizontal measurement between the center of the intersection of the seat tube and head tube. Top tube length will obviously affect the bike's reach. A given top tube length, however, can produce varying reach results depending on





seat tube angle. Quite a few bike companies size the bikes based on top tube length, but bike A with a top tube length of 545mm and a 73° seat tube will have a shorter reach than bike B with a 545mm head tube and a 74° seat tube meaning that simply looking at the top tube length will not give a good indication if the frame is a good fit.

## Stem length

The stem is mounted onto the top of the steerer tube, perpendicular to the head tube. Stems for road bikes typically come in lengths from 60-140mm. They also have an inclination relative to the head tube and steerer tube of -6° to -17°. Because of the perpendicular mounting of the stem, the value is given relative to 90° of the steerer. A frame with a 73° head tube and a -17° stem would thus have its stem horizontal and a -6° stem would have a slight rise. The upturned stem produces a shorter reach for a given length than the horizontal stem.

Stem reach is added to the frame s&r to determine the reach to the handlebar tops. This is the most upright position on the bike, typically used for climbing or resting, eating or drinking. Shorter stems (under 90mm) typically have slightly twitchier handling, while stems longer than 130mm not only make for slower steering but also present a lever that more easily flexes the steerer/spacer/headset and stem base itself. Taken together, all of the elements might introduce a slight vagueness in the handling of the bike.

Our bikes are designed to work well with stems from 90-130mm in all sizes. Longer or shorter stems are not recommended because of

their negative effect on bike handling and feel.

## Handlebar reach

The handlebar reach is measured from the center line of the top of the bar to the center line of the drops. Our recommended bars have a reach between 78-110mm. This measurement is purely theoretical as the actual stack and reach value is measured at the point where your hands rest on the hoods when the hoods are mounted with a flat transition to the tops and horizontal to the ground plane. This mounting is the correct position for the hands when the frame choice fits correctly without having to resort to angling stems, bars or hoods to compensate. Our short reach bar will typically result in a 10-15mm longer stem than our lightest bar option, the Schmolke TLO. The short reach bars will enable faster transitions between the tops and the drops whereas the longer reach bars will offer alternate hand positions along the ramps.

## Handlebar drop

This is the center/center measurement between the ramps and the drops. We believe in a handlebar drop that allows the rider to have a similar back position in the drops and on the hoods. Our 'short & shallow' or 'compact' type bars will always ensure a comfortable position in the bars - with the added benefit of enabling rapid hand transition between drops

and hoods.





## Seat tube length

The seat tube length is measured as the effective length to an imaginary top tube. A higher seat tube naturally places the top tube higher thus reducing standover height, the distance between the top tube and the rider's pelvis. We believe that stand over clearance on road bikes is a non-issue as most riders will not be able to jump off a bike with both feet flat on the ground. When stopping most people lean the bike and put one foot down, so for most people this does not pose a problem if one does not want to straddle the top tube like the pros do before a race.

The distance between the seat tube and top tube junction and the saddle cradle defines the length of the seat post. Our frames and posts are tuned to produce a cantilever that will optimize the ride quality with about 180mm tall seat post. Typically when fitted properly on our bike you should end up with at least this length of post.

## Seat tube angle

The seat tube angle is measured as the angle between the seat tube and the horizontal. This angle will affect the saddle setback and thus the weight distribution of the bicycle. Throughout the sizes our bikes all have a seat tube angle that typically will result in a correct setback (by using the offset range allowed in modern saddles and rails) without using a setback seat post. Another notable, and perhaps counter intuitive, difference the seat post angle has on the overall frame geometry is that a steeper angle will produce more reach for a given top tube length. Why? Because the seat tube 'pushes' the top tube forwards as the seat tube becomes increasingly steep. If you were to shorten the top tube, then the traditional sizing technique would no longer work because, for example, a size 54 frame would in fact have a shorter top tube.

Traditionally, most bike manufacturers have steepened the seat

tubes in the smaller frame sizes thus effectively increasing relative reach, and consequently stack to reach ratio, as the sizes go down (see the sizing diagrams). A steeper seat tube angle will also lead to a saddle that is mounted higher with respect to the ground for a given seat height (remember that seat height is measured from top of where your sit bones rest on the saddle to the bb) therefore making it slightly harder to set your foot down on the ground while seated. Our bikes are designed so that the rider is balanced over the bottom bracket with very little weight on the arms, yet allowing the upper body to form an effective counterweight to the upward thrust of the pedaling forces.

## Bottom bracket drop

The bottom bracket drop is measured from the center of the bottom bracket to the wheel centers. Lowering the bottom bracket will lower the center of gravity of the bicycle but, since the effective center of gravity of the rider and bicycle is about 800-1000mm, the actual effect will only be 2-3%. The argument usually put forward for a low bottom bracket is that it lowers the center of gravity and therefore improves stability. (For a discussion on center of gravity, please see below.)

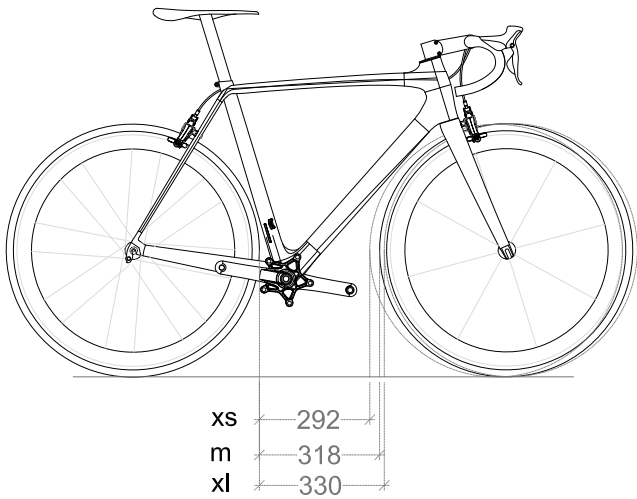
Anecdotal evidence indicates riders reporting a difference in the 'feel' of a dropped or raised bb, especially in the mountain bike world. However, lowering the saddle a very small amount will always lower the center of gravity more than dropping the bb within the range typically available. Our brains are very astute at detecting even the minutest differences in seating height. Raising the bottom bracket even a little, shortens the chainstays and the down tube on the frame; conversely, lowering it will lengthen them. This is because the wheel center remains constant as do the rear dropouts. The front fork remains the same, as does the bottom of the head tube of the frame. If these points of the frame remain constant, raising or lowering the bottom bracket shortens or lengthens the lower tubes

of the frame, but it also raises or lowers the top tube and therefore lengthens or shortens the head tube.

Lowering the bottom bracket could increase the comfort of the frame because of the lengthening of the tubes through the extra vibration damping this might offer. A lower bb will also affect how easy it is to put a foot down while in the saddle (our relatively slack seat tube angle also does make it easier to put a foot down on the ground while in the saddle, see above). It will also affect the ground clearance and ability to pedal through corners. As noted above, the bike will handle best if you put your weight on to the outside crank in its lowermost position when cornering, and most cyclist will want to avoid pedaling through corners. Cornering clearance should really only be an issue if you ride a fixed gear. “If you are pedaling through a corner, you weren’t going fast enough on the straight,” according to Greg LeMond.

### Wheelbase

The wheelbase is the distance between the wheel centers of the bike. A bike with a longer wheelbase will inherently be more stable, and a shorter wheelbase bike will likely be more easily turned ‘on a dime’. Because the diameter of the wheels is constant between sizes and the wheels typically constitute about 2/3 of the wheelbase, front wheel to bottom bracket measurement tends to be fairly constant in order to avoid toe overlap. The front wheel turns less on a short wheelbase bike on any given corner which translates into having to lean less to get around



Size - Wheelbase Comparison

a bend. Considering that the difference in wheelbase between bicycles typically is about 6-7%, front-end geometry is even more important in determining the bike’s handling characteristics.

### Chainstay length

Chainstay length is the distance between the center of the rear wheel and the center of the bottom bracket. For standard road race bikes, chainstay length ranges from 390mm to 420mm. In practice we have found that lengthening the chainstay in itself does make any difference in bike stability. It significantly affects ride comfort because it places the rear axle further away from rider, thus fully utilizing the dampening characteristics of the carbon fiber lay-up. We have also found that a chainstay length of less than 400mm will adversely affect the shifting characteristics, mainly by being noticeably less tolerant to cross chaining.

### Seatstays

The seatstays connect the rear drop-outs to the seat tube thus completing the rear triangle of the diamond frame. Seatstays in most modern road bikes fall broadly in to two main categories: fat and skinny. Skinny stays typically connect at or near the top of the seat tube where it connects to the top tube, whereas most fat stays connect lower on the seat tube. The two designs typically come with some sort of claim of either, in the case of the skinny ones, adding comfort, or, for the fat ones, being aerodynamic.

The notion of seatstays contributing to the comfort of the bicycle by flexing, either as a result of the shape or adding inserts of exotic materials, is however effectively debunked by FEA analysis, semi-static bench testing as well as placing strain gauges on control points on the bicycle and collecting live data while riding.

Looking at the notion from a structural point of view, if the seatstays flex, then another element of the rear triangle would also have to

flex. If the seat tube were to flex, then it would pull the top tube back - which would require a huge amount of force. The only other option would be for the chainstays to flex but that would make for a weak and flexible frame around the bottom bracket.

Most of the lateral comfort giving flex is in fact taken up by the seatpost and seat tube in that order. The seatstays are in fact the most unstressed part on the bicycle, but by virtue of geometry they contribute to about 25% of the torsional stiffness of the frame. Seatstays are therefore essential to the power transfer and handling of the bicycle.

They also do provide an important element of comfort. Thin, curved stays eliminate road buzz far more effectively than fat, straight stays, in much the same way as happens on the chainstays.

## Center of gravity

Typically, for a normal sized rider on a racing bicycle the center of gravity will be around 800-1000mm above the ground.

Center of gravity, however, is simply not a big issue on a bicycle. A bicycle does not have to and will not provide lateral support like a three, or four, wheeled vehicle. It leans into the corners because it has to be in line with the forces acting on it, inertia and gravity, to stay upright. On a three, or four, wheeled vehicle the center of gravity needs to stay low to enable high speed cornering because the centrifugal force will want to tip the vehicle over. A bicycle leans into a corner and is assisted in traction by the centrifugal forces pushing it into the ground. A bicycle and rider with a lower center of gravity will react slightly quicker to input though, mainly because the length of the lever arm decreases, in the same way that a pencil falls over faster than a broomstick.

## Front-end geometry

To a large extent, the front-end geometry will determine how your bike handles, how it reacts to your steering input, how stable it is while riding and how well it holds the line through corners. An ideal bike is naturally stable yet responds intuitively and instantly with precision to your input. The perfect handling bike will hold a chosen line to the limit of tire adhesion with only subtle input from the rider. Handling can be a balancing act between stability and agility.

## Head angle and wheel flop

The head angle is measured as the angle between the center line of the steerer tube and the horizontal.

If the head angle of a bicycle was vertical (90°) the front and rear hubs would be in the same plane when turning the handlebars to go around a corner. Because the steerer tube of the bike is angled forward, as the steering is turned, the fork blade on the inside drops and the outside rises. This dropping of the front end when turning the bars is called wheel flop and acts to reinforce steering input and stabilizes the bike through centrifugal force as the front and rear hub are no longer in the same plane. Going through a turn, the front wheel leans slightly more than the rear wheel. This will stabilize the bike because the front wheel is outside the center line of the frame.

Because the front wheel is leaning slightly more than the rear wheel, it is turning at a tighter radius creating oversteer. So as centrifugal forces are pushing the bike wide on the corner, oversteer is counteracting this force.

Wheel flop refers to steering behavior in which a bicycle tends to turn more than expected due to the front wheel “flopping” over when the handlebars are rotated. Wheel flop is caused by the lowering of



the front end of a bicycle as the handlebars are rotated away from the “straight ahead” position. This lowering phenomenon occurs according to the following equation:

$$f = b \sin \delta \cos \delta$$

Where:

$f$  = “wheel flop factor,” the distance that the center of the front wheel axle is lowered when the handlebars are rotated from the straight ahead position to a position 90 degrees away from straight ahead

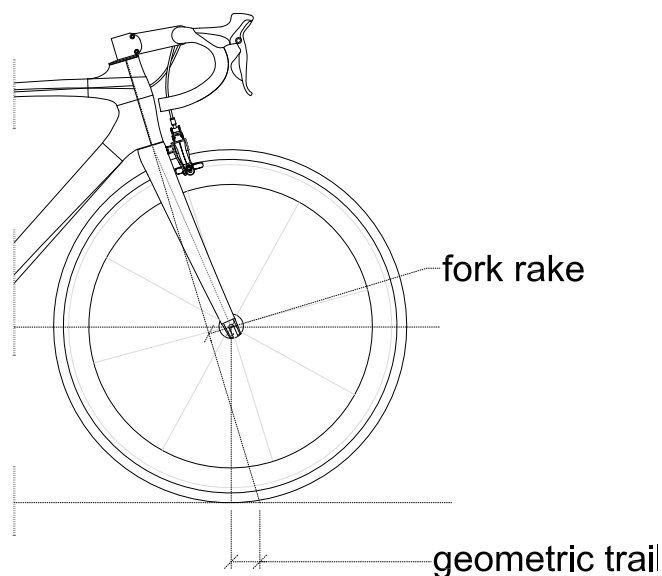
$b$  = trail

$\delta$  = head angle

Too much wheel flop makes the bike wander when going at low or moderate speeds, making it more difficult to stay on course when climbing or going slow in traffic. Too little flop makes the handlebars slightly harder to turn at slow speeds, making it feel unresponsive.

As you can see from the formula above, a shallower head angle increases the wheel flop, and a steeper head angle decreases it.

Increasing the weight borne by the front wheel, like when shifting the weight distribution forward and putting more weight on your hands - such as when moving from the hoods to the drops - will increase the wheel flop effect. Decreasing the rotational inertia of the front wheel by decreasing its mass will increase the severity of the wheel flop effect whereas increasing the rotational speed will counter it.



The interaction between head angle and fork offset (see below) is the chief determining variable for bike handling.

## Fork offset or fork rake

The fork offset (also called fork rake) is the distance between the wheel center and the steering axis. It does not matter if the fork is straight or curved, if the offset is the same the bike will exhibit the same handling characteristics. With carbon composite forks, lateral fork flex and thus comfort is not so much a function of the amount of rake as of the material properties of the fork. Together with the head angle, the fork offset will determine the bike’s geometric trail.

## Geometric trail

Geometric trail is defined as the distance from the steering axis, - an imaginary line through the center line of the steerer tube and extend it to where the wheel meets the ground - to the contact point of the front wheel. The distance between these two points is the trail. Trail has been a widely discussed and misunderstood variable, and remains so to this day.

For decades it has been an established truth that increasing trail (making the front wheel behave more like a castor) will make the bike more stable, and conversely lessening the trail would make for a more nimble bike. The theory of trail and thus front end geometry pretty much started and ended there.

A high trail bike would also be less stable (through wheel flop) on the straight or at low or moderate speeds.

The reverse of the high trail bike, a low trail bike, would be more stable a low speeds than the large trail bike and increasingly nervous as speed builds. This has been the general theory and precious few bicycle frame designers have ever expanded on it.

As a generalized assumption the theory is still correct, but as you will

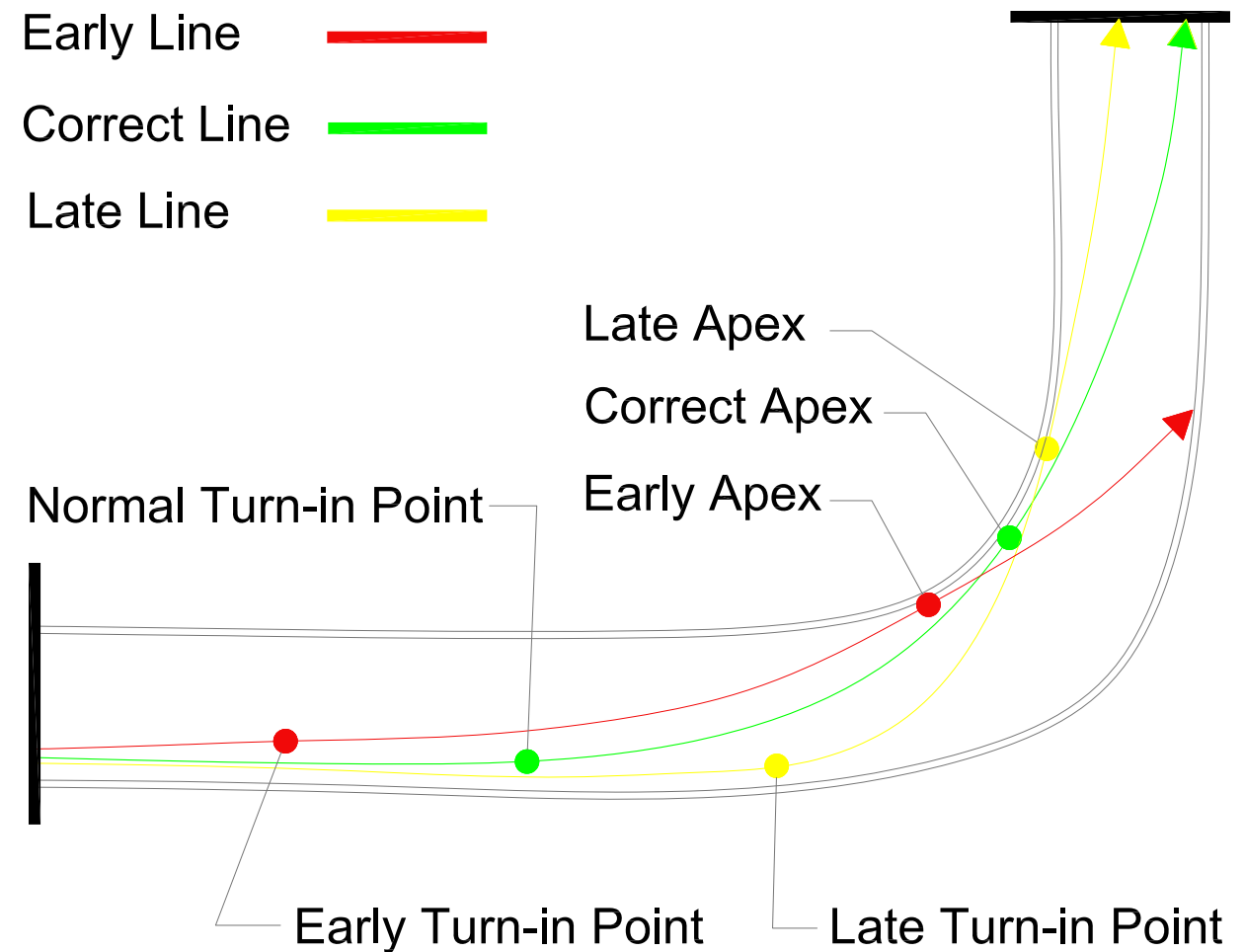
see below there are at least two more critical aspects to consider.

The trail of a bicycle makes it easier to ride because it links the lean angle of the frame with the turning angle of the fork. If you have ever pushed a bicycle by its saddle as you walk alongside, you probably noticed that you can make the bicycle turn by leaning it to one side. As the bike leans, the front wheel turns into the turn. Why does this happen?

The brief answer is that the center of gravity of the bicycle and that of the front wheel move together. As the bike turns to one side, the center of gravity of the frame and rear wheel drop vertically and move to the side of the turn. The front wheel's center of gravity will then also drop by the same amount, and in the same direction. Conversely, if the center of gravity of the front wheel moves to one side and drops, that of the rest of the bike will follow. For each lean angle, there is a corresponding steering angle where the frame is lowest, and the fork will turn towards that angle while that lean is occurring to achieve equilibrium. These are the same forces that make a bicycle function and make it rideable.

Let's take a look at the extreme cases. The lower the amount of trail, the more the front of the bike will have a tendency to turn and to snap in the direction of the turn. The reason is that the lower the trail the more unstable the bike will be. As an illustration, imagine that you push the bike on a straight line and let go. At some point, which can be calculated as a function of the trail, the bike will turn and fall over. In the extreme example, the bike will turn immediately as you release it because it is completely unstable. The concept though is that a certain degree of instability is inherently good because it makes the bike feel agile and nimble.

In reality a 'more stable bike' with a large trail, in other words a bike with a strong self-correcting tendency in its steering, will be harder to adjust mid corner and have a less precise steering. It would, with increasing trail, handle more and more like a shopping cart. A larger



trail would for example make it harder to negotiate a decreasing radius turn, or adjust the line to avoid potholes and other similar obstacles. Most astute riders will have experienced the need to adjust the lean or steering input three or four times through long sweeping turns. This is because most production bikes come with a fairly generous self-stabilizing trail (typically along 59mm, when done right, but typically greater in smaller sizes). Manufacturers generally want to provide that little bit of extra safety factor for the less astute rider with slow reflexes and a vaguely preferred direction with no clear sense of apex.

Having a less generous trail of 56mm coupled with the added stability of a longer chainstay and a low bottom bracket our bike will take you through that same sweeping turn with one intuitive input and one lean angle making fast descents not only faster but also more enjoyable and less tiring.

## Crosswind

The sensitivity to crosswinds is another factor that is greatly affected by trail. Trail will act like a lever arm for the ground force to move the steering. As the front wheel is anchored at the contact point, the lever arm created by the trail will turn the bike's wheel in response to the crosswind. On a bike with high trail, the sideways force will turn the fork towards the wind like a weather vane. This countersteering will reinforce the instinctive downwind lean of the bike and rider which was already initiated by the wind pushing against the bike and rider. The result is a rapid change of direction that is very difficult to counter.

The majority of modern carbon frame manufacturers only offer forks with one rake thus increasing the trail on smaller frame sizes through their typically slacker head tubes. These smaller frames will be vulnerable to the effect of higher trail in crosswinds, especially with modern high profile aero carbon rims. The road exerts a much longer lever on the steering on these bikes; crosswinds will turn the wheels with much greater force.

Smaller and typically lighter weight riders are thus doubly affected by the slack head angles and high trail of the small size bikes that are commonly offered in today's marketplace.

By combining all of the critical elements mentioned above, from the engineering, to materials selection, to production methodology, to the manufacturing process we believe that our bikes are unparalleled on the market today. The consistent fit and predictable, proportional handling characteristics make our frames the most comfortable, agile and linear feeling bicycles available.