A FRESH LOOK AT STEERING GEOMETRY

by Chris Kvale with technical and mathematical assistance by John Corbett

Reprinted in December, 2006 from a copy marked, with Kvale's corrections, Original Draft - Copy

The authors:
Chris Kvale is a custom framebuilder from Minneapolis.He has been cycling for fifteen years, is currently a Senior Category I rider, and with his brother Kevin set the transcontinental record in 1977 (since broken).
John Corbett, who teaches mathematics at the College of St. Thomas in St. Paul and the University of Minnesota, has also been cycling fifteen years, has built many frames, and runs a small business specializing in bicycle frame design and research.

While we all know it is the motor that counts, a bicycle frame that gives optimum handling characteristics for a given event will increase efficiency, and therefore performance. One area of frame design which has been often misunderstood because of lack of information, misinformation, and general confusion is front end design, specifically the relationship between head angle and fork rake. With the advent of high-ouality American-made frames available throughout the country, it is important for the rider to understand some of the factors which will affect his choices in geometry. The following discussion, based on years of original and secondary research, will illustrate the complexity of the problem and lead to some tentative conclusions.

Current References

The most frequently repeated myth regarding head angle and fork rake is the idea that there is a formula relating them to trail which results in a frame which neither rises nor falls as the wheel is turned; this is then called "neutral" steering and is thought to be the ideal. This formula was developed by A.C. Davison and published in Cycling in 1935. He had discovered that when rake equals trail, the frame does not rise or fall when the wheel is at 90°. However, the frame does rise or fall while the wheel is beering turned to the 90° position, and this can be proven mathematically. At 73° the Davison formula should give a rake of 50.8 mm, with this rake the frame will drop 3.65 mm at the 60°point. In fact, the front of the frame will always drop unless the rake is far longer than would ever be used, i.e., at 73° a rake of 104 mm would be required; at this point the frame doesn't fall, it rises. With all steering geometries of practicable design, the frame will drop as the wheel is turned. However, the most important point to understand about the Davison formula is that its relationship to "neutral" steering is purely coincidental. In the 1930's head angles were flatter and the Davison formula seems to give a satisfactory explanation for a very stable feeling frame. For example, with a wheel diameter of 680 mm (typical tubular), a head angle of 71° and a rake of 57mm, the trail of 57mm would give this frame a very stable feeling which might be described as "neutral". However, with 74° a fork rake of 48 mm yields 48 mm of trail, and most riders would find this a little on the sensitive side, far from what would be described as "neutral." The fact is that the amount of trail seems to be the operative factor affecting steering and the Davison formula would vary the trail much more than experience indicates, especially with steeper head angles. (Figure I)

The fact that bicycle design is an incredibly complicated business is well illustrated by David Jones in *Physics Today*, April, 1970. Using a computer and advanced mathematics Jones has probably produced the most accurate and authoritative formulas governing bicycle design and amongst other things, disproves the myth of the magic formula for head angle and fork rake which results in a frame which neither rises nor falls as the wheel is turned. He also makes the point that it is impossible to attempt to isolate one factor of frame design from the others and predict changes in performance and handling by only dealing with that single factor.

In their authoritative book, *Bicycling Science, Ergonics and Mechanics*, (MIT Press, 1974), Frank Whitt and David Wilson virtually ignore the subject of steering geometry, giving it a page and a half and one table. However, they do stress the extremely important point that the man—machine relationship is so complex and so variable that mathematical models and absolute statements are at the very best only a rough guide.

Joe Kossack, in his generally accurate and excellent booklet, *Bicycle Frames, A Close—up Look,* (World Publication, 1975) devotes a paragraph to this aspect of frame design, stating that "There is a formula for fork rake versus head angle, resulting in a frame that neither rises nor falls as the front wheel goes through a turn," again promoting this misconception, although he doesn't give the formula. He also seems to contradict himself in that he opens his paragraph stating that "steep head angles and short fork rakes result in quick and nervous handling" and ends with "too little rake...makes for 'heavy' steering..."

The Proteus Framebuilding Handbook, Barry Konig, ed., (Proteus Press, 1976) treats the subject of head angle—fork rake with a few sentences which are so general that they are hardly useful, much less accurate, i.e., "a longer rake will also tend to be more stable."

Richard Talbot's new book *Designing and Building Your Own Frameset* (Manet Guild, 1979) continues the myth of the magic formula where the front of the bike neither rises nor falls, describing this as "neutral" steering. He introduces the terms "understeer" and "oversteer" in an attempt to shed some light on the subject, but his discussion, although generally correct, does not provide enough specifics to be useful for the cyclist tackling this subject for the first time.

In his article for *Velo-News*, "The Up-front Story on Good Handling," (December 8, 1978), Dave Moulton again repeats the Davison formula by incorporating it in his graph as the "neutral" steering line. However, he has realized that there's something amiss with it as he had another line labeled as "ideal handling characteristics" and explains the discrepancy by saying that "oversteer" is necessary for a racing frame. The point he's missing is that the Davison formula does not fit modern angles and has nothing to do with "neutral" steering.

One of the best of the popular references is Fred DeLong's *Guide to Bicycles and Bicycling, the Art and Science*, (Chilton, 1974). DeLong notes the Davison formula but does not make the same claims for its applicability to today's frames, and he notes that there are many other very important factors.

Original Research

The reader should keep four important points in mind during the following discussion.
1. The research and conclusions are based on middle—sized frames, about 52 to 62cm, and that frames towards the ends of this range are more difficult to design to accommodate the rider's body while maintaining desired handling characteristics.
2. As some of the more far-sighted authors above noted, this a complex situation and no one factor should be totally isolated.
3. The conclusions are made for normal riding speeds. At very low speeds the trail does not seem to have the same effects.
4. The research and conclusions are based on unloaded frames (racing frames) and do not apply to loaded touring frames.

As indicated by the trend of previous research the relationship between head angle and fork rake, resulting in trail, is probably the most important factor in determining the steering characteristics of a frame. The other factors which appear to have some effect are, in no particular order, bottom bracket height, front wheelbase (bottom bracket center to front axle), overall wheelbase, and the resulting weight distribution.

One of the first things Corbett and I did was to accurately measure (Table 1) six frames with which I was intimately familiar I had found that the two frames which gave the greatest hands-off stability and still responded quickly were the Strawberry Track bike and CKC 7601; both of these frames have a fork trail in the low sixties. The Cinelli and Masi road frames, with trail in the high forties, steered lightly and easily but neither has exceptionally easy to rides no-hands. The Cinelli pursuit frame I rode several years on the road converted to a five-speed time trial bike; it was extraordinarily stable no-hands, but was very heavy feeling in the corners, seeming to require actual physical steering rather than mere leaning. It is important to note that this bike handles perfectly in its event--steady track time trialing, the very long trail making it easy to stay right on the pole line without wandering around the sponges. The anomaly in this table is the Famous Custom Frame. Although the numbers would indicate that this bike should have been easy to ride no-hands, it wasn't. In fact, it was so squirelly, even with hands on, that it kept the other riders off my wheel in criteriums. The problem was, I think, that the combination of a top tube which was too short and the short front wheelbase moved the center of gravity so far forward that it had an adverse impact on steering.

From these and many others bikes I've ridden, I've come to the conclusion that the optimum trail for a racing frame should be in the high fifties to low sixties. I would describe this trail as giving a stability which enables the bike to be ridden easily under the most adverse conditions--cross wind and uneven road surface. The rider will not be riding no-hands, but this kind of stability helps keeps the front of the bike from wandering around, which requires energy to correct regardless of whether the rider is aware of it and would be fatiguing in a long road race. This stability also enables the rider to easily take a hand off to reach in a pocket, grab a bottle, wave to the crowds, and so forth while keeping the bike in the same line.

A good way to visualize the effect of trail on steering stability is to view the front wheel from above. Instead of fixing the ground and moving the bicycle forwards, fix the bicycle and move the ground backwards as a treadmill. (Figure 2) As the wheel turns to the left, rotating about its steering axis (line through the center of the head tube), the point of contact, trailing behind this axis is displaced to the right. The greater the trail, the longer this lever, and the greater its resistance to the turning force. A short lever (i.e., low amount of trail) does not resist as much as a longer one and has a "light" feeling, while the longer lever feels "heavier" as it resists the turning force.

Since the trail can be maintained while juggling the head angle and fork rake (Tables 2 & 3), it is necessary to understand what effects those two factors have with constant trail. Flatter head angles (72-73°) require a longer fork rake to maintain the trail. This combination is more comfortable on rough roads but does not seem to sprint or climb as well as a steeper angle-shorter rake combination since the wheel is farther in front of the rider. In an out-of-the-saddle sprint it seems to go farther in each direction with each leg thrust than the other combination. On the other hand the steeper angle-less rake (74-75°) puts the wheel more underneath the rider. In a violent sprint this combination seems to have a feeling of pivoting and not going as far from side to side with each leg thrust." The trade—off, of course, is comfort. The steeper angle-less rake frame will transmit more shock to the rider's body with consequent fatigue. For the rider who can only support one frame instead of a whole fleet, a compromise of 73.5° seems to be adequate for criteriums without being unnecessarily fatiguing in long read races. Many riders specializing in shorter events feel that compromises for the sake of comfort are unnecessary, but they should remember that a very stiff frame will bounce more on rough roads and that the stiffness isn't doing them any good at all if they can't keep the tires on the ground.

It is also important to realize that the type of materials from which a the frame is made have a great effect on feel and handling, especially on a rough road or in a sprint. For instance, a fork made of Reynolds 531 continental oval (old style) with a standard forged fork crown would probably flex much more side—to—side in an out—of-the-saddle sprint than would a fork of identical geometry made of Columbus SP (road-heavy gauge) with an investment-cast crown.

It is a mistake to attempt to judge the amount of fork rake by sighting the fork from the side. Many Italian frames made with Columbus tubing appear to have little fork rake but this is an optical illusion caused by the very gradual curve of the factory-bent (as opposed to custom-bent) Columbus blade. Some of the curves in the factory-bent Reynolds blades are much sharper and a fork built with these could appear to have more rake but actually have significantly less.

The question then is, how do the Italians get away with building frames with steep head angles and relatively large fork rakes with consequent little trail? (Colnagos are typically 74-75°, 50mm fork rake, and 42mm trail). It seems that the bottom bracket height contributes to--and complicates the problem of— stability. Most Italian frames have medium-low bottom brackets, usually around

70mm drop--about 10.55in from ground, and it is probably this fact which helps compensate for the relative lack of trail. Nonetheless, most of these frames are still a little on the nervous side and tend to wander a bit when one's attention is taken from the front. Most of them are more difficult to ride no-hands under adverse conditions than many American frames, which tend to have shorter top tubes and less fork rake. This again illustrates the interdependence of all aspects of frame geometry and raises another important question: How does a frame with this solid no-hands steering stability still handle quickly? Keeping the overall length of the frame down, especially the front wheelbase, seems to promote quick handling. It is very important at this point to distinguish between "light" feeling and responsive handling. A frame with fork trail in the forties will often feel very light and easy-steering. A frame with trail in the high fifties or low sixties will be more stable yet still very responsive without being nervous if short as described above.

An interesting illustration of this point was made with a homemade frame which Corbett repaired. Since the front triangle had to be removed from this frame, the owner decided that the top tube was too long, and when the repair was made Corbett shortened the top tube 4.5cm. The head angle and fork rake were maintained, but the new shorter frame differed markedly in its handling, becoming much more responsive.

One of the other experiments Corbett performed was to build and ride a fork with an adjustable wheel position (Figures 3 & 4). By fixing the head angle and changing the fork rake, he was able to ride one of his bikes with trail from -21mm to 110mm in 20mm increments and evaluate its steering characteristics. He found that the steering characteristics fit into the pattern described above, i.e., with trail in the low forties the bike felt nervous, with a trail of 55mm it had the sort of hands-off stability which seems desirable yet still turns easily, and with a trail of 74mm it was very heavy feeling. Again, it is important to note that the weight distribution changes as the wheel is moved in the fork, and this probably has an effect in addition to the difference of trail.

With all this in mind, are there any conclusions which can be drawn which would be useful? The answer is probably yes, and it seems to be that for middle-sized frames, the head angle-fork rake combination which gives a trail in the high fifties to low sixties will give a no-hands stability which is desirable for a racing frame. The angle of the head tube will be chosen for the event, but it is quite possible to make entirely satisfactory compromises.

Table 1: Comparison of six frames

Bike	Head Angle, deg	Fork Rake, mm	Trail, mm	BB Drop, mm
Strawberry Track	74	35	61	61
CKC 7601	73	40	62	67
Cinelli Road	73.25	52	48	70
Masi Road	73	55	46	73
Cinelli Pursuit	72.5	39	66	68
Famous Custom	74.25	32	63	64

Table 2: 6

Fork Rake	Head Angle												
	71	71.5	72	72.5	73	73.5	74	74.5	75	75.5	76	76.5	77
20	95	91	88	85	82	79	75	72	69	66	63	50	57
25	89	86	83	80	77	73	70	67	64	61	58	55	52
30	84	81	75	74	71	68	65	62	59	56	53	50	47
35	79	76	72	69	66	63	60	57	54	51	48	45	41
40	73	70	67	64	61	58	55	52	49	45	42	39	36
45	68	65	62	59	56	53	49	46	43	40	37	34	31
50	63	60	57	53	50	47	44	41	38	35	32	29	26
55	58	54	51	48	45	42	39	36	33	30	27	24	21
60	52	49	46	43	40	37	34	31	28	25	22	19	16
65	47	44	41	38	35	32	29	26	23	20	27	14	11
70	42	39	36	33	29	26	23	20	17	14	12	9	6

Table 3: Fork Trail for 680 mm Diameter Wheels

Fork Rake	Head Angle												
	71	71.5	72	72.5	73	73.5	74	74.5	75	75.5	76	76.5	77
20	95	92	89	86	83	79	76	73	70	67	64	61	57
25	90	87	84	80	77	74	71	68	65	62	59	55	52
30	85	82	78	75	72	69	66	63	60	56	53	50	47
35	80	76	73	70	67	64	61	57	54	51	48	45	42
40	74	71	68	65	62	58	55	52	49	46	43	40	37
45	69	66	63	60	56	53	50	47	44	41	38	35	42
50	64	61	57	54	51	48	45	42	39	36	33	30	27
55	58	55	52	49	46	43	40	37	34	31	28	25	22
60	58	50	47	44	41	39	35	32	28	25	22	19	16
65	48	45	42	39	35	32	29	26	23	20	17	14	11
70	43	39	36	33	30	27	24	21	18	15	12	9	6

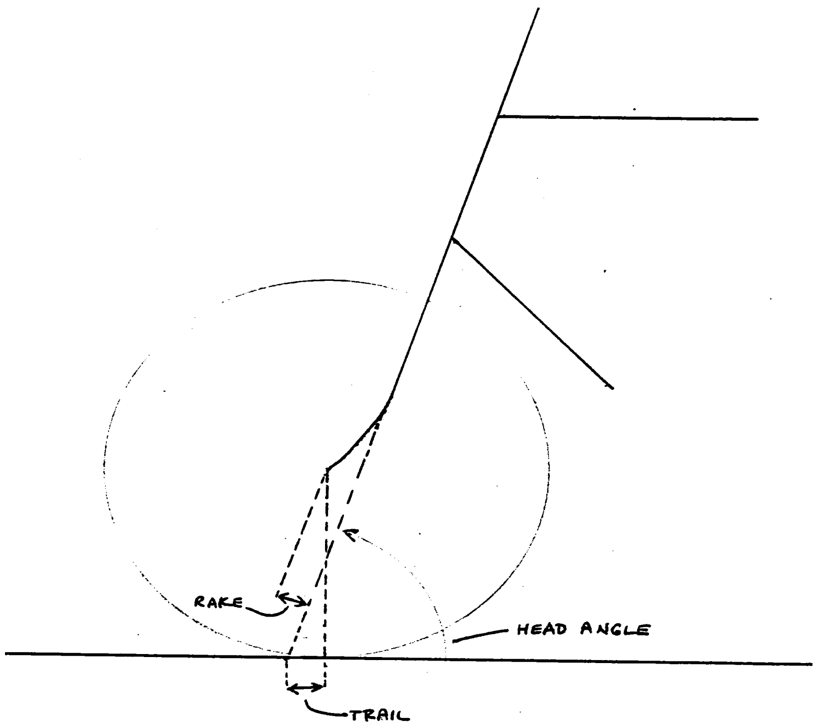

Fig 1: Lateral view of front wheel and fork, showing trail

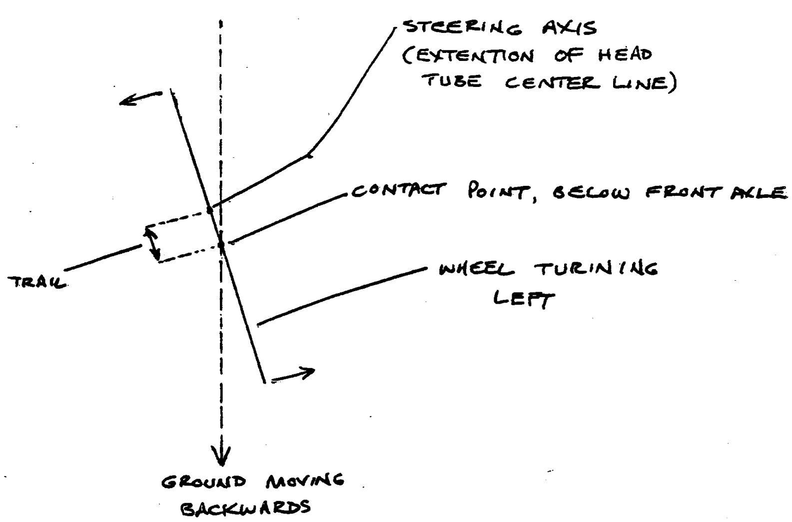

Fig 2: Top view of front wheel showing effect of trail

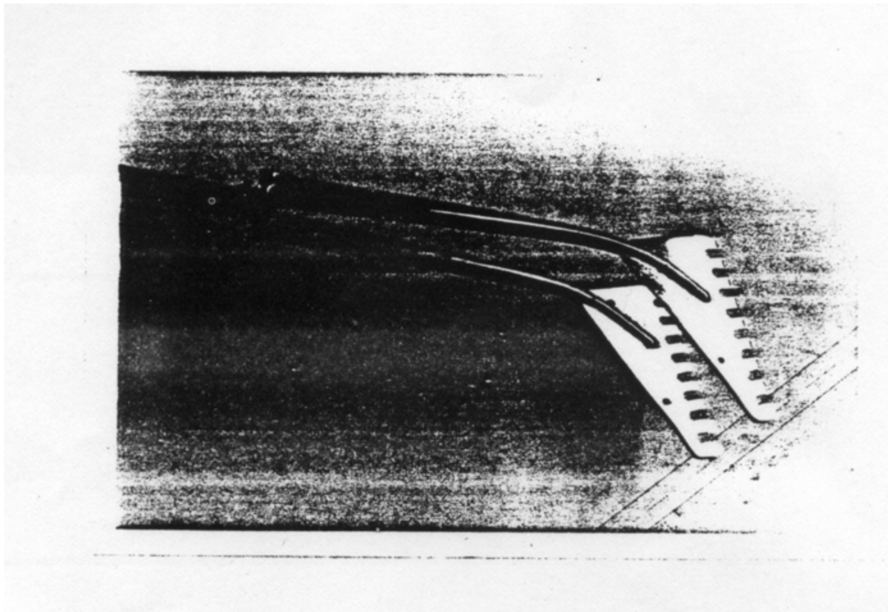

Fig 3: Front fork with multiple axle slots for different rakes

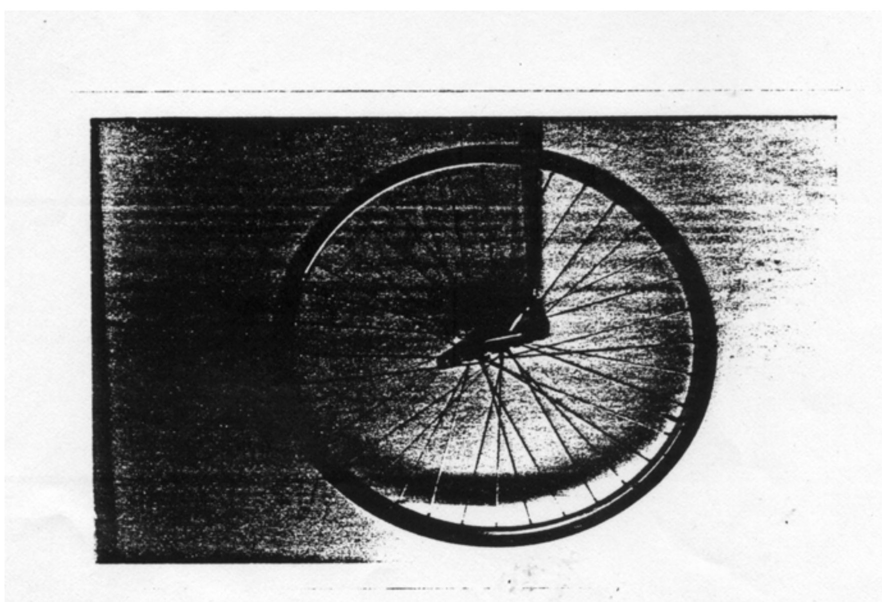

Fig 3: Multiple-slot front fork with wheel in place