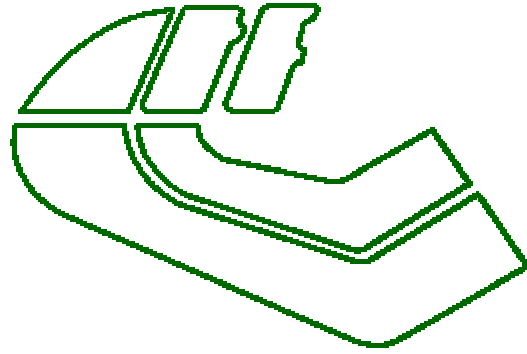


TONY FOALE DESIGNS

Star Vista 30
03759 Benidoleig
Alicante
España / Spain



~~Tel/Fax: +34 96 640 4389~~
~~Tel mobile: +34 608 079 225~~

~~Email: tony@tonyfoale.com~~
~~Web: <http://www.tonyfoale.com>~~

Some Technical Aspects of Tilting Trikes

By

Tony Foale. B.Tech. M.Eng.Sc. C.Dip.A.F.

© 21 March 1999

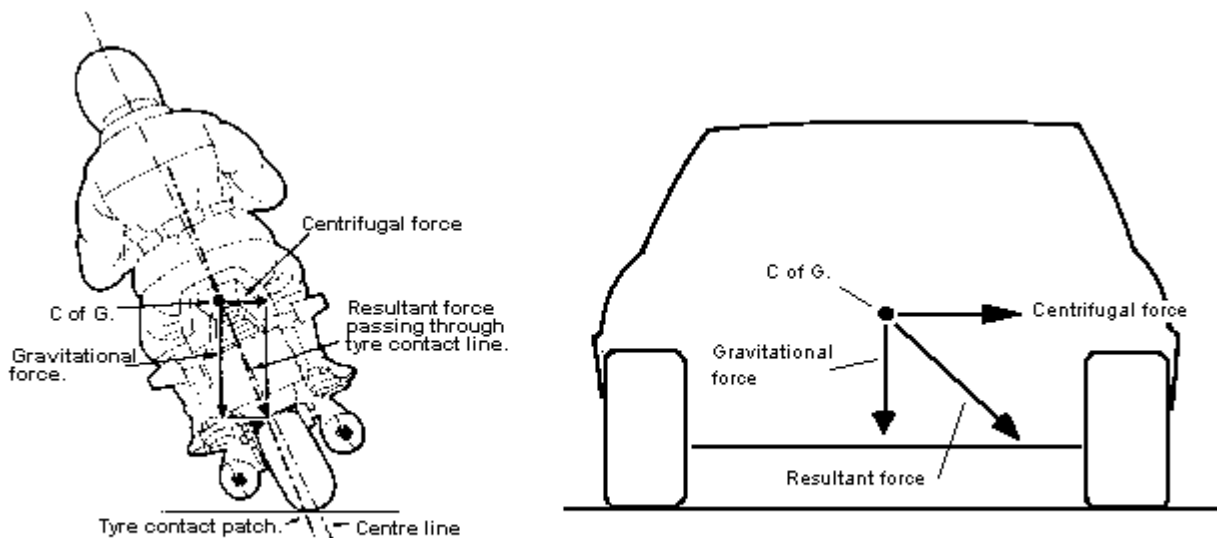
Table of contents

Why tilt?	3
Classification	3
1. Wheel layout.....	3
2. Leaning control.....	3
3. Leaning limit	4
4. Number of leaning wheels	4
No tilting wheels.	4
One tilting wheel.	4
Two tilting wheels.	4
Three tilting wheels.	5
Leaning mechanisms	6
Natural.....	6
Forced.....	6
Control strategies	6
Tyres.....	7
Suspension Loading	7
General characteristics	8
Virtual motorcycles.....	8
1F2R with non-leaning rear wheels.....	9
Roll over.	10
Steering effects.	10
Pitch/Lean coupling.	12
1F2R & 2F1R with all leaning wheels.....	12
1F2R with all leaning wheels.	13
2F1R with all leaning wheels.	13
1F2R or 2F1R with no leaning wheels.	13
Specific examples	13
Summary of features	13
All leaning wheels.....	14
Transit Innovations P32 (US. Patent No. D407,348 1997 - ongoing)	14
Mercedes LifeJet F300 (1997 – ongoing)	15
Millenium Tracer (1996 - ongoing)	16
Calleja (US patent No. 5,611,555 1997- ongoing)	18
Two fixed one leaning wheel	19
Ariel (1970s) and Honda (1980s – ongoing)	19
General Motors Lean Machine (US patent No. 4,065,144 + others, mid 1970s – early 1980s)	20
Jephcott’s Micro (US. Patent 4,660,853 early 1980s - 1988)	22
Vandenbrink Carver (199? – ongoing)	22
No leaning wheels	24
Ingram “Zero G”	24

Why tilt?

Narrow multi-track vehicles have an increased tendency to roll-over under cornering, compared to wider machines, unless built proportionally lower. Leaning single-track vehicles, bicycles and motorcycles, do not have this problem because they lean into the bend and the roll-over tendency is balanced by a counteracting gravitational moment.

Therefore, if multi-track vehicles also leant inward, then they could be made narrower whilst still retaining good stability. A side benefit to this lean is that the occupants will experience the additional loads of cornering as an increase in their apparent weight, rather than as a side load trying to force them out off their seats, as is normal in ordinary cars.



The motorcycle has the resultant of it's weight and cornering force acting through the tyre contact patch. Whereas with the car the resultant force acts closer to the outside wheel, increasing the roll-over tendency.

Traditionally, three wheeled cars have less roll-over stability than their four wheeled brethren, but if allowed to lean into the corners then that disadvantage disappears or is greatly reduced. Obviously three wheeled cars have the advantages of less mass, lower manufacturing costs and the potential for making a smaller vehicle overall. It is not surprising then, to find that most current world activity in tilting car development is concerned with three wheelers or "Trikes". The following discussion is principally aimed at these "Tilting Three Wheelers" or TTW, although some of the comments will apply equally well to tilting four wheeled vehicles.

Classification

There are a number of developments in various parts of the world concerned with Tilting Trikes and there is a considerable amount of diversity in their layout and manner of leaning control. For purposes of review it is useful to try and classify the main features into four groups.

1. Wheel layout

There are two basic possibilities, which have also been described elsewhere in this book. i.e. The 1 Front 2 Rear (1F2R) configuration and the 2 Front 1 Rear (2F1R).

2. Leaning control

The simplest form of lean control is that used by motorcycles. This "natural" leaning is purely a result of rider input and the physics of the machine. Unlike a motorcycle where the rider simply puts a foot on the ground to balance, in an enclosed vehicle it is necessary to have some form of lean lock or brake to hold the leaning section upright whilst stationary.

Another form of control is by some type of forced or active lean. Either hydraulic rams or some form of electric jack is used to force a lean angle, which has been predetermined by processing signals from various sensors. Whilst sensors and signal processors will mainly be electronic there are various proposals for all hydraulic control mechanisms. Reliability may well be enhanced by this approach.

Dual mode or switched mode control has been suggested. This would use elements of both of the above schemes with some form of change-over when the control system deems appropriate.

3. Leaning limit

Some motorcycles typically have a lean limit of 45 → 50 degrees before grounding the lowest and widest parts of the machine. These angles represent between 1 → 1.2 G. of lateral cornering acceleration, as these angles represent extreme cornering requirements it means that these vehicles have no practical lean limit. This is necessary with a single-track machine because there is only one viable lean angle under a particular set of conditions. A completely free leaning trike balances and leans just like a motorcycle and so it must be capable of leaning to an extent to cater for the maximum lateral accelerations to be expected.

Some designs do not physically lend themselves to sufficiently high lean angles. As any non-leaning multi-track vehicle has some cornering capability without leaning, it can be seen that a trike can have a range of lean angles that will be stable under any specific set of cornering circumstances. The wider the track the less critical will be the lean angle. However, some form of forced lean or other roll stiffness is necessary to allow the machine to operate at a lean angle different to that necessary for a fully coordinated turn.

4. Number of leaning wheels

Surprisingly leaning three wheelers have been built or suggested with all possible configurations of tilting wheels within the range of 0 → 3.

No tilting wheels.

This system uses a non-leaning chassis with the wheels attached, like a conventional car, mounted to this chassis will be the leaning passenger compartment. Equally suited for use with 1F2R or 2F1R wheel configurations. This was suggested by Cliff Ingram in the late 80s. for a tilting trike. This is also the basic system used in tilting trains.

It's very important to keep the roll axis of the leaning pod as low as possible to give the maximum roll-over margin.

One tilting wheel.

This has been tried with the 1F2R layout, the passenger compartment and front wheel assembly leaning in relation to a rear non-leaning compartment containing the engine, transmission, rear suspension and wheels. Depending on detail design this layout can be made to have a high value for the angular lean limit.

This was the system chosen for the last of the General Motors' Lean Machines, which was free leaning. The Jephcott Micro also used this layout but had hydraulic active lean, controlled by a lean error sensor. The current Brink Dynamics machine uses an hydraulic lean control also, but the lean angle is a function of steering torque.

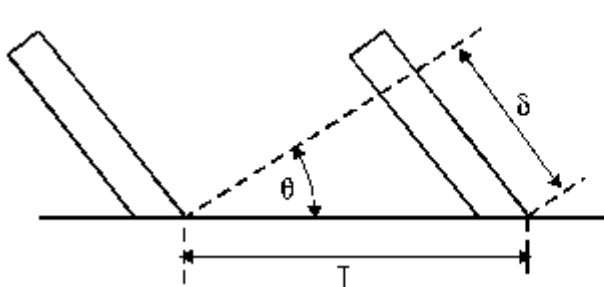
No examples of the 2 upright front 1 tilting rear layout are known. Assuming that the passenger pod leant with the rear wheel then forward visibility during fast cornering might well be a problem.

Two tilting wheels.

It's difficult to see any reason for the use of this scheme and no examples are known. A sophisticated control system would be necessary to keep the non-leaning wheel upright or normal to the road surface.

Three tilting wheels.

Can be used with either the 2F1R or the 1F2R configuration. It is the only layout stable enough for use with a very narrow track. However, it becomes less suitable for wider track vehicles as the amount of necessary wheel movement becomes excessive at large lean angles, unless the maximum lean angles are restricted.



δ = Relative wheel displacement

θ = Lean angle

T = Track

Then

$\delta = T \sin \theta$

and single wheel movement = $\frac{1}{2} T \sin \theta$

This is the required movement for a lean to one side only, to allow for leaning to either side the total single wheel movement must be twice this value. To this we must add the normal bump absorbing suspension movement. Let's look at the values required for a 45° lean with various values of track, and with a total of 5" of bump suspension, arranged as 3" bump and 2" rebound.

Track	Required upward movement	Required downward movement
12.50"	9.25"	8.25"
25.00"	15.50"	14.50"
50.00"	28.0"	27.00"

The table above shows the impossibility of using unrestricted lean angles with wide tracks. The total range of movement required for the wheels on a vehicle with 50" track would be 55".

Now let's consider the required values if the machine has a 20° lean limit.

Track	Required upward movement	Required downward movement
12.50"	5.27"	4.27"
25.00"	7.55"	6.55"
50.00"	12.10"	11.10"

With a 50" track the required wheel movement is still large but at least is within the realms of possibility.

Another reason for a lean limit with designs that drive through the two laterally opposed wheels is to restrict angularity of the drive shafts.

Proposals have been made to use three tilting wheels in combination with a non-tilting body. Whilst this concept would cause an inboard shift of the CofG during cornering, reducing roll-over effects, it would do nothing to relieve the driver of any lateral load. Improving driver comfort is one of the main reasons for tilting, and so it is not expected that this layout will find many advocates.

Leaning mechanisms

Natural

It may come as a surprise to most car drivers, and many motorcyclists as well, to realize that on a motorcycle or bicycle to initiate a turn to the left the rider must initially steer slightly to the right. Termed “counter-steering”, for most riders this action is accomplished subconsciously and unknowingly. In racing, riders often make use of deliberate counter-steering to achieve the high roll rates necessary under those extreme conditions. Briefly, it is the combination of precessional moments and centripetal force that causes or requires this counter-steering action.

Imagine riding a motorcycle and turning the front wheel to the *right*. There are three main effects to be observed.

1. A steering action to the *right*, will produce a small gyroscopic tendency to lean the machine to the *left*.
2. This steering action will also cause the machine to start turning *right*, and just as in a car, centripetal force will cause a lean to the *left*.
3. Gravity will then augment the banking effect and this, in turn, will give rise to gyroscopic reactions helping to steer the front wheel back into the curve.

Unlike a car the motorcycle has no roll stiffness and will continue to lean in more until the counter-steering is removed. Exactly the same mechanisms are available in the case of tilting trikes that have leaning front wheels. As there must be little roll stiffness with this mode of control it follows that no roll moment is transferred to the tyres.

Whilst it is likely that motorcyclists will feel happy with this form of control, those more used to driving a car will probably be less comfortable, and in emergency situations may well apply inappropriate control responses.

Forced

Unlike the “natural leaners” above the steering action is made similar to that of a normal car, to turn *right* we steer to the *right*, the same *left* leaning tendencies still exist and must be overcome by the leaning actuators.

Often called active lean, typically there will be a sensor that measures the error between the actual lean angle and the desired lean angle, the output signal will likely be processed by a “black-box” and the result sent to the actuating rams. In addition to overcoming the counter-leaning tendencies, mentioned above, the lean system also has to provide an additional torque to give the required roll acceleration.

Control strategies

For systems with active or forced control there are varied possibilities. Arguably the most obvious is to try and maintain a fully coordinated, motorcycle type turn, at least for required lean angles less than any mechanical lean limit. This could be done by using the output from a lateral accelerometer attached to the leaning portion, the control system and actuators would work to zero the accelerometer output. For vehicles with a lean limit some form of cushioning would need to be built in as the lean approached the limit in order to reduce unsettling effects on both the machine balance and driver feel/comfort.

An alternative algorithm might be to aim for the lean limit to be reached at the maximum anticipated lateral acceleration. Some law of proportionality could then be used to decide on lean angles appropriate to lesser cornering demands. This would mean that the lean angle would always be less than that required for a coordinated turn, and the driver would feel some lateral force. For both roll-over margin and driver comfort it is the maximum case which is of most importance anyway, and that is determined by the lean limit. Tests have shown that some lateral acceleration of the driver is desirable to provide cornering feedback. When the road wheels are leaning like motorcycles there is less direct feedback through the steering, and so lateral force on the driver can be an important means of indicating the degree of cornering.

Many other control strategies have been suggested, for example using vehicle speed and steering angle as the main inputs and then calculating the required lean angle. A potential problem with this type of approach is that the steering angle required to produce a certain lateral acceleration will vary with surface conditions.

Another factor to be considered is the lateral acceleration perceived by the driver during the leaning in process, if the roll acceleration is high then the driver will feel excess lateral force during the transient phase.

The maximum roll torque that can be applied before the inside wheel lifts is reduced as lean angle increases, therefore the control system must take due account of this during maneuvers that are required whilst leant over. The total roll torque must be reacted against by the tyres at the end with two wheels, this is accomplished by increased loading on the outer wheel and decreased loading on the inner. Therefore, there is a maximum roll torque that can be applied before the inner wheel is completely unloaded and roll-over occurs. A wider track will increase the maximum possible roll torque.

This becomes more critical under hard cornering with the one front leaning wheel only configuration. The vehicle will have the outside rear tyre more heavily loaded than the inner tyre under a steady state turn, this will introduce a certain degree of over-steering tendency. If we now have to steer deeper into the corner for some reason, brick in the road perhaps, then the extra transient roll torque will decrease the roll-over safety margin and further load the outside tyre thus increasing the tendency to oversteer. In extreme cases this may actually lead to loss of adhesion at the rear even though the lateral acceleration is well below the steady state capabilities of the vehicle.

The all wheels leaning layout, operating within any lean limit, performing a balanced turn will have a balanced side to side load on the tyres under steady state cornering, and there will be no roll torque needed from the lean actuators to maintain the lean. During transient conditions though, there will be the same lateral weight bias shift as mentioned above.

In addition to the control responses required for normal turning we have to consider the lean requirements under abnormal situations. Control algorithms can be designed to handle various emergency scenarios, such as losing grip on a slippery surface, only time will tell how successful these might be.

There is still much work to be done in deciding on optimum control algorithms.

Tyres

Motorcycles generate much of their cornering force as a consequence of the large tyre camber angle (camber force), whereas a typical car relies mainly on slip angles to produce the cornering force. Any non-leaning tyres on a tilting vehicle will be subject to similar conditions to those on a normal car and so normal car tyres should prove quite suitable. Conversely, any leaning wheels operating in a coordinated turn will experience loading akin to that on a motorcycle in nature and provided that the load ratings are not exceeded these tyres are the obvious choice.

However, tyre choice is less straight-forward in the case of leaning wheels on a vehicle with a lean limit below that required for balanced cornering. Consider for example cornering hard at 0.8G. on a machine with a 20 degree lean limit. That lean value can balance a lateral acceleration of $\tan(20) = 0.36G$. in a coordinated turn. Therefore, there is an excess lateral acceleration of 0.44G. to be supported as a side load on the tyre. This loading is way outside of the range usually expected of a motorcycle tyre, as is the requirement for the slip angle necessary to generate this lateral load. Neither are car tyres designed to operate well at camber angles of 20 degrees. Some kind of new tyre type obviously needs to be developed if vehicles with these characteristics are to become common place. Something combining various properties from both car and motorcycle tyres being necessary.

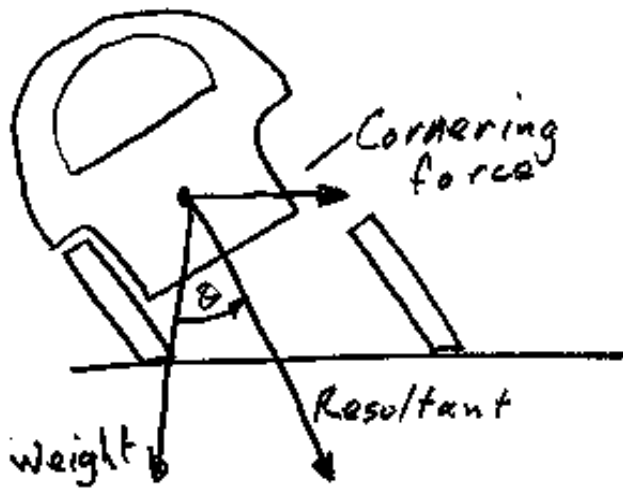
The profiles and dimensions of the wheel rims will possibly be in line for review also. Motorcycle rim profiles are not designed to handle such large side forces nor slip angles.

Another consideration for tyres occurs with those tilting trikes with all leaning wheels. Tilting increases the track and hence will introduce some lateral tyre scuffing as the vehicle leans into curves and straightens up coming out.

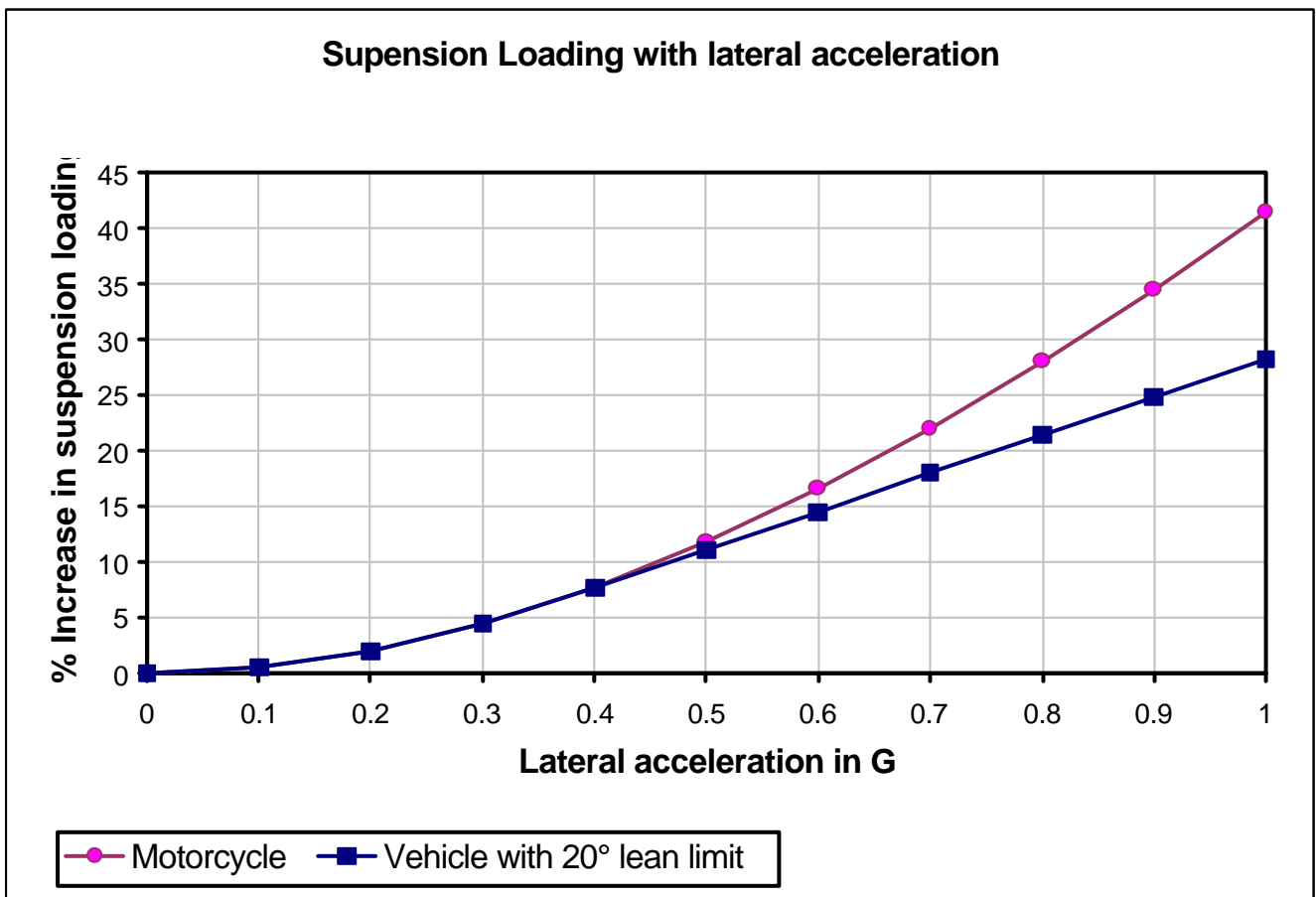
Suspension Loading

The resolution of cornering forces on a leaning vehicle is such that there will be increased load on the suspension system of the tilting wheels, just like a motorcycle. This will be greatest at high cornering speeds on those machines without a lean limit. In some cases this may require springing to be stiffer than would otherwise be chosen for comfort reasons.

Cornering force with a normal car is basically a side load at tyre contact level. When a tilting vehicle is cornering harder than any lean limit the suspension system (of the tilting wheels only) will be subject to a combination of motorcycle and car type loading. That is, there will be side loading but with some increased compression of the suspension system.



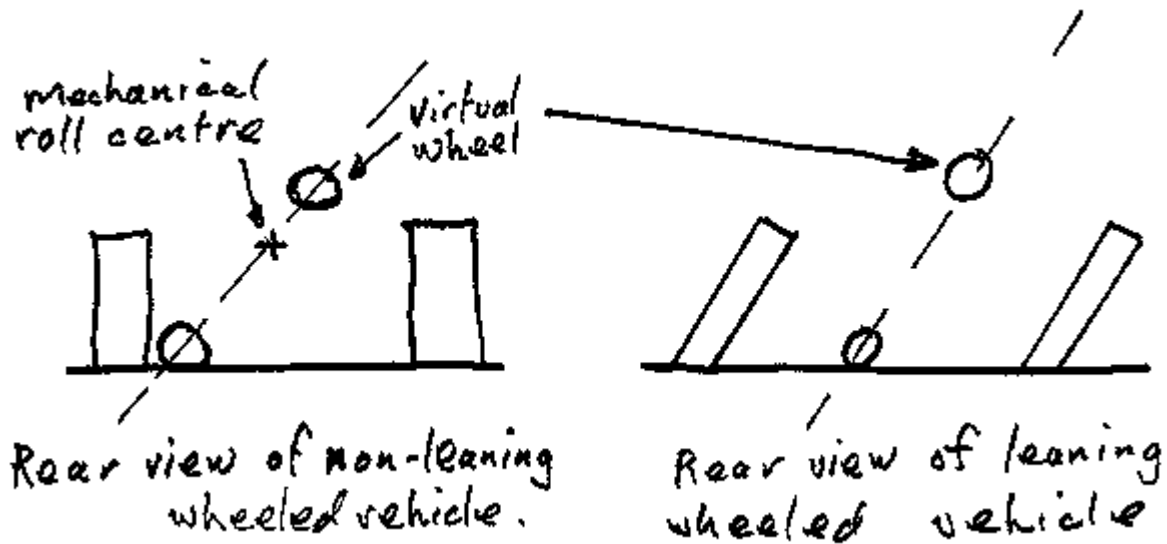
Resultant in line with the body = $\frac{\text{Weight}}{\cos \theta}$



General characteristics

Virtual motorcycles.

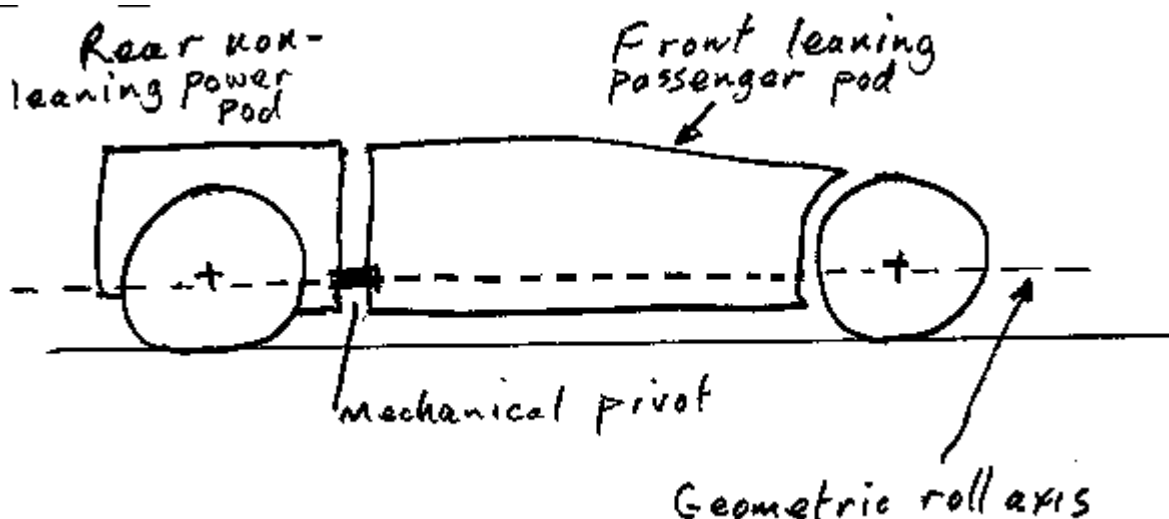
For some purposes of analysis it can be useful to regard a tilting trike operating within its lean limit as being a virtual motorcycle. Consider the longitudinal plane of symmetry of the leaning portion of a TTW as being equivalent to the similar plane on a motorcycle. Then at the end with the two laterally opposed wheels it can sometimes be useful to replace these two wheels conceptually with one "virtual" motorcycle wheel. Roll over stability is achieved when the virtual wheel is laterally inboard of the two actual wheels.



The following looks at some typical configurations and goes into greater depth about their characteristics and requirements.

1F2R with non-leaning rear wheels.

The front leaning pod will typically house the passengers, instruments, controls, front suspension and front wheel. While the rear non-leaning pod will contain power source (gasoline, diesel or electric), transmission, suspension and rear wheels. The two pods are normally joined by some form of fixed mechanical pivot, defining an axis which controls the relative movement between each section. This roll axis is a geometrically determined axis relating the two halves, it is not the dynamic roll axis of the vehicle as a whole. The orientation of this "roll axis" has a vital bearing on the rollover margin as well as the steering dynamics.



Generally speaking, vehicles of this layout can be built with large lean angle possibilities and so are equally suited to either natural or active lean control.

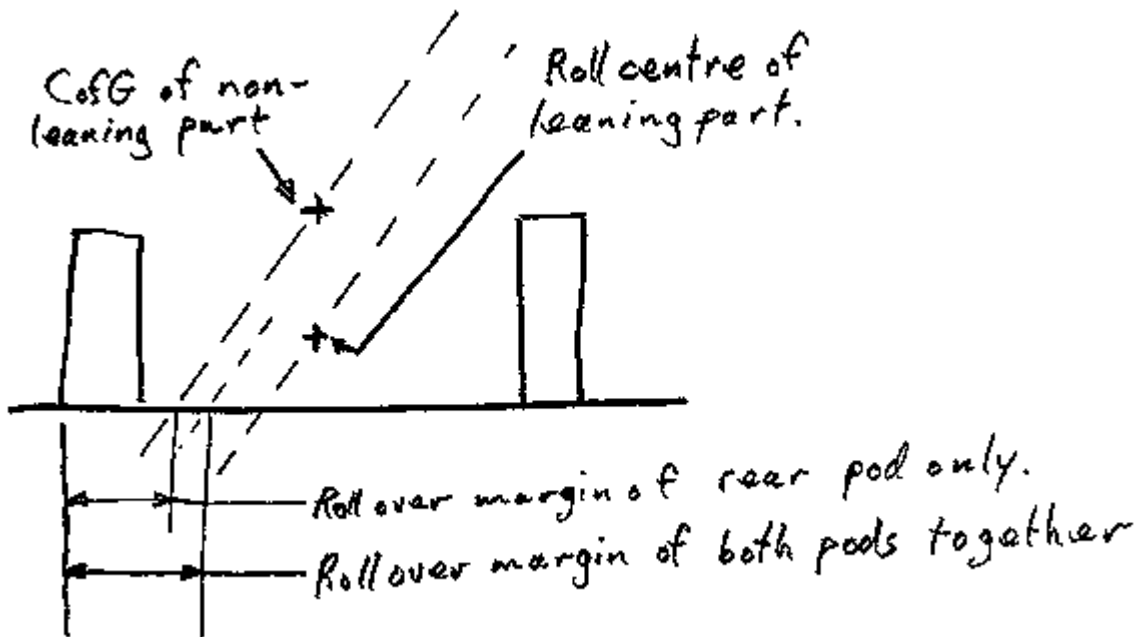
The suspension of the leaning front wheel will be subject to increased compression under cornering, as mentioned earlier. The non-leaning rear suspension will not be subject to this effect.

Whilst all known machines of this type use a fixed "roll axis", it is possible to conceive of several layouts which join the two halves through a number of links, providing a virtual roll axis that would move about depending on roll angle.

Roll over.

There are two aspects to the calculation of the roll over characteristics. There is a separate contribution to roll over from both the leaning and the non-leaning pods. The non-leaning section will behave in similar manner to a conventional non-leaning three wheeler, described elsewhere in this book, with the principal parameters being wheelbase, track and C of G location.

Considering the leaning part as a virtual motorcycle, the rear virtual wheel will contact the ground at a point determined by the height of the geometric roll axis at the centre of the rear wheels. The figs. show that if this height is lower (the expected situation) than the C of G of the non-leaning part then the leaning portion will actually reduce the roll over tendency to a value lower than that of the rear portion alone.



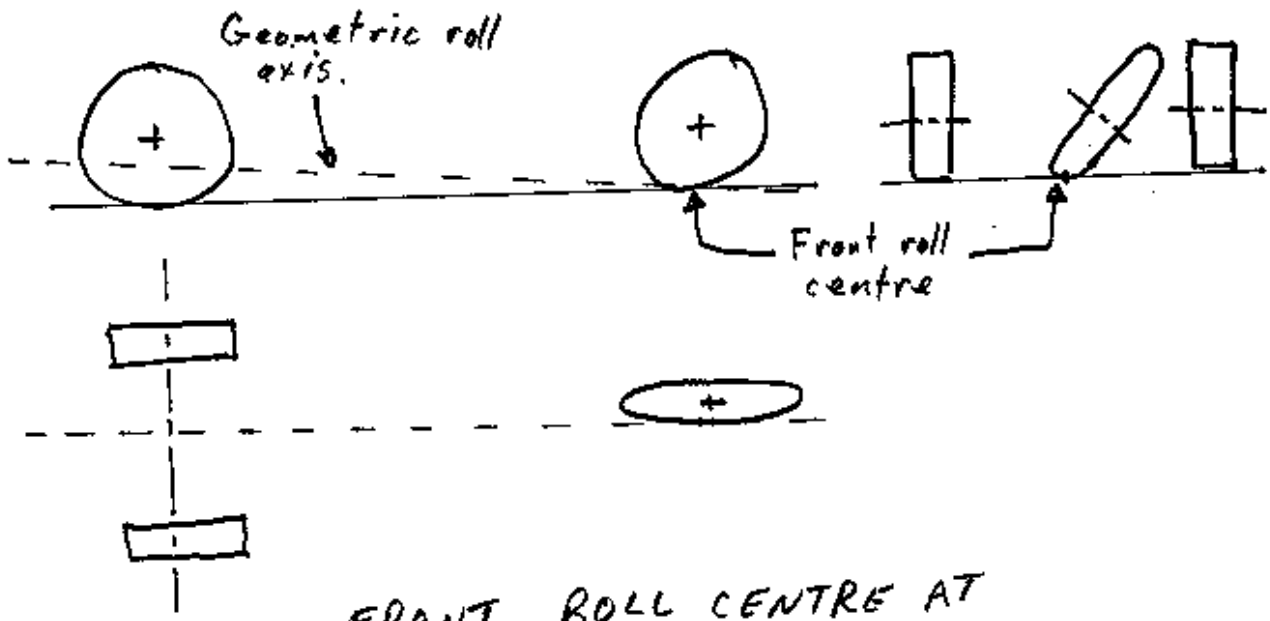
It is important to locate the rear geometric roll centre as low as possible. However, in a properly balanced turn the CofG height of the leaning pod is unimportant as far as roll over is concerned, although it will obviously have an influence on roll response and longitudinal load transfer under braking and acceleration.

The situation changes for those vehicles with a residual roll moment, such as from an active lean control that does not give a fully coordinated turn and or those with a lean limit less than that required. In these cases the CofG height of the leaning pod is important to roll over and should be as low as possible, just as in a conventional three wheeler.

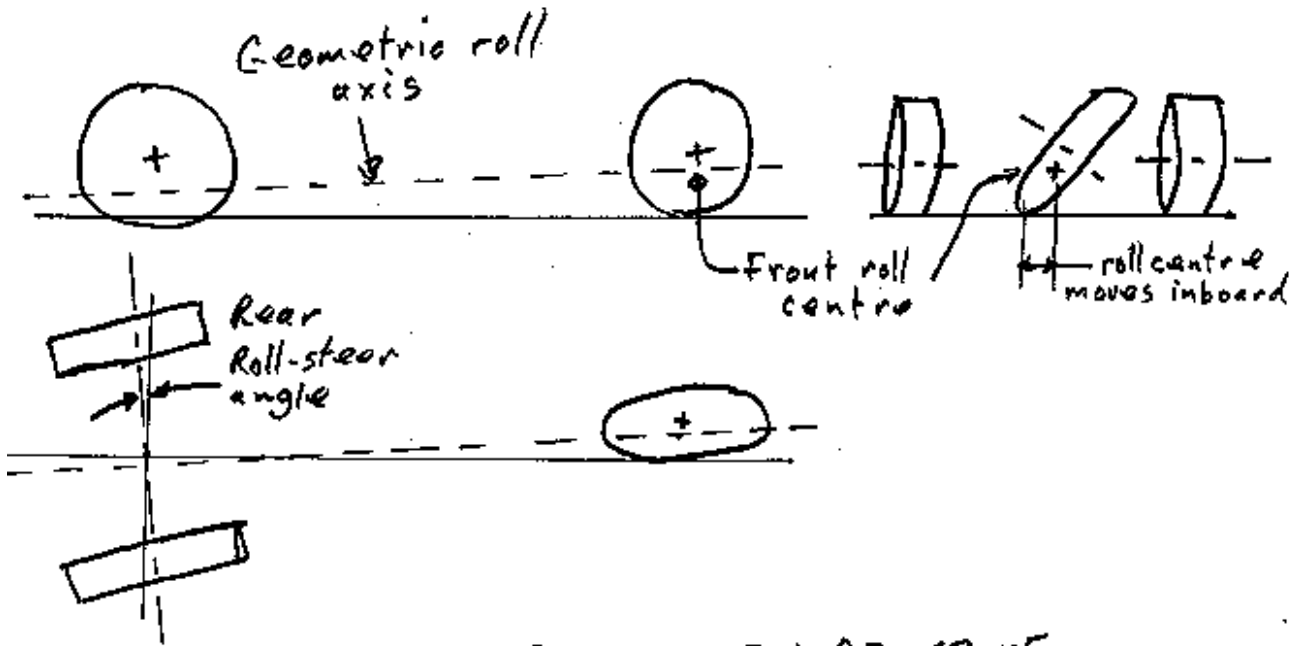
In all cases the ability to move the overall CofG position inboard whilst cornering will reduce lateral load transfer and hence lower the oversteer tendency inherent in non-leaning 1F2R trikes.

Steering effects.

The location of the geometric roll axis has an influence over the attitude of the rear pod akin to what is commonly called rear wheel steering (RWS). More properly called "roll-steer" in this case. If the front geometric roll centre is not at ground level then as our virtual motorcycle rolls into a corner the geometric roll axis will move in a way that will steer the whole rear pod relative to the virtual motorcycle. If the front roll centre is above ground level then this roll-steer will be into the corner.

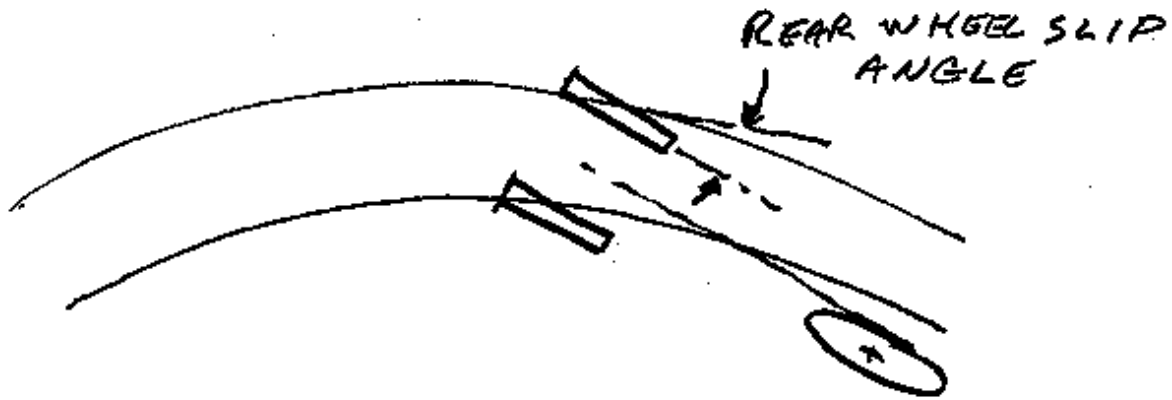


FRONT ROLL CENTRE AT GROUND LEVEL



FRONT ROLL CENTRE ABOVE GROUND LEVEL

The front leaning wheel will generate much of its cornering force from camber force, however, the non-leaning rear wheels have to provide this force by means of a slip angle. If we didn't have this roll steer effect then all of the slip angle would have to be provided by a yaw attitude of our virtual motorcycle.

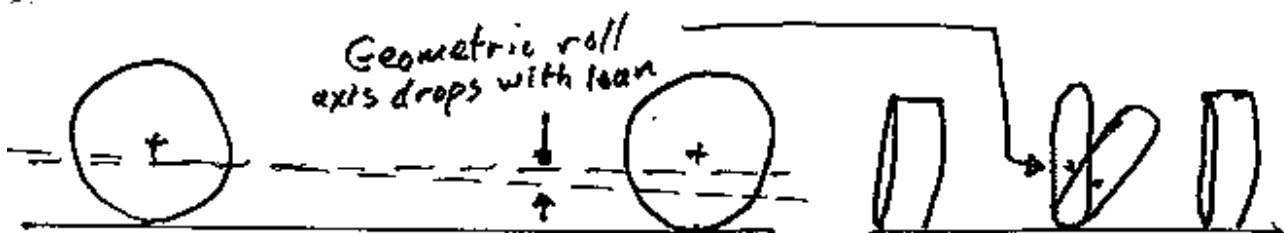


WITH NO REAR ROLL STEER
ALL SLIP ANGLE MUST BE PROVIDED BY A YAW ATTITUDE.

Despite this steering benefit, there is a potential downside to this coupling between roll and RWS. Motorcycles can exhibit various wobble/weave instabilities and analysis has shown that tilting trikes can be subject to the same problems. This roll/yaw coupling could be of detriment to these problems.

Pitch/Lean coupling.

An additional geometric effect of the front roll centre not being at ground level is that of a pitch change with lean. If the roll centre is above the ground then the pitch rotation will be forward, centered about the rear wheel axles.



The converse is obviously true, pitch tendencies will produce lean moments. For example a rearward pitch as experienced under acceleration will generate a tendency to lift the front and reduce any lean, therefore acceleration whilst cornering will try and straighten the vehicle. Braking on the other hand will tend to reinforce the lean.

Of course these effects are more important for a natural leaning vehicle, those with active lean control should have the lean angle determined solely by the control system and actuators.

1F2R & 2F1R with all leaning wheels.

Both types of machine in this category, have some leaning characteristics determined by the width of track. In order to maintain tyre contact with the ground under lean conditions, it is necessary to allow wheel movements in excess of that required for bump absorption. There are obvious practical limits to the amount of movement that can be provided. Wider tracks mean a smaller maximum lean angle for a given maximum wheel movement and therefore dictate some maximum lean limit. If this lean limit is below that required for coordinated turns, within the expected range of cornering situations, then the vehicle is unsuited to use as a complete natural leaner and some form of active control is needed.

On the other hand, vehicles with a very narrow track are incapable of supporting much of a roll moment and so are unsuited to the use of active lean control. So we can generalize by saying that narrow track permits the high lean angles needed for natural leaning but cannot be used with active lean control. Wide track machines will have limited lean capability, which will require a lean limit and some form of active lean mechanism.

In many respects these vehicles with all leaning wheels are simpler to analyze. The virtual wheel will be mid-way between the two actual wheels. In a fully balanced turn there will be no residual roll moment and hence no roll-over tendency. Thus, the narrow track machine will be at no disadvantage as regards roll-over, the extreme case of this is a motorcycle. Wider track vehicles, when operating against the lean limit or otherwise held in a non-balanced state by the control system, will have a residual roll moment and thus have some degree of roll-over tendency. This is easily analyzed by normal means taking into account the lateral CofG displacement.

1F2R with all leaning wheels.

These will generally be expected to have the front wheel steerable with the engine and transmission to the rear, driving the rear wheels. The large vertical wheel movements could cause problems with extreme angularity in the joints of the drive shafts, unless some special design features are employed.

In fully coordinated turns the lack of lateral load transfer will eliminate the normal oversteer tendency of this configuration of non-leaning trike. When the lean angle is less than that for a balanced turn there will be some lateral load transfer and also some over-steering tendency.

2F1R with all leaning wheels.

The front wheels will probably be used solely for steering leaving the single rear to handle the driving requirements. This introduces no special problems with the drive system.

The usual under-steering tendency of this layout will be reduced due to the lower lateral load transfer as explained above.

1F2R or 2F1R with no leaning wheels.

Essentially similar to the system used on tilting trains. Typically, this layout will have a fixed non-leaning chassis connecting all three wheels and their suspension systems. The power unit and transmission is likely to be fixed on this chassis also. It is probably less suited to road vehicles however, due to the mechanical difficulties of locating the roll axis of the tilting pod low enough. The fixed chassis spatial requirements will probably force this roll axis to be higher than desirable.

Therefore, this type of vehicle will probably have similar roll-over characteristics to a non-tilting machine. There would still be benefits for passenger comfort though, as the lean would reduce or eliminate lateral forces on the driver.

Specific examples

Let's now consider how some of the general attributes have been implemented in some actual vehicles. At the time of writing most but not all of these vehicles have been proof of concept machines, with only a few either in current or anticipated production.

Summary of features

This list is not meant to be exhaustive, those machines included are done so to illustrate particular features.

Name of Vehicle	Wheel Layout	No. Tilting wheels	(P)owered or (F)ree lean	Lean limit In degrees	Special features
Transit Innovations P32	1F2R	3	P	Approx. 15	2 side by side seats
Mercedes Lifejet F300	2F1R	3	P	30	2 tandem seats
Millenium Tracer	2F1R	3	F	37	Motorcycle based, 1 seat
Calleja	1F2R	3	F	45	Very narrow track.
Ariel & Honda	1F2R	1	F	??	Production vehicles
GM. Lean Machine	1F2R	1	F(+ pedals)	50	By major car manufacturer
Jephcott Micro	1F2R	1	P	30	Early all active control
Vandenbrink Carver	1F2R	1	P	45	All hydraulic control
Ingram Zero G	2F1R	0	P	??	Proposal only

All leaning wheels

Transit Innovations P32 (US. Patent No. D407,348 1997 - ongoing)

This is configured as 1F2R with two side by side seats. It has a lean limit of approx. 15 degree which will allow for balanced turns at up to about 0.27G. This should cater for the vast majority of non-aggressive driving requirements. Driving power is provided by two 25 hp. electric motors, one for each rear wheel. Top speed is governor limited at 79 mph.

To avoid the problems of excessive drive shaft angularity whilst leaning, these motors are cleverly mounted in a yoke attached to the suspension arms. This will of course add to the effective unsprung mass, but this is minimized because they are moving up and down at a rate less than the wheel assembly. Leaning is accomplished by an hydraulic cylinder controlled from an electronic black box.

Wheel track is wide for this class of vehicle at 51" and was chosen to reduce lateral load transfer and the attendant oversteer tendency. A parallelogram linkage system controls the location and leaning of the rear wheels.



Dimensions: Wheelbase 2490 mm. Track 1295 mm. Target Weight 455 kg.

Mercedes LifeJet F300 (1997 – ongoing)

This vehicle is all the more remarkable because it has come from a large manufacturer with a reputation for high quality luxury cars. The F300 is unashamedly designed as a fun vehicle.

A mid mounted petrol engine drives the single leaning rear wheel, the two front wheels lean and steer. There is space for two occupants arranged in tandem fashion. It has an active lean control system and a lean limit of 30 degrees allowing for coordinated turns of up to 0.58G., although the control algorithm is designed to maintain some lateral force on the driver for feedback reasons. This is achieved by leaning less than the angle required for balanced turns and so there will always be a residual roll moment, along with lateral load transfer and some consequent understeer tendency. The control system is adaptive and alters lean response in accordance with the observed style of driving. 0.9G cornering capability is claimed.

Motorcycle tyres have been used, although a test rig has been commissioned to investigate tyre performance and requirements at large camber angles and loads.



A 1.6 litre engine from the A-class Mercedes produces 100 bhp. and gives the machine sports car like performance. 0 to 60 mph in 7.5 secs. with a 130mph top speed.

Dimensions: Length 3954 mm. Width 1730 mm. Height 1527 Weight 800 kg.

Millenium Tracer (1996 - ongoing)

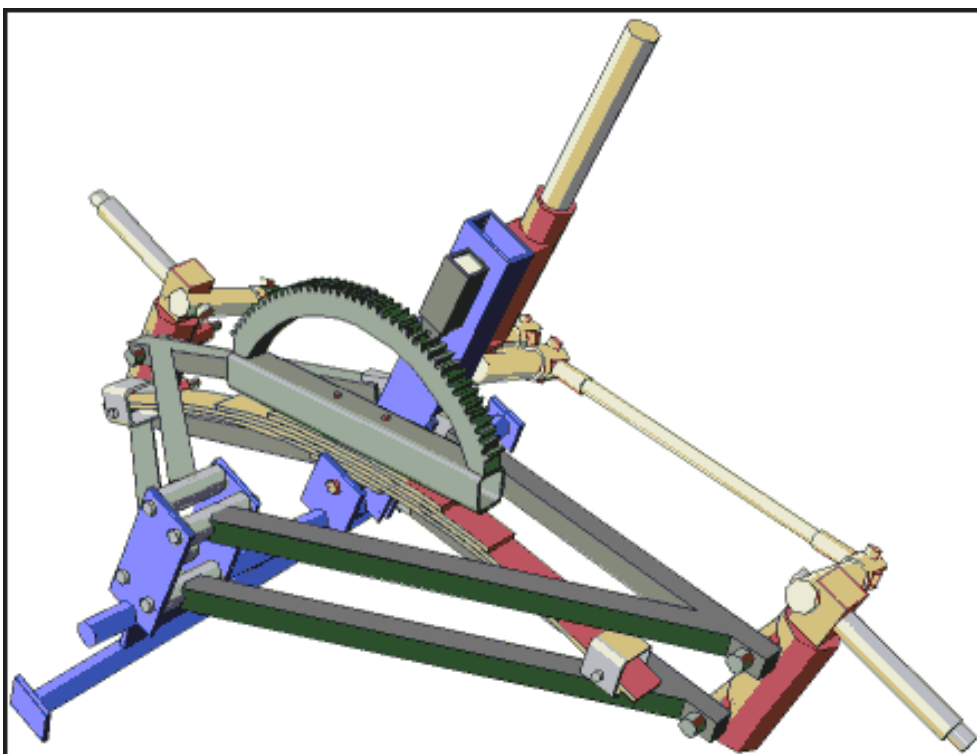
This Australian machine was originally conceived as an all weather motorcycle. It shares the same basic configuration as the F300 but with a higher lean limit of 37 degrees and natural leaning. Therefore, it has to always maintain a balanced turn and can do this up to the maximum cornering acceleration of $\tan(37) = 0.75G$. This should be high enough for all but the most spirited driving.

Unlike the motorcycle from which it was conceived, it is not possible for the driver to put his foot on the ground for balance when stationary and so a lean lock is incorporated which allows the vehicle to be held vertical even when stopping on a cambered surface. The lean locking mechanism is electrically operated under rider control.

To date one vehicle has been built and performed well in tests and daily use. A second machine is now under construction and the main differences are concerned with automation of the lean locking system, to this end provision is being made for a form of active control at low speeds. This change is intended to make the machine acceptable to more drivers within a wide range of driving skills.

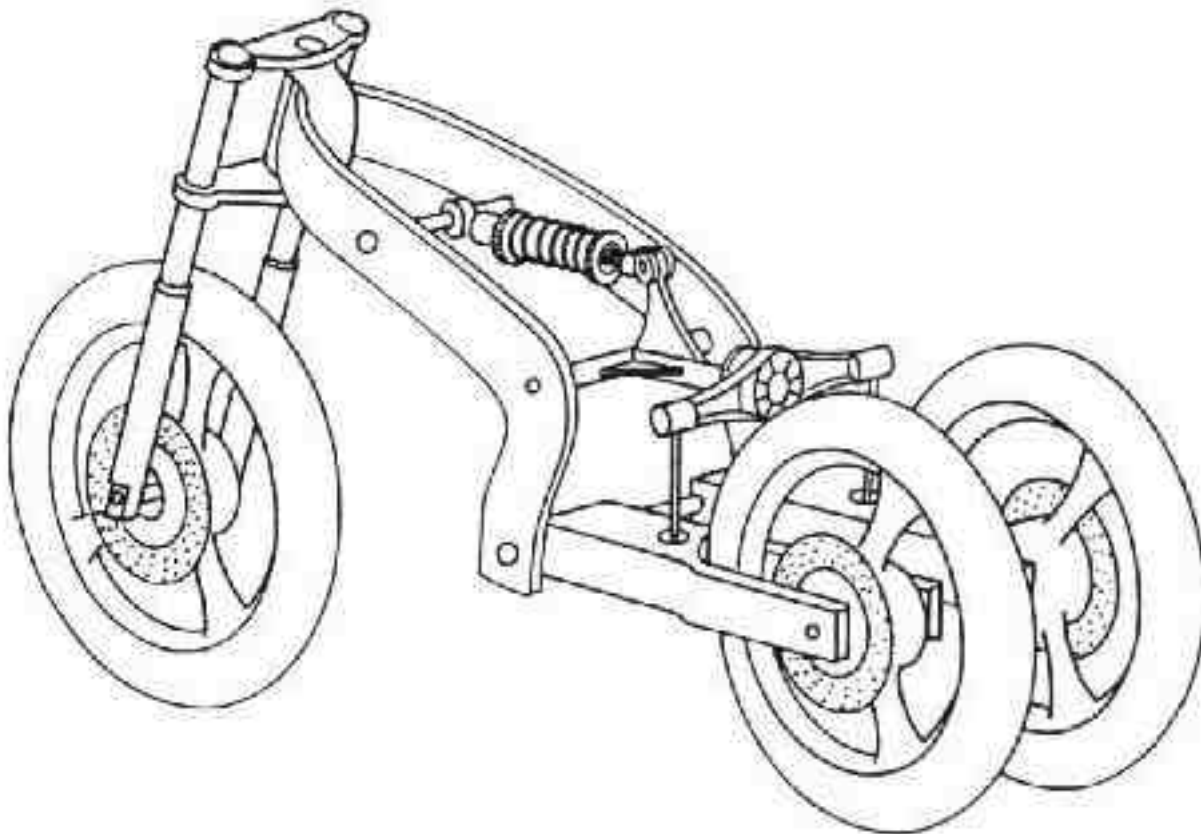


Dimensions: Length 3150 mm. Track 860 mm. Wheelbase 1830 mm. Weight Dry 280 kg.



Calleja (US patent No. 5,611,555 1997- ongoing)

All wheels leaning with 1F2R, this vehicle has been constructed on a motorcycle base with the two rear wheels spaced close together for a very narrow track. This Spanish designed vehicle has been built to very high standards as a proof of concept machine. The intention is that the system be applied to narrow cars. The narrow track dictates that it leans naturally, and tests on the prototype show that control and feel are in fact identical to a motorcycle. The narrow track also allows for a large lean limit of approx. 45 degrees, which will cater for all expected cornering conditions.

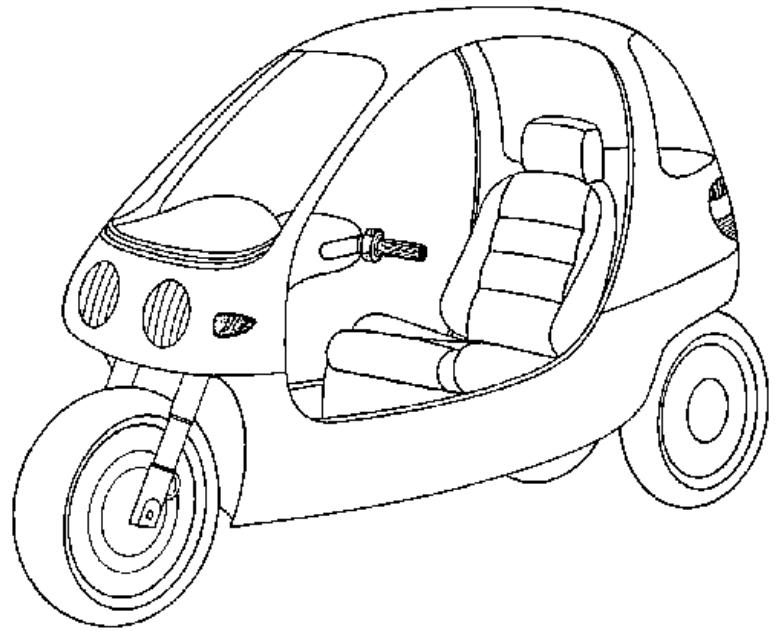


The clever feature of this design is the rocking yoke (balancer) which permits free leaning of the vehicle combined with normal suspension movement, only one suspension unit is necessary for the two rear wheels. In the centre of the yoke is a drum brake used for a lean lock when stationary. This brake is electrically operated under manual control, and allows for parking with the machine vertical even on extremely angled surfaces.

In common with its motorcycle base, both rear wheels are chain driven. There is a special differential that rotates on the same axis as the rear suspension trailing arms, the chains from which are not subject to the normal motorcycle problem of the length between the sprocket centres varying with suspension movement.

Of all the systems considered here, this one has the narrowest track by far and as such has great potential for small one or two place city cars. The narrow track though, means that it is hard to envisage that active lean is an option, meaning that any potential drivers would need to be confident with the need for motorcycle type balance skills.

Dimensions:



Two fixed one leaning wheel

Ariel (1970s) and Honda (1980s – ongoing)

Probably the first tilting machine to be on general sale, the Ariel 3 was basically a 3 wheeled moped with 1F2R configuration. A single seater it had a luggage box behind the rider for carrying the shopping, in keeping with one of it's target markets. Like a motorcycle the rider could put his feet on the ground for balance. Balance was achieved when parked by means of a torsion bar connecting the front and rear pods.

The Honda "Gyro" came later, although it had a similar configuration it did away with the torsion spring. The absence of the Ariel's torsion spring made a parking lean lock necessary. A more recent model is the Honda "Canopy" with an extended windscreen continuing into a complete roll-over structure.

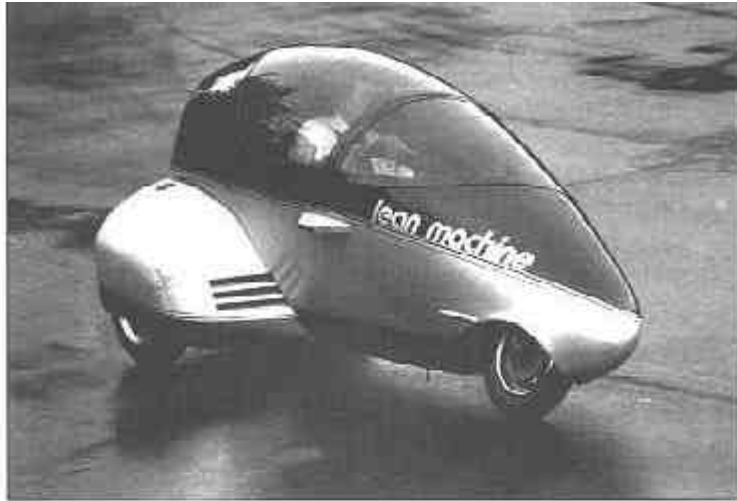
In keeping with the low price nature of these machines, no attempt at active lean control was incorporated.



General Motors Lean Machine (US patent No. 4,065,144 + others, mid 1970s – early 1980s)

Conceived as an economy vehicle during the oil shortages of the late 70s and early 80s, this machine never made it into production even though many prototypes were constructed over the course of several years. Early patents show vehicles with chain drive, very narrow track and all three wheels leaning, with the lean controlled by linkage from the steering. The last prototypes show a wider track although still narrow compared to some others. The later models were basically natural leaners but with the addition of pedals. These pedals were intended to be the primary lean mechanism, so removing the need for the driver to counter-steer as normal with a free-leaner. The pedals also would obviously be useful as a balance aid whilst slowing down.

With a claimed lean limit of approx. 50 degrees representing a balanced cornering limit of 1.2G. (higher than any expected cornering acceleration) it can be said that it is without any real lean limit.



GM's Lean Machine leans into turns for high-speed cornering.



A narrow 711-mm (28-in) rear track would normally lead to poor cornering capabilities. With its leaning passenger pod, Lean Machine could negotiate 1.2-g turns.

Dimensions: Track 710 mm. Length 2615 mm. Width 915 mm. Height 1220 mm. Weight 181 kg.

Jephcott's Micro (US. Patent 4,660,853 early 1980s - 1988)

Two vehicles were built by Dr. Jephcott in England. The first was a scooter based machine with pedals a la Lean Machine, this was built purely to test the concept. The second machine was built to a higher standard with tandem car type seating in an attractive fibre-glass all-enclosing body, designed by Richard Oakes. This machine made it's appearance in the early 80s. at about the same time as the Lean Machine, no doubt inspired by similar concerns over energy shortages and road congestion.

This machine was unique in having an all hydraulic active lean control, although the possibility of electronic control was acknowledged in the patent documents. A pendulum device mounted on the leaning pod acted directly on an hydraulic valve. When the front pod was not in a balanced turn the pendulum would not be lined up and the valve would direct oil to an actuating cylinder to increase or decrease the lean to restore balance. The hydraulics on this machine were underpowered and control response was too slow. There was a noticeable delay between driver input and lean response, which is not intuitive to the driver, and also caused him to be flung sideways when the delayed lean came into play.

This second prototype was built to show potential manufacturers the concept with a view to licensing the technology. It's believed that there was some interest from Honda at the time, but no production has been forthcoming and the patents have been allowed to lapse.

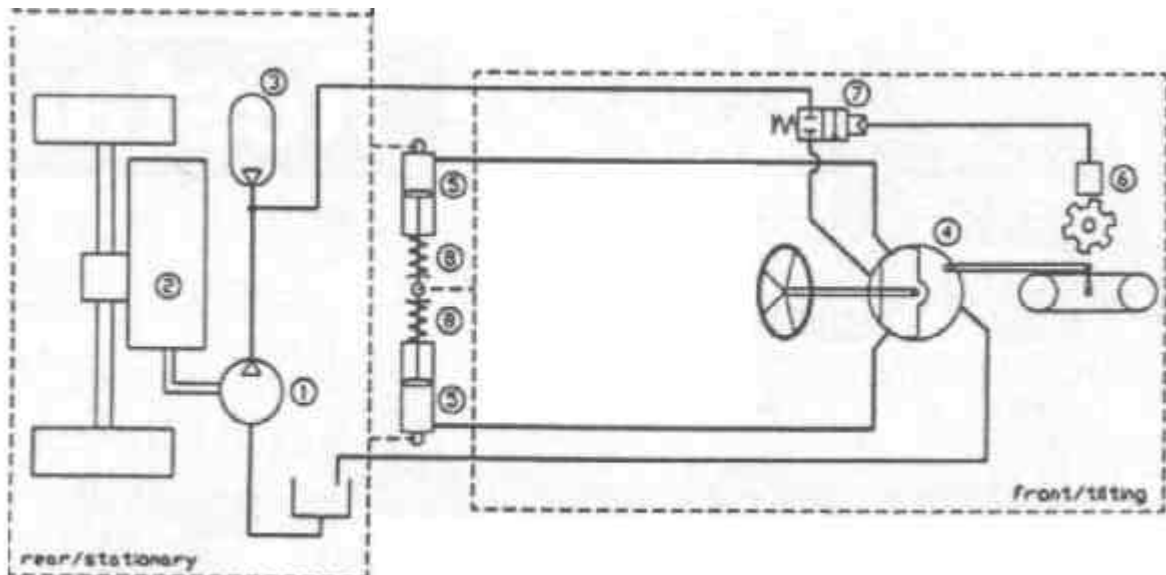
Dimensions: Length 2590 mm. Width 915 mm. Height 1420 mm.



Vandenbrink Carver (199? – ongoing)

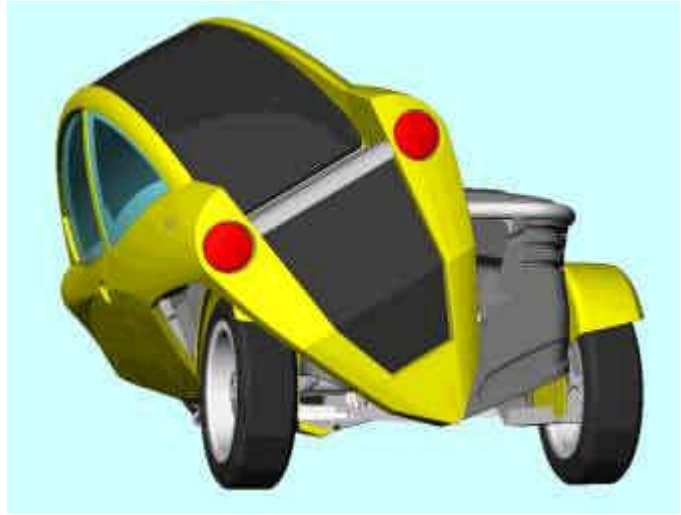
Of all the models reviewed here, the Carver is unique in that it is the only one actually scheduled for production, albeit limited. Winner of an inventor's award, this vehicle was conceived by a Dutch company which should have production models on the streets by the time this is published. A 1F2R design with about 45 degree lean possibility. Like the Micro it has all hydraulic lean control, but the system is very different. Called Dynamic Vehicle Control or DVC, this control system is based on the premise that with motorcycle type steering, there will be no steering torque when the machine is executing a steady state turn with a balanced lean angle. (Author's note: This is not strictly true but in general the torque will be low in value and will depend on such factors as tyre parameters, road surface and conditions. However, it is likely that steering torque will disappear at a lean angle not too far away from that for a fully coordinated turn.) The steering is coupled to a valve similar to that used for power steering on a car, which reacts to steering torque. As the driver applies torque the valve permits the actuators to lean the passenger section, to a first approximation the roll rate is proportional to applied steering torque. Naturally, the system is more complex than that in practice. There are controls to limit the roll rate, a time delay valve to smooth the initial roll in and some "artificial" lean dependent steering force feedback to give the driver a feel for the degree of cornering.

This system has the great advantage that there is little or no delay between the application of a steering/leaning request and it's leaning response, unlike the more usual system of sensing an error in the roll attitude and then applying the lean correction. Therefore, the machine tends to be very responsive.



Minimal components for the Vandenbrink DVC system

1. Hydraulic pump
2. Engine
3. Accumulator, keeps pressure at 120 bar
4. Steering valve
5. Actuating cylinders
6. Speed sensor
7. Shut off valve, in combination with the speed sensor this prevents lean actuation under 10 Km/hr. or in reverse.
8. Springs to keep the machine upright, in event of hydraulic failure or parking.



Most machines of this type with a mechanical roll axis use a structurally poor cantilevered bearing at the front of the rear pod. In contrast the Carver features an up and over addition to the front structure which connects to the pivot axis at both the front and rear of the rear section.

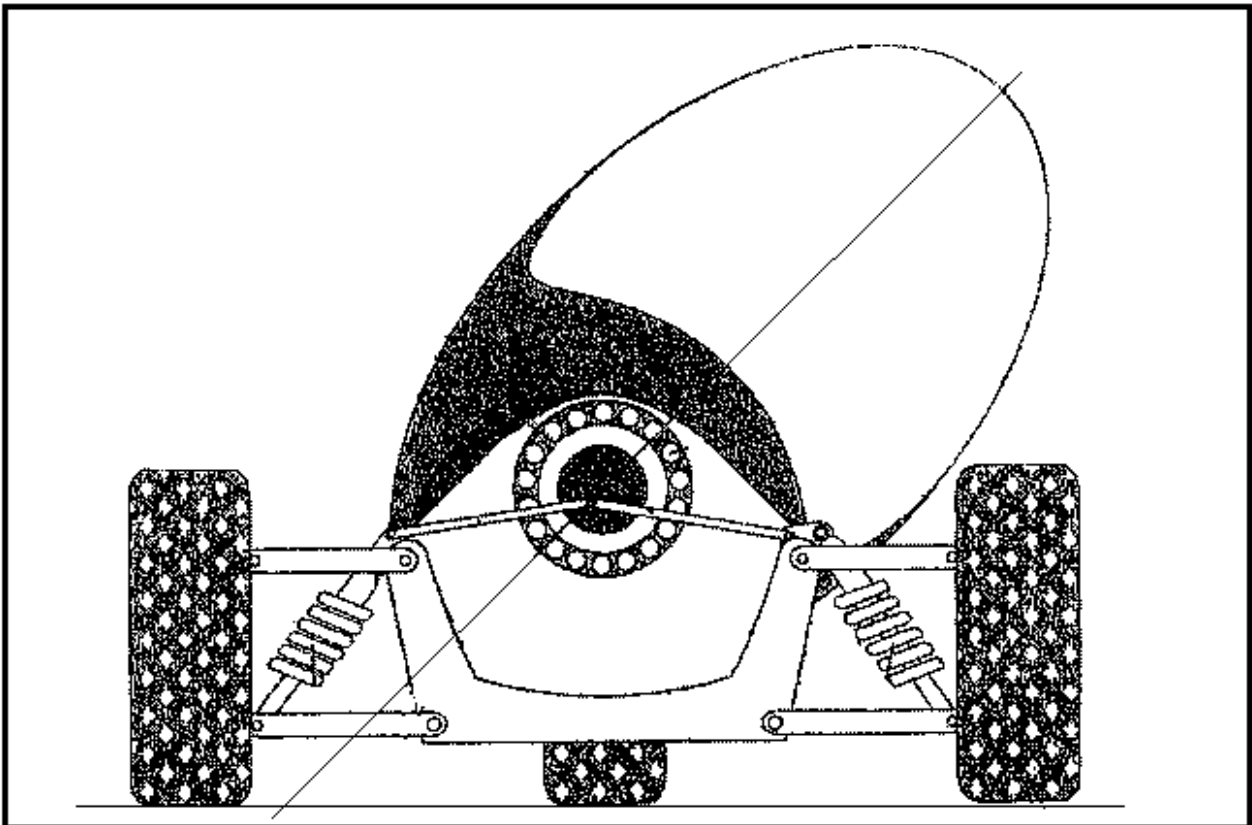
Dimensions: Wheelbase 2,600 mm. Length 3,400 mm. Width 1,200 mm. Weight empty 550 kg.

No leaning wheels

Ingram "Zero G"

Little is known about this machine as it was just a proposal.

The natural lean mechanism is absent from this type of design and so we can assume that the intention was for active lean control. In order to improve on the non-leaning roll-over performance of such vehicles the geometric roll centre of the leaning pod must be as low as possible, this is difficult to achieve because of the space demands of the non-tilting chassis. The illustration of the Ingram indicates that this roll-centre is probably close to the CofG of the pod, in which case the leaning will not improve the roll-over margin. It will though improve driver comfort, relieving him of lateral loading, and the vehicle name indicates that perhaps this was the main intention. A side benefit of having the roll centre and the tilting pod CofG coincident is that the power requirements of the actuating mechanism are reduced, little force is required to maintain any given lean angle and the roll moment of inertia of the passenger compartment about the axis is minimized.



Cliff Ingram's design with no tilting wheels. As drawn the tilting pod's roll axis is too high for good roll-over stability. At the angle shown the CoG of the pod would need to be very close to the front wheels to avoid roll-over.