The Design of A Motorcycle Featuring Fully Independent Adjustability for Front Suspension and Steering Geometry

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Abstract. The paper presents a feasibility study for a prototype motorbike (bike in short) with an alternative front suspension. Novel features include the adjustability of steering axis inclination, front trail, and anti-dive effect i.e. the main parameters affecting rider feedback and perception as well as motorcycle behaviour. Although being based on the well-known double-wishbone layout, the system can be adjusted to replicate the geometry of a conventional fork as a baseline for experimental testing. Unlike similar concepts that can be found in literature the kinematics can be modified by means of straightforward adjustments that do not require complex disassembly. Independent adjustability is provided for each parameter. These innovative features enable a back-to-back comparison between significantly different settings, in order to explore a wide range of characteristics in terms of dynamic response, handling properties and rider’s perception with a single vehicle. The project is aimed at fostering knowledge on motorcycle dynamics within the research group and especially on rider feedback and subjective perception, somehow a neglected topic in current literature. It was undertaken under the form of a student educational project in mechanical engineering and named “F.A.B.” (Fully Adjustable Bike). The paper is mainly focused on front suspension kinematics; chassis design and related structural aspects are outlined as well.

1. Introduction

The dynamics of single-track vehicles like motorcycles and bicycles is a consolidated subject. Authors like Cossalter [1] and Sharp ([2-11] among many others) explain the dynamic equilibrium equations and the importance of steering geometry. [12] describes the development of motorcycle suspension over the years and explains pros and cons of the fork as a front suspension system vs alternative layout e.g. the Hossack system [13].

The need for an adjustable front-end geometry to cater for different requirements on a motorcycle has long been felt. [14] for instance is a well-known patent owned by Bombardier regarding a fork head with adjustable steering axis inclination. A similar system is currently the standard in racing, where bike set-up is often adjusted to suit riding style, circuit characteristics and weather conditions. [15] is again a patent where the fork inclination (aka rake) can be modified in order to adjust the trail without affecting steering axis inclination. Such concepts require front suspension dismantling and re-assembly in the workshop, and do not provide independent adjustability for rake and trail. [16] is one of many patents owned by motorcycle manufacturers (Honda in this case) and dealing with the tendency to nose dive under braking, a typical consequence of conventional telescopic fork kinematics, as described in [17, 18].
In Europe, USA and Japan the motorcycle is mainly seen as a leisure vehicle. These markets are notoriously very demanding, leading to an offer made of particularly refined, high-end products, where the emotional aspects play an extremely important role [19]. As a matter of fact riding a bike on a twisty road can be a deeply involving experience. It is well known that riding position, feedback of interface commands such as the front brake and gearbox lever, throttle response and engine sound [20], and even the quality of powerplant vibration all add to the “character” and “personality” of a motorbike and should be carefully designed to suit a specific rider “family”. In other words, in a market made of discerning customers the quality of emotional feedback is considered at least as important as objective dynamic characteristics like outright engine power, overall performance, stability, and active safety for instance.

Steering feedback and response in particular are among the main factors affecting the riding experience in terms of subjective perception. They involve turn-in, bike roll transient and all those subtle interactions between rider’s body and bike balance. However, it seems that the impact of objective design factors like motorcycle geometry on rider perceptions is still a fairly unexplored zone, at least outside of the manufacturers’ design and R&D departments. Apparently, road and/or track testing performed by experienced riders is still the most straightforward route to an effective correlation between subjective “feelings” and engineering parameters.

Automobile steering feeling is often considered to be the most important among driver feedbacks, see [21-25] among many others. This is a largely explored topic, especially with the advent of Electric Power Steering (EPS), driving simulators and Advanced Driving Assistance Systems (ADAS). On the other side it is true that various papers deal with rider/motorcycle interaction from the control theory point of view (from “historical” works like [26-29] to the renowned research of R. Sharp, again [2-11], to recent contributions [30]). However, there is not much evidence of similar studies concerning rider feedback, steering feeling and subjective-objective correlation assessment, although the role of perception is acknowledged as the core of riding a motorbike.

The authors felt the need for an attempt at bridging this gap and building their own experience on the subject, also in order to guide the students in motorcycle-related projects such as future Motostudent competitions. These are the reasons why the project of a concept motorcycle with fully adjustable front end was born, where set-up changes could be easily made “on the go” in order to enable a back-to-back comparison between different steering geometries hence between different characteristics in terms of dynamic response. The design enables independent adjustment of each relevant parameter without taking the bike apart:

- Steering axis inclination
- Front trail arm
- Front anti-dive percentage

The prototype will undergo manufacturing and assembly in the next months and road test results will be addressed in a future publication.

2. Material and Methods
The Automotive Group of the University of Brescia has been active in the fields of vehicle dynamics and design, research on high-performance vehicles and sustainable mobility for many years. With regard to racing cars for instance, a work dealing with lap time simulation of a professional single-seater racecar is [31], including optimal control application. The interaction of ground-effect aerodynamics with non-linear suspension dynamics is dealt with in [32], while a thorough revision of the working principles of the limited-slip differential and its impact on vehicle behaviour are described in [33]. Recent involvement in student design competitions like the Formula SAE and Motostudent contests has boosted applied research in the automotive sector along with the build and development of some one-off vehicles, as shown by papers like [34] (on the development of a peculiar front suspension and steering geometry for a FSAE racing car), [35] (describing four-poster vibration testing on a FSAE car aimed at the development of a suspension friction model, to be incorporated into vehicle dynamics simulations), and [36, 37] (describing estimation methods for the so-called
Vehicle Sideslip Angle). Research on the impact of intensive use of light alloys for chassis substructures is described in [38-43]. Experimental vibration testing on cars and motorbikes is also dealt with in [44-46]. Some papers are related to human-vehicle interaction like [21], describing how friction affects driver’s feedback from the steering system, as well as the results of a related experimental campaign. A peculiar approach to energy management for hybrid vehicles is presented in [47].

The vital role of student design competitions in engineering education through experiential learning and “learning by doing” is described in [48, 49] according to the theory outlined by authors like Wankat and Oreovicz [50], Bandura [51, 52], Siddique at al. [53], Kolb [54, 55], and a world-famous article written by cognitive psychologist Miller [56]. Among others, [57] states the specific value of motorsport-related design competitions in engineering schools.

Along with the guidelines above, the design of a motorbike with a fully adjustable front end was undertaken as a final project in mechanical engineering [58]. It is based on the experience recently gained by entering the 2016 international Motostudent event with BRX 250, a small racing bike fully designed, built and developed by students (again [48], and Fig. 1). So far, this project resulted in extended knowledge within students and university staff and is aimed at generating guidelines for future designs.

![BRX 250, the 2016 Motostudent project of the University of Brescia.](image)

2.1. Fundamentals of Bike Geometry

![Motorcycle front end geometry](image)

With reference to [1], a simple bike model with no suspension is composed of four rigid bodies: the front wheel is connected to the front end i.e. the steering system, and the rear wheel is connected to the chassis by means of revolute joints allowing for wheel rotation. A third revolute joint connects the front end to the chassis; the relative rotation between these two parts and around the steering axis is the steering angle, to be directly controlled by the rider. Additional degrees of freedom are the longitudinal motion and the roll angle. The basic geometry can be described by means of the following...
three values, all defined in the bike vertical plane (Fig. 2) and related to the basic handling characteristics:

1. Steering axis inclination (aka caster angle)
2. Normal front trail i.e. the distance between the steering axis and the front wheel contact patch centre
3. Normal rear trail i.e. the distance between the steering axis and the rear wheel contact patch centre

Table 1. Motorcycle front end geometry: Reference range for the main parameters.

| Motorbike type | Racing | Sports | Touring |
|----------------|--------|--------|---------|
|                | track racing only | road-going motorbike, high power-to-weight ratio | suitable for long-distance travelling |
| Handling requirements | ← agile | stable → |
| Caster angle | 20°-25° | 25°-30° |
| Normal trail ratio (front/rear) | 5-7% | 6-8% | 7-9% |
| Front trail (on ground plane) | 75-100 mm | 90-130 mm |
| Wheelbase | 1300-1500 mm | 1400-1600 mm |

Reference is usually made to the so-called front trail (namely the projection of the front normal trail on the ground plane when the bike is in the upright position), and to the wheelbase, as these dimensions are easily understood. Table 1 shows a typical range for these parameters that play a fundamental role in determining the bike handling “character” in terms of dynamic response. A large front trail in particular makes for a large self-aligning moment on the front wheel and results in a very stable bike with heavy steering, at the expense of agility on a twisty route. Nearly all the models on sale feature the conventional fork as front suspension/steering system. In general, the fork is deemed to ensure a good compromise in terms of handling, comfort, reliability, and production costs, and offers the traditional look that is normally appreciated in such a largely conservative market. Apart from inherent friction between the sliding components, the main drawback of the fork is related to the tyre contact patch trajectory which is inevitably aligned with the fork axis. As the suspension is compressed the wheel moves backwards resulting into a so-called “pro-dive” effect. Such a geometry gives favourable ride comfort on bumps but amplifies the effect of the longitudinal load transfer in braking, resulting in larger pitch angles (up to a 100% increase and beyond, see Table 2) with the related “lazy” feeling in transients plus a reduction of the front trail, at the expense of stability [1, 58, 59]. A modern, non-kinematic solution to this typical behaviour is active damping control, see [60].

Currently BMW is one of the few high-volume manufacturers to offer alternatives to the fork: the well-known Telelever® (Fig. 3; corresponding to a McPherson system in automotive terms) and the Duolever®, originally known as the Hossack system [12, 13] (Fig. 4), corresponding to a double-wishbone layout in automotive terms. The handlebar pivots directly on the chassis and it is connected to the front wheel carrier by means of a scissor link. In the BMW case these bikes usually combine a mass well beyond 200 kg with a fairly high power-to-weight ratio, long-distance touring capabilities and a high-tech look as well.

Table 2. Comparison of the F.A.B. concept with a reference bike model.

| KTM Duke 690 | F.A.B. concept |
|---------------|----------------|
| Engine        | KTM “mono”     | Aprilia V-twin |
| Capacity      | 690 cc         | 550 cc         |
| Power         | 54 kW          | 50 kW          |
| Dry weight    | 150 kg         | 120 kg (estimate) |
| Wheelbase     | 1467 mm        | 1450 mm        |
| Front trail   | 115 mm         | 110 mm         |
| Caster angle  | 26.5°          | 21°            |
Such systems decouple steering geometry parameters from the front wheel contact patch trajectory in bump, enabling reduced pro-dive or even anti-dive properties to be built in the front suspension, hence reducing pitch angle in braking and shortening the related transient [1, 12, 17, 18]. From the subjective point of view this is usually perceived as a noticeable advantage, especially when riding a heavy touring bike with passenger and luggage.

Figure 3. The BMW Telelever® front suspension (source: www.bmw-motorrad.de).

2.2. The F.A.B. (Fully Adjustable Bike) Concept
The F.A.B. has been conceived as a road-going, single-seater, naked-style motorcycle (Fig. 5). It features a spaceframe chassis made of 25CrMo4 tubes accommodating a stock Aprilia SXV V-twin, 550 cc engine, which is extremely light and compact. This unit was readily available as it was previously employed on the FSAE racing cars. The rear suspension is as simple as possible, featuring a Honda CRF 450 swing-arm in cantilever configuration and a 4.5” wheel fitted with a 160/60-17 tyre. A progressive linkage is deemed redundant as there is no passenger seat.

With regard to the front end, suspension geometry is usually fixed on customer motorbikes, whereas the F.A.B. concept provides quick, easy and independent adjustability of the main parameters including the amount of anti-dive effect. This led to the design of an unconventional layout akin to a double-wishbone or SLA (Short-Long Arm) system like the Hossack and BMW Duolever®, where the hardpoints have been purposely located to guide the front wheel centre/contact patch along the desired...
trajectory. A proprietary tool based on a spreadsheet has been used to define the in-plane kinematics (Fig. 6) along wheel travel, and to automatically define the geometry in the CAD software accordingly by means of a parametric baseline. This model, also used by the authors for race car suspension design, can be applied to any combination of the adjustments outlined in the following sections in order to plan the testing activity, and will be described in a future publication. Low-friction, motorsport-type ball joints connect the suspension arms to the chassis (side joints) and each wishbone to the wheel carrier (main joints): the main joints are of the wide-angle type to allow for the required steering angle and their centres define the actual steering axis, hence the nominal caster angle and front trail values.

Figure 5. The F.A.B. project assembly.

Figure 6. Spreadsheet-based model for kinematics design.

Table 2 compares the F.A.B. design configuration with a roughly similar bike available on the market. The anti-dive percentage has been computed statically i.e. at the beginning of braking, before any pitch occurs, assuming brake bias is 100% on the front wheel. The Centre of Gravity height was estimated at 745 mm with the help of the CAD solid model comprehensive of a 95-percentile rider equipped with full-face helmet.
Unlike the Duolever® the handlebar is connected to the wheel carrier by means of a rocker coupled with a pair of conrods in parallel, allowing for kinematic compatibility within the adjustability range while also reducing the required working space ahead of the handlebar in combined bump and steer (Fig. 7).

Springing is provided through a Formula 1-style pushrod system acting on a coaxial spring-damper unit via a rocker located just behind the handlebar (Fig. 8). The design configuration is based on a motion ratio equal to 1.4 with a progressive trend in bump. The motion ratio characteristic could be easily modified by changing the shape of the rocker. The spring-damper unit is located on hand above the engine/airbox for easy adjustments, and eventually hidden under a dummy fuel tank cover, while the actual fuel tank is located under the saddle.

3. Results and Discussion
The bike in itself is a stripped-down, all-essential design hence potentially it is extremely light and sensitive to setup changes: 140 kg in running order, according to an estimate based on the CAD solid model. On top of this, removing the fork provides further potential in terms of weight reduction - unsprung mass reduction in particular- and yaw moment of inertia optimization.

While similar prototype bikes feature machined plate-style wheel carriers, currently the F.A.B. wheel carrier has been designed with light-alloy plates accommodating steel tubes running down to the wheel pivot, a layout that should ensure a torsional stiffness comparable to an upside-down fork (Fig. 7). It is possible to replace steel with lighter materials like CFRP or even titanium as a cost-no-object option. Eventually fatigue should also be taken into account carefully for these advanced solutions.
3.1. The Baseline Configuration

The baseline or design configuration is positioned in the middle of the range available for all the three adjustable parameters. In kinematic terms it is equivalent to a geometry suitable for an agile bike with prompt response to rider inputs. The anti-dive amount and its variation along wheel travel are similar to a Duolever® layout. A fork-equivalent geometry is available at the lower end of the anti-dive adjustability range (see section 3.4).

3.2. Front Trail Adjustment

With regard to caster angle and trail it is possible to apply significant set-up changes to the front geometry with simple tools and some training, even during a short stop along the road. There is no need to take the motorbike apart in a workshop, and this means a back-to-back comparison between different configurations is made possible.

Suspension arm ball joints are connected to the wheel carrier by means of machined blocks, bolted to the fork-style plates and conceptually similar to the so-called camber blocks on single-seater racecars. The front wheel carrier position relative to the chassis can be offset by changing the thickness of the shims located between each block and the top and bottom plates (Fig. 9). Therefore, the front trail can be modified by simply releasing a few Allen screws while keeping the steering axis angle and position as well as the whole suspension kinematics characteristics unaltered. As shown in Table 3, front trail adjustability is very wide and covers nearly the whole range specified in Table 1. The original wheelbase length and ride heights can be eventually restored by adjusting the longitudinal rear wheel position relative to the swingarm and the front spring-damper unit length respectively. The latter modification might require action on the spring platform like changing the rear preload, an ordinary adjustment often made when preparing a touring bike for a trip with passenger and luggage.

| Offset modification | Front trail | Front trail variation | Wheelbase & variation | Comments |
|---------------------|-------------|-----------------------|-----------------------|----------|
| Top Shim            | Bottom Shim |                       |                       |          |
| -5 mm               | +5 mm       | 81 mm                 | -29 mm                | +27 mm   | Minimum trail available |
| 0                   | +5 mm       | 93 mm                 | -17 mm                | +16 mm   | Bottom shim mod only    |
| -5 mm               | 0           | 98 mm                 | -12 mm                | +11 mm   | Top shim mod only       |
| +5 mm               | +5 mm       | 104 mm                | -6 mm                 | +6 mm    |                        |
| 0                   | 0           | 110 mm                | 0                     | 1450 mm  | Design configuration    |

Table 3. Front trail adjustability range.

Figure 9. Shim adjustment for front trail variation.
3.3. Steering Axis Inclination Adjustment
The lower wishbone has been conceived for quick length adjustability as the ball joint is installed via a threaded bushing clamped in the suspension arm. By releasing the clamp and a locknut and rotating the bushing with the help of a spanner the caster angle can be adjusted continuously. Alternatively, the top wishbone length can also be modified by adjusting the ball joint length. In this case the adjustment is discrete as the ball joint can be rotated by 180° at a time. This modification requires lifting the bike off the ground. Once again, the adjustability range is very wide. Figures 11 and 12 show the combined effect of wishbone length variation on the caster angle, as well as the consequent trail variation, to be eventually restored by means of shim replacement with the help of the spreadsheet-based model. A ~10% caster increase for instance (from 21° to 23°) can be achieved with a length adjustment of 5.5 mm on the bottom wishbone only. This will result in a 11 mm front trail increase approx, to be corrected by removing a 5 mm shim from the top only. These figures show that large geometry modifications can be easily performed in order to achieve significant changes in terms of handling properties and rider’s perception.

Figure 10. Variable-length lower wishbone. A threaded insert and a clamp hold the main ball joint in place and allow for continuous adjustability.

Figure 11. Caster angle adjustment with suspension arm length variation.
3.4. Anti-dive Adjustment

Adjustment of the anti-dive characteristics is more complex since it inevitably requires re-locating the suspension arm mounting points: this modification cannot be made “on the go”. Nevertheless, it is quick and relatively easy: three different positions have been designed for each wishbone on the chassis side. They are located 12 mm apart in the vertical direction and along an arc (Fig. 13), hence no suspension arm length modification is virtually required. Again, a ride height compensation can be eventually made by acting on the front spring-damper unit length. Small corrections to caster angle and front trail might be required as well and can be computed by means of the kinematics model.

It should be stated that unlike a fork, the Hossack geometry produces variable anti-dive properties along suspension displacement. The BMW Duolever® for instance features a very progressive trend from mild pro-dive in static configuration to anti-dive in full bump. That’s how the F.A.B. front end was designed as well, although the remarkable arm length will generate a more consistent characteristic in this case. Table 4 lists the pick-up point combinations available with the related anti-dive percentage from static to full bump.

Figure 12. Caster angle and front trail adjustments with suspension arm length variation.

Figure 13. Adjustable suspension arm pick-up points for anti-dive modification.
Table 4. Anti-dive variation in bump and adjustability range.

| Pick-up points vertical position | % anti-dive range (pro-dive if <0) | Comments                          |
|---------------------------------|------------------------------------|-----------------------------------|
| chassis side                    |                                    |                                   |
| Upper arm                       |                                    |                                   |
| +12 mm                          | -12 mm                             | -110%                             | -36%                              | Full pro-dive (equivalent to fork) |
| +12 mm                          | 0                                  | -79%                              | -1.5%                             |                                     |
| 0                               | -12 mm                             | -47%                              | +11%                              |                                     |
| +12 mm                          | +12 mm                             | -47%                              | +30%                              |                                     |
|                                | 0                                  | -40%                              | +41%                              | **Design configuration**             |
|                                | -12 mm                             | -34%                              | +52%                              | Similar to BMW Duolever®             |
|                                | 0                                  | -8%                               | +67%                              |                                     |
|                                | -12 mm                             | 0                                 | +77%                              |                                     |
|                                | -12 mm                             | +28%                              | +95%                              | From mild to full anti-dive          |

3.5. Structural Requirements

FEM analysis was carried out on the chassis with main focus on stiffness. A rigid chassis is vital to guarantee a responsive behaviour and to stay away from dangerous dynamic effects like wobble oscillations [10]. The F.A.B. engine is semi-stressed as it is bolted directly on the chassis, therefore the FEM model takes the engine block into account as a dummy solid structure (Fig. 14) and shows that it contributes heavily to overall structural performance. With regard to torsion stiffness, simulation results are beyond 200 kNm/rad. This is probably overestimated: welding is not yet taken into account for instance, however the value is well within the desirable range suggested by [1] (100-300 kNm/rad). Moreover, it is in line with the results of a previous study on the Aprilia RS 250 chassis [61], still considered a benchmark structure for compact, light and sporty road bikes. The FEM model was composed of the chassis alone in this case (Fig. 15), as the engine is not stressed. In any case the construction of a stiffness test rig is under way within the Motostudent project: it should allow for FEM validation.

Chassis pick-up points, suspension arms and ball joints were also verified for strength under the main load cases found in the literature [1]. Future experimental tests on the above-mentioned rig will be required to evaluate longitudinal, side and torsion stiffness for the front suspension assembly.

Figure 14. Chassis FEM model with and without engine contribution.

Figure 15. FEM mesh of the aprilia RS chassis.
4. Conclusion
Although it was fairly successful, the recent design and construction of a Motostudent racing bike highlighted the need to gain knowledge and experience on the effects of steering geometry on the motorbike dynamic behaviour. Even more important, it was also found that correlation between rider perception and bike geometry seems to be a neglected topic in literature. As an attempt to fill such a gap the design of an experimental motorcycle with a fully adjustable front end was undertaken from scratch under the form of an educational project.

The paper presents the first stage of the project i.e. a feasibility study including overall motorbike layout, a spaceframe chassis, and a traditional rear suspension. The focus is placed where rider interaction with the bike is most significant: the front end, featuring a peculiar layout for a Hossack-style front suspension with built-in adjustability of the most significant parameters influencing rider feedback as well as motorcycle dynamics.

The overall concept and methodology were inspired by typical racing car suspension system design: steering axis inclination, front trail arm and anti-dive amount are adjustable separately. A wide range is available for each parameter, thus offering the opportunity to change the bike “character” noticeably. Geometry modifications can be performed easily, even by the rider alone with the bike resting on the centre stand. There is no need to take the front end apart.

The following F.A.B. project stages will be addressed in a future publication: the final design, manufacturing and construction, and the results of a back-to-back testing campaign focused on subjective-objective correlation, which should give more insight and issue guidelines for future projects. The overall longitudinal, lateral and torsion stiffness of the front end will also require careful assessment in order to avoid dynamic effects that might jeopardize rider perception and motorcycle performance. The reduction of both steering and suspension friction is also a challenge to be tackled during the manufacturing process and might require further developments in the concept design as well.

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