Bicycling safety and the lateral stability of the bicycle

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ABSTRACT

The number of fatalities and seriously injured among bicyclists in traffic is still high and trends show that it increases with time. What is the underlying cause of these accidents? One aspect of bicycling is the vehicle itself: the bicycle, a very versatile but also inherent laterally unstable vehicle. This paper focuses on the current knowledge on the stability and control of bicycles.

Keywords: bicycle, stability, control, handling, accidents, safety.

1 INTRODUCTION

A quarter of all fatalities and half of all seriously injured in traffic in the Netherlands are bicyclists. The mortality rate among bicyclists decreases less than the one among other modes of transport. But even more alarming is that in the last 10 years the number of seriously injured bicyclists is steadily increasing [1]. This increase is for a large part among the elderly, where the types of accidents are so-called single vehicle accidents. The bicyclist is not hit by a car or a bus, he just falls over. One aspect of this falling over can be attributed to the stability of the vehicle, the bicycle.

The bicycle as we know it now, is over 120 year's old, and is developed in an evolutionary and thus incremental and timely process, see Figure 1. Then, is there still room for any fundamental changes in the design of this concept? There certainly is, in particular in the case of non standard applications, like for instance a folding or a recumbent bicycle. These vehicles are becoming more and more popular but still show poor handling and stability. Here evolution has not reached the final stage of optimal design yet. Another category, which is very important for road safety, is a bicycle for the elderly. Recently there has been an increase in the number of bicycles especially designed for the elderly. However, experience shows that these are not very popular, and one can question if they are designed for optimal handling and stability. In this paper we examine the current knowledge about the handling and lateral stability of the bicycle.

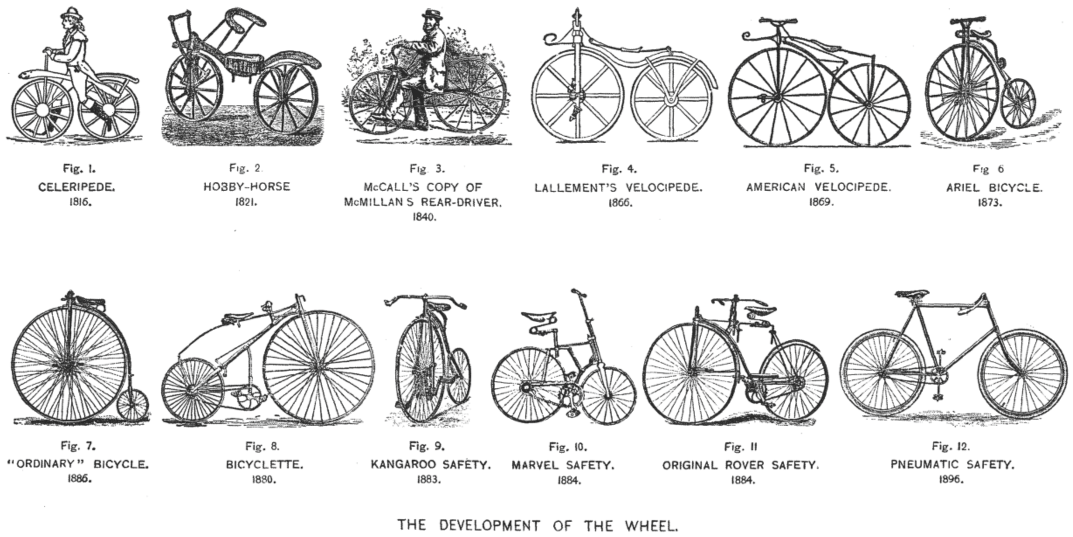

Figure 1. The evolution of the bicycle; starting from the initial hobby horse design by Karl von Drais, from around 1820, to the final and current safety bicycle, having equally sized wheels, a chain drive and pneumatic tires, from around 1890 [2].

2 LATERAL STABILITY OF THE BICYCLE

With only two contact points on the ground, the bicycle is a laterally unstable vehicle. When released at rest it will fall over. But given some forward speed most bicycles seem to stay upright and show the ability to balance themselves. Since the birth of the modern safety bicycle, a bicycle having equally sized wheels, a chain drive, and pneumatic tries, around 1890, scores of people have investigated this selfstability, either for a dissertation, a hobby or sometimes as part of a life's work on vehicles. Around this time, in 1899, the French mathematician Emmanual Carvallo [3] and the Cambridge undergraduate Francis Whipple [4] were among the first who used rigid body dynamic equations to show in theory, what was already know in practise, that some safety bicycles, moving in the right speed range, can balance themselves. Since then it has been an ever returning subject both in scientific literature as well as in the popular press. Unfortunately most publications show different results for nearly identical models, and none of these publications compare results among each other. A recent publication by Meijaard *et al.* [5] presents a validated model for the lateral dynamics of a bicycle which can be used for a benchmark. In the same paper a historic overview and review of the bicycle dynamics literature is presented.

It is fairly easy to demonstrate in an experiment that a common bicycle can be selfstable, given enough forward speed. Take any bicycle and a wide open space, like an empty car park. Bring the rider-less bicycle up to speed and release it. When the forward speed is low (<15 km/h) the bicycle will start a steadily increasing oscillation after which the bicycle finally falls down. But given enough forward speed the bicycle will show lateral oscillatory stable motion. Once hit sideways it will oscillate, but the oscillation will die out and the bicycle stays uptight. This stable behaviour can be seen in videos at [6].

However, even with the dynamic equations for the lateral dynamics at hand [5], it is not straightforward to see why bicycles can be selfstable. Common claims for bicycle selfstability are the gyroscopic effect of the wheels and the trail of the front wheel. Where trail is the distance of the front wheel contact point to the steering axis, see Figure 2. And indeed, Klein and Sommerfeld in their four volume book on gyroscopes [7] claim in part four, which was written by Fritz Noether, that the gyroscopic effect of the front wheel is necessary for bicycle selfstability. The necessity of trail for bicycle selfstability is presented in a widely popular paper from the 70's by David Jones [8]. But are these two effects necessary? No. In a recent publication in Science [9], Kooijman *et al.* demonstrate, both theoretically as well as experimentally, that gyros and trail are not necessary for selfstability. They do not deny that, in a normal bicycle, they can contribute to the selfstability, but they are not *necessary* for selfstability. Other parameters like the mass distribution also can play an important role, as demonstrated by their selfstable two-mass-skate bicycle [10]. The bicycle, see Figure 3, which looks more like a scooter than a normal bicycle, has no gyroscopic effect because of the usage of small and counter rotating wheels. And the front wheel has no trail, that is, the wheel contact point is on the steering axis. This bicycle is selfstable because of the somewhat strange mass distribution.

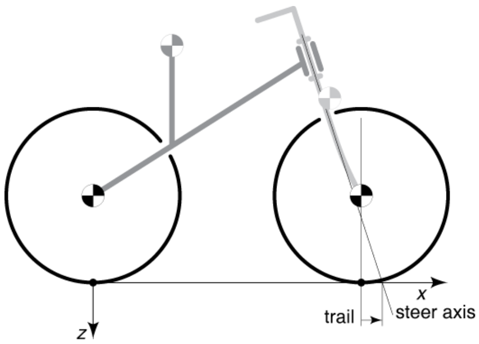

Figure 2. Bicycle model with steer axis and front wheel trail.

Figure 3. Two-mass-skate bicycle, a selfstable bicycle without gyros and trail [9,10].

As a rule they have found that any selfstable bicycle can be made unstable by either misadjusting the gyros, the trail or the mass distribution of the front assembly. But they also found that many unstable bicycles can be made selfstable by adjusting one of these three design parameters. Clearly, current bicycles are designed by an evolutionary and thus incremental process, as can be seen in Figure 1. The results from Kooijman *et al.* [9], show that the possible useful design space for bicycles is much larger than assumed until now. This gives new opportunities for designing out of the ordinary bicycles like folding bicycles, recumbent bicycles or bicycles for the elderly, with a focus on handling and control.

3 BICYCLE BALANCE

To understand the balance of a bicycle we first look at a simpler problem. How do we balance a stick on our open hand? We balance the stick by moving the support in the direction of the undesired fall. In the same way a bicycle can be balanced. However, we can not move the ground which supports the bicycle. But we can use the steering to move the contact points. This steering does not do anything for balance when the bicycle is standing still. But in a moving bicycle the steering rolls the contact points sideward. To move the contact point to the right we steer to the right and vice versa. So when the bicycle falls to the right we have to steer to the right to get the contact points under the bicycle again. This mechanism is called "steer into the fall" and is a necessary condition of selfstabilty [9]. An in-depth discussion on the possible mechanisms for bicycle balance can be read in the electronic supplementary material to [9].

Despite this basic balance mechanism, little is know about how a rider balances a bicycle. The rider has to steer into the fall, but we do not know how the rider senses that the bicycle is falling and how he reacts. Recent observations of bicyclists on an instrumented bicycle (Figure 4) have shown that most of the rider control is done by steering [11]. One can ride a bicycle without hands, and balance with upper body motions, which indirectly move the steering. But in normal bicycling we observe that the rider prefers steering and only move their upper body to compensate for the periodic pedalling motion. We have found that at low speed suddenly lateral knee motion is used as an extra balance mechanism. This can be explained as follows: at low speed the steering becomes less effective in moving the contact points sideward, and therefore an extra balance mechanism is recruited. This mechanism can also be observed in a famous picture from Albert Einstein riding a bicycle, as shown in Figure 5.

Figure 4. Instrumented bicycle and rider for rider control observations and measurements. Positions are measured with an active marker system and the bicycle is ridden on a large treadmill at the Free University Amsterdam. [11].

Figure 5 Albert Einstein riding a bicycle, note the position of the knees.

3 BICYCLE CONTROL

How does a rider maneuvers his bicycle around? Obviously by steering, but what does the rider do exactly when he wants to change direction and enters a turn? The answer is rather counter intuitive. To make a turn to the left the rider briefly steers to right and then let go of the handle bars. In order to stay in a steady turn to the right the bicycle has to lean to the right. The rider can lean the bicycle by moving the contact points; therefore he has to steer to the left to let the bicycle fall to the right. By next letting go of the handle bars the bicycle will steer into this right turn. To maintain the turn the rider keeps the steer in the desired turning position. Most bicyclists are not aware of this counter steer mechanism, and this might also be the reason why riding a bicycle is an acquired skill, you cannot learn it by only reading the manual.

4 CONCLUSIONS AND RECOMMENDATIONS

The increase in the number of older cyclist and the increase in the usage of electrically assisted bicycles require a closer examination into the controllability and stability of the bicycle. In particular because of the increase in the number of seriously injured among the older rider. For successful design the complete bicycle plus rider system should be considered. Validated computer models for the bicycle are now readily available. Unfortunately, bicycle rider models are still in its infancy, and future research should be directed towards generating experimentally validated bicycle rider models.

With a lot of clever tinkering bicycles evolved to a great design in about 1890. Maybe now with careful experiments and validated computer models we can move past that 19th century bicycle evolution to a 21st century bicycle revolution.

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