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Development of a multi-lane cargo bike with a view to driving behaviour

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Abstract: Cargo bikes are a suitable alternative to cars for transporting food or loads for private individuals or delivery services, especially in city centers. Major advantages are that the use of cargo bikes is emission-free and causes no noise. In comparison, the intensive use of private cars in inner-city traffic is very harmful to the traffic system and the environment. In order to solve this problems, this project deals with the product development of a multi-lane cargo bike, which is designed for the transport of loads over short and medium distances. The funded *SteigtUM* project therefore developed an urban mobility concept based on micromobiles. One part of these micromobiles are the cargo bikes mentioned above, which are used with an app-based hire system. The aim for the newly developed cargo bike with two wheels in the front is to achieve a driving behavior that is comparable to the driving behavior of conventional single-lane bicycle. The reasons for the multi-lane design are an autonomous parking function, which is one of the overall objectives of the project and a safe standing even with loads. In order to gain a comparable driving behavior like single-lane bicycles, the strong dependence of the geometric design on the steering head angle and the caster must be given special consideration. In addition, the torsional stiffness and the track adjustment of the multi-lane axle are of great importance. The developments in the overall project take particular account of suitability for everyday use. Furthermore, they are based on various user studies on driving behavior and thus ensure a high level of acceptance and usability. Cargo bikes therefore offer a great opportunity to further strengthen sustainable inner-city mobility and reduce the use of cars as a means of transport.

Keywords: Cargo bicycle, Tricycle, self-stabilization, steering wobble, steering geometry

1 Introduction

Cargo bicycles, also known as cargo bikes, are currently one of the fastest growing bicycle model groups. For example, sales in Germany rose from 60.100 in 2018 to 212.800 cargo bikes sold in 2022 [Association (2023)]. The customer can choose from many fundamentally different designs. Next to single-lane designs, like long-john or long-tail bikes, there are also tricycles. Some of them have two wheels in the front (tadpole tricycle) and some have two wheels on the rear axle (delta tricycle) and sometimes tricycles are equipped with a tilt technology. Each of these designs has its own driving characteristics. Large turning circles, unusual cornering behavior or a bad load arrangement with a high center of gravity are typical problems. To avoid unacceptability and to evaluate the expectation of potential users of the *SteigtUM* rental system, a cargo bike testing event in corporation with the *Technische Universität Chemnitz* was held. Twenty study participants tested four different types of cargo bikes on a specially prepared course with and without external load. Next to three commercial cargo bike solutions, one long-john and two tricycles, a self designed single-lane long-tail with two load platforms was tested. Due to a similar driving behavior as known by the participants from common bicycles, the self designed long-tail is certified to have a safe driving experience [Kreißig et al. (2021)]. But the single-lane long-tail is not fulfilling the project specific requirement for the possibility to implement autonomous driving functions. Therefore, this article deals with the development of a new constructional design for a cargo bike based on the single-lane long-tail. Starting from an overview about the driving behavior of tricycles and bicycles, special construction design features such as the tilt mechanism and the steering geometry of the developed cargo bike are described. Furthermore, a test rig for investigating the optimum track setting to achieve a safe driving behavior is presented.

1.1 Driving behavior of rigid tricycles

Naturally rigid tricycles, independently of whether designed as tadpole tricycles or delta tricycles, have different handling characteristics compared to a single-lane bicycle. The low weight of tricycles compared to the drivers weight and the drivers high center of gravity results in a high overall center of gravity. The usual small dimensions of tricycles (track, wheelbase) lead to the vehicle trying to roll over to the outside of a curve while driven fast. This is the reason why tricycles are generally considered to drive unstable [Hilgers (2016)]. The advantage of rigid tricycles is their driving stability at low speed without dynamic influences, keeping the tricycle in an upright position.

1.2 Driving behavior of bicycles

Single-lane bicycles on the other hand have the ability to tilt to the inside of a curve. The resulting unstable balance of centrifugal force and gravity allows fast and dynamic cornering, depending on the drivers skills. With the whipple-model, the self-stabilization

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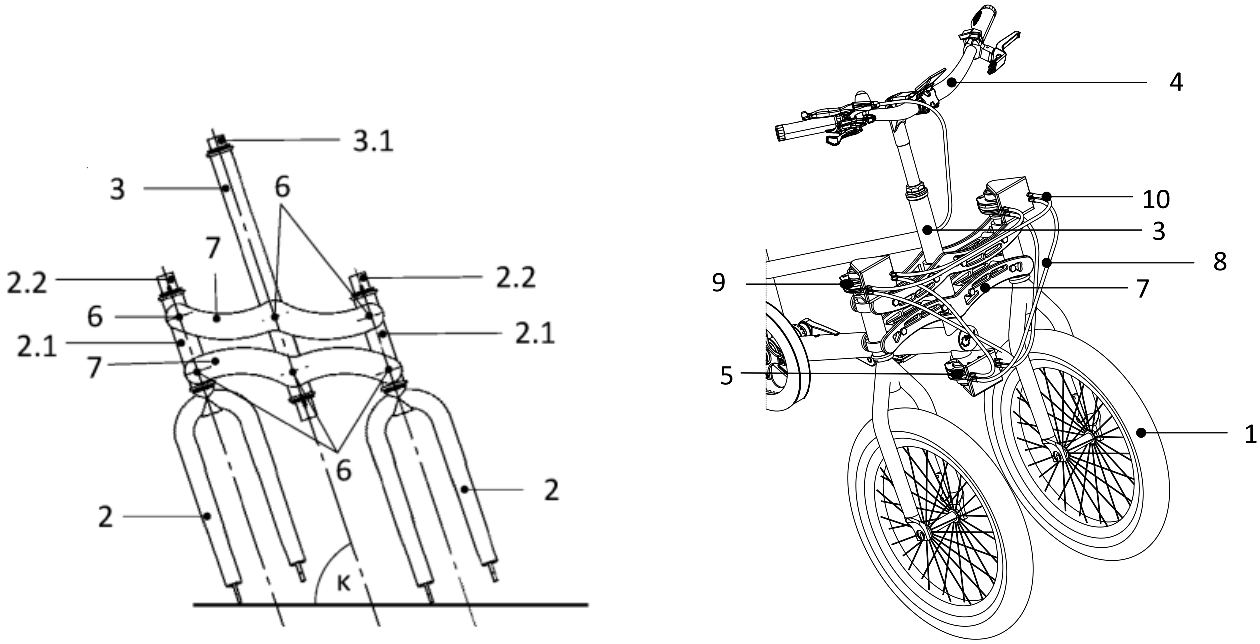

Fig. 1: Design of the double fork construction and the steering system; definition of the tilt angle κ [Gerschler and Kröger (2022)]

of a bicycle even without interventions of the driver in defined speed ranges can be proofed [Whipple (1899)]. The whipple-model is a mathematical model of a bicycle consisting of four rigid objects: front wheel, rear wheel, main frame with rider mass and front fork with handlebar. Klein and Sommerfeld (1910) attributed the self-stabilization of a bicycle to the existence of gyroscopic effects. Jones (2006), in his effort to design an unrideable bicycle, refuted this hypothesis by constructively canceling the gyroscopic forces on the front wheel and still being able to experimentally demonstrate that this bicycle also have a self-stabilizing behavior. In his opinion, the front axle geometry with the steering head angle and the fork offset shows a big influence to this characteristic: the ground contact point of the wheel and the intersection of the steer axis with the ground builds a trail. Kooijman et al. (2011) on the other hand proved that neither gyroscopic moments nor a trail are required for the self-stabilization of a single-lane vehicle. This theoretical proof was confirmed experimentally by using a test vehicle with eliminated gyroscopic effects and a small negative trail and an additional mass wide in the front, causing the front assembly mass is forward of the steering axis. This vehicle is still able to stabilize its own. The self-stabilization of a bicycle is therefore attributed to an interaction between the front axle geometry and its trail, the gyroscopic forces and the mass distribution of a bike.

2 Design of a tricycle with tilt technology

Considering these results, the new developed cargo bike is based on the self designed long-tail bike mentioned above, whose driving characteristics are confirmed as pleasant. Additional it is equipped with a multi-lane front axle construction that prevents the bike from falling over during autonomous driving maneuvers. The contact points of the three wheels, two at the front and the electrically driven rear wheel, form the stability triangle. Since the autonomous driving functions are only used for parking without external load at low velocity and on flat surfaces, dynamic influences of the bike´s stability against falling over are minimal. The bike is therefore considered stable as long as its center of gravity is located within the imaginary stability triangle, as discussed in Emam et al. (2017). The full maneuverability (steering, accelerating, braking) is given. Enabling the tilt function of the front-axle construction allows the bike to roll around the tilt angle κ, so that the driving characteristic compared to a single-lane bike is not influenced. In this mode, the bike is not prevented from falling over until the tilt function is locked in the upright position. The steerable and tiltable double fork design prevents negative influences on the interaction between steering and longitudinal wheel forces due to unequal braking forces or street bumps. This is an advantage to other cargo bikes, e.g. the tested *Model B* as discussed in Kreißig et al. (2021).

2.1 Construction details

The tilt mechanism of the front-axle construction is based on a tilt parallelogram shown in Fig. 1. To form this parallelogram, four crossbars (7; upper, lower; front and rear resp.) are rotatably mounted in the planes in front of and behind the primary head tube (3) transversely to the direction of driving using ball bearings (6). The ends of the upper and lower crossbars are rotatably connected by two secondary head tubes (2.1). Following this design, the installation angle of the two secondary head tubes is equal to the primary head tube angle. Regardless of the tilt angle κ they are always parallel. The secondary head tubes are used to support the forks (2), which are guiding the front wheels (1). Using commercially available forks with an offset, the resulting trail remains unchanged for the corresponding wheel size. A steering tube (3.1) rotatably mounted within the head tube transfers the steering torque from the handlebar (4) to a cable pulley (5). Four Bowden cables (8), two for the right side and two for the left side steering, transmit the steering torque to two outer cable pulleys (9), which are fixed to the fork shafts (2.2). In addition, two

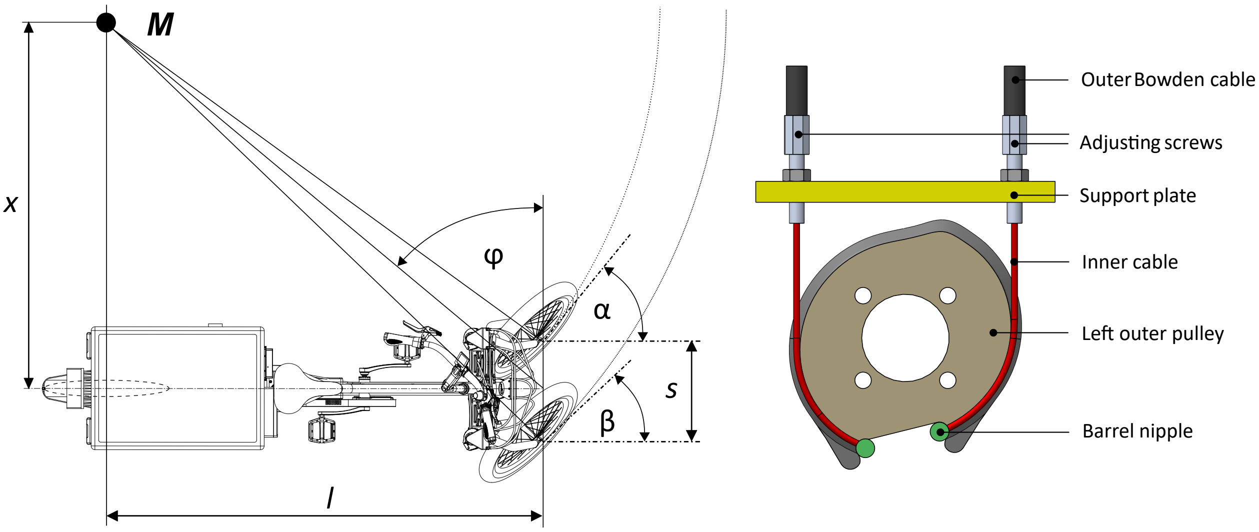

Fig. 2: left: steering geometry of a tricycle with the position of the instantaneous center of rotation M (for velocities near zero); definition of the steering angle φ, the wheel angles α and β, the track s and the wheelbase l
right: components of the steering system and geometric design of the left outer pulley

Bowden cables (10) connect the two outer pulleys for reasons of redundancy. This design allows to select a steering angle φ that is independent of the tilt angle κ and makes it possible to achieve high steering angles up to $\varphi = 70°$. This results in a small turning radius in comparsion to other cargo bikes.

2.2 Steering geometry

Cornering without lateral wheel slip can only be achieved approximately through a correct steering geometry for velocities near zero. According to Ackermann´s law [Pfeffer (2013)], the steering geometry comply with Ackermann´s condition if the extensions of all wheel axles intersect at one point, the instantaneous center of rotation M. In consequence, the wheel inside of a curve of a multi-lane steered tricycle has to have a larger steering angle compared to the wheel outside of a curve ($\alpha > \varphi > \beta$), see Fig. 2 left. To achieve this with a steering system using Bowden cables it is necessary to realize variable transmission ratios between the giving cable pulley and receiving cable pulleys. The variable transmission ratio depends on the steering angle φ given by the driver. In order to determine the correct geometric design of the receiving pulleys, the position of the center of rotation has to be determined first. Based on a rigid behavior of the entire construction, the center of rotation is located in the extension of the axle of the rear wheel and depends on the wheelbase l of the bike and the selected steering angle φ, calculated by Eq. (1):

$$x = \frac{l}{\tan\varphi}. \tag{1}$$

Constant wheel contact points, independent of the steering angle φ and tilt angle κ are assumed. Using the wheelbase l and the constant track s, the required following angles α and β of the front wheels are calculated by Eq. (2) and (3):

$$\alpha = \arctan\left(\frac{l}{x - \frac{s}{2}}\right) \text{ and} \tag{2}$$

$$\beta = \arctan\left(\frac{l}{x + \frac{s}{2}}\right). \tag{3}$$

The required transmission ratio, depending on the steering angle φ, is calculated from the ratio of the steering angle φ to the following angles α and β. Since a left-steered left front wheel has the same required following angle like a right-steered right front wheel, Eq. (4) and (5) are used to calculate the required transmission ratios for the left pulley for $\varphi > 0$ resp. $\varphi < 0$:

$$\frac{1}{i(\varphi, s, l)} = \frac{\partial\alpha}{\partial\varphi} = \frac{4l^2}{4l^2 - 4ls\cos(\varphi)\sin(\varphi) + s^2\sin^2\varphi} \quad \text{for } \varphi > 0 \text{ and} \tag{4}$$

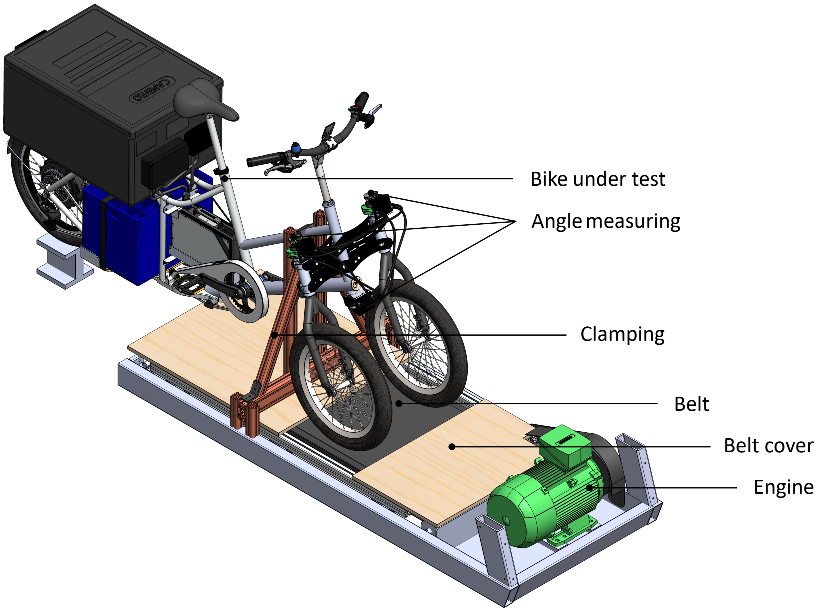

Fig. 3: Belt test rig for investigating the dynamic behavior of the front axle construction

$$\frac{1}{i(\varphi,s,l)} = \frac{\partial\alpha}{\partial\varphi} = \frac{4l^2}{4l^2 + 4ls\cos(\varphi)\sin(\varphi) + s^2\sin^2\varphi} \quad \text{for } \varphi < 0. \tag{5}$$

Using a circular giving cable pulley with the radius r_{in} and $i = r_{out}/r_{in}$, the path of the receiving pulleys r_{out} is calculated as a function of φ by using Eq. (6) and Eq. (7):

$$r_{out}(\varphi,s,l,r_{in}) = \frac{r_{in}\left(4l^2 - 4ls\cos(\varphi)\sin(\varphi) + s^2\sin^2\varphi\right)}{4l^2} \quad \text{for } \varphi > 0 \text{ and} \tag{6}$$

$$r_{out}(\varphi,s,l,r_{in}) = \frac{r_{in}\left(4l^2 + 4ls\cos(\varphi)\sin(\varphi) + s^2\sin^2\varphi\right)}{4l^2} \quad \text{for } \varphi < 0. \tag{7}$$

The resulting shape of the rope groove of the receiving pulleys for the dimensions of the CityPed with s = 400 mm and l = 1692 mm is shown in Fig. 2 right. Tests were able to proof that this pulley design leads to a slip-free cornering on tightly driven curves at low velocities, for example during parking maneuvers, whereas a cylindrical receiving pulley leads to cornering with slip.

2.3 Track adjustment

By modifying the pretension of the Bowden cables using the adjusting screws, see Fig. 2 right, the torsional stiffness c of the steering system can be adjusted. In addition, it is also possible to set up a defined toe-in or toe-out angle by rotating the adjusting screws in different directions. The required torsional stiffness of the steering system of cargo bikes is defined in DIN 79010. Fixing the front wheels and applying a torque of M = 50 Nm on the handlebar, the handlebar is only allowed to rotate a maximum by φ = 1° per M = 7 Nm ($\frac{\partial\varphi}{\partial M} \leq \frac{1\,^\circ}{7\,\text{Nm}}$ for $0 \leq M \leq 50$ Nm). To pass the test, high pretensions of the Bowden cables are required. High pretensions lead to a significant increase in steering torque due to the internal friction of the Bowden cables. Practical driving tests have shown that a high steering torque has a negative impact on the driving behavior of the bike and disables its self-stabilization. On the other hand, a low torsional stiffness increases the tendency of steering wobble, which is a speed-dependent oscillation of the front wheel forks $\alpha(t)$ and $\beta(t)$. A steering wobble can be responsible for loosing the control of the bike and, in the worst case, causes the driver to fall. Steering wobble is also known to occur on conventional single-lane bikes and can be prevented by holding the handlebar.

The aim is to find the adjustment of the steering system that reliably prevents steering wobble and at the same time keeps the steering torque as low as possible. Therefore, the behavior of the multi-lane front axle construction is investigated on a belt test rig, see Fig. 3. The belt test rig allows the front axle construction to be accelerated up to a velocity of $v = 50\ \frac{\text{km}}{\text{h}}$. The clamping allows the bike to be tilted in a small range, also it is not vertically fixed. After manual deflecting the handlebar about φ = 4°...7° at different velocities and simultaneously measuring the angles (φ, α, β) of the handlebar and both front wheels it is possible to evaluate the behavior of the front wheels, whether the oscillations increase or decrease.

By focusing on the toe-in or toe-out angle and the torque stiffness of the steering system, all other parameters that have an influence on the oscillation behavior, such as the tire inflation pressure, are kept constant during the experiments. Fig. 4 shows the results for a high and a low pretension of the Bowden cables with a neutral track setting. High pretension of the Bowden cables means a

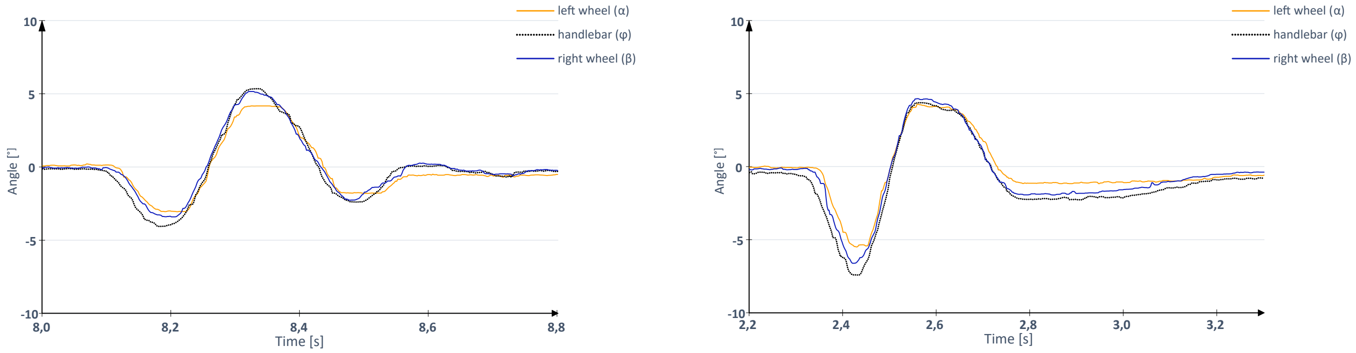

Fig. 4: Oscillation behavior of the front axle with neutral track setting at $v = 25\ \frac{\mathrm{km}}{\mathrm{h}}$;
left: low pretension of the Bowden cables; right: high pretension of the Bowden cables

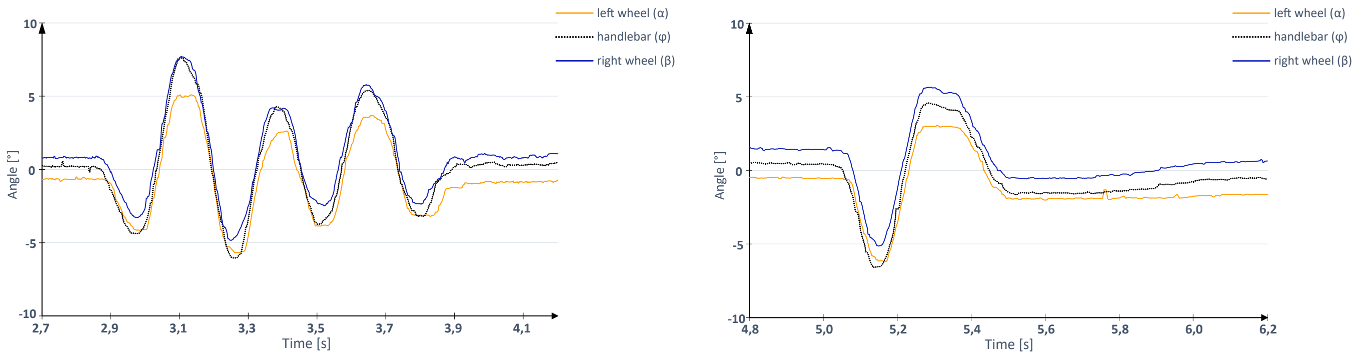

Fig. 5: Oscillation behavior of the front axle with a set toe-in angle of $-\alpha = \beta = 0.55°$ at $v = 25\ \frac{\mathrm{km}}{\mathrm{h}}$;
left: low pretension of the Bowden cables; right: high pretension of the Bowden cables

torsional stiffness of the steering system of $\frac{\partial \varphi}{\partial M} = \frac{1\,°}{7{,}1\ \mathrm{Nm}}$, which leads to a steering torque of $M = 12$ Nm, whereas low pretensioned Bowden cables lead to a steering torque of $M = 6$ Nm. With neutral track adjustment of the front wheels, without a toe-in or toe-out angle, a rapidly decreasing oscillation behavior for both, high pretensioned and low pretensioned Bowden cables, is observed. The adjustment of a toe-in angle of only $-\alpha = \beta = 0{,}55°$ combined with low pretensioned Bowden cables, leads to a slower decrease in the oscillations, see Fig. 5 left. This increases the probability of a steering wobble. This effect can not be observed with the same toe-in angle but highly pretensioned Bowden cables, see Fig. 5 right, even with a larger initial deflection angle of nearly $\varphi = 7°$. This is probably due to the internal friction of the Bowden cables, which act like a damper and drain energy from the system. The movement of the handlebar also shows differences between the high pretensioned and the low pretensioned Bowden cables. Because of the lower torsional stiffness with low pretensioned Bowden cables and the rotational inertia of the handlebar, the rotation angle of the handlebar $|\varphi|$ in relation to the front wheel angles $|\alpha|$ and $|\beta|$ is higher than with high pretensioned Bowden cables. In summary there are two ways to achieve safe driving behavior without the risk of increasing oscillations in the front wheels. Either the track is adjusted precisely to a neutral track setting or the pretension of the Bowden cables is set to a high level. Since, as described above, the driving behavior of the bike deteriorates with high pretensioned Bowden cables due to the increase in steering torque, the preferred way to operate the bike is to adjust medium pretensions of the Bowden cables but precisely set a neutral track, checking the track regularly and adjust it if necessary.

3 Conclusion and outlook

In summary, a multi-lane cargo bicycle was designed with similarly good driving characteristics compared to a single-lane long-tail bicycle. This was achieved by only slightly influencing the main geometric details, such as the head tube angle and the trail as the gyroscopic moments as well. Furthermore, the front axle design was examined with regard to its oscillation behavior. Experiments have shown that even a small toe-in angle has a negative influence on the oscillation behavior of the front axle construction. This can be prevented by adjusting a high pretension of the Bowden cables used for steering. In this case the driving behavior such as the self-stabilization of the bike deteriorates. The best way to reach a safe and usual driving behavior is to precisely set a neutral track, which allows the adjustment of a medium pretension of the Bowden cables. On this way the steering torque and the probability of steering wobble decreases at the same time. Future investigations will include more parameters, e.g. the tire inflation pressure or different types of profiles of the front tires, which were kept constant in this work. Also the influence of an toe-out angle will be investigated. Based on initial experiments, it is not expected that a tow-out angle will improve the oscillation behavior compared to a neutral track setting. In order to achieve more reproducible results, a mechanical construction for the initial deflection of the handlebar with constant angle φ and constant time to reach this angle will be included in the test rig.

4 Acknowledgment

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