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Design of a spring-loaded brake for automated cargo bikes

Diseño de un freno de muelle para bicicletas de carga automatizadas

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Abstract: Automated cargo bikes can be a viable means to improve last mile efficiency by providing automated driving functions in situation, where riding the bike would be unproductive. During the automated ride without a rider, safe operation of the cargo bike in urban traffic is mandatory. For this purpose, an analysis of all possibilities during the automated ride is carried out. The outcome of these analysis results the need for an emergency stop system that can decelerate the cargo bike to a safe standstill. Since, all the alternatives found, have limitations that preclude their use as an emergency braking system for this particular type of vehicle, a spring-loaded brake has been developed based on a commercial bicycle brake. The system is designed to meet the legal requirements of comparable vehicles. And to fulfil the functional safety guidelines, this emergency brake system is also provided with status monitoring. This paper describes the development, commissioning, operation, integration, testing, and evaluation of a spring-loaded brake into the safety system of an automated cargo bike. It is based on the previous development in the completed research project *AuRa* and describes the forthcoming implementation into the small-scale produced cargo bike *ONO* as part of the *Eaasy System* project.

Keyswords: Automation; Cargo bike; Fail-safe-design; Urban logistics
Palabras Claves: *Automación; Bicicleta de carg; Diseño de seguridad; Logística urbana*

1. Motivation

The rising number of motor vehicles in cities leads to increase in air pollution, noise, and traffic for the residents. As a result, more traffic-calmed areas are created. Therefore, a traffic turnaround must take place and new solutions have to be found. An alternative for the use of cars and delivery vans can be electrically powered micro-vehicles.

For the private transport, especially around the last mile, a bike sharing system with automated driving cargo bikes has been developed in the completed research project *AuRa* [1]. It offers the possibility to provide a cargo bike to any user at any place and at any time. This bike-sharing system uses three-wheeled bikes that can be operated without a rider. Another factor in the increase in traffic is the rising number of parcel deliveries due the growing online trade. This leads to a great challenge for parcel and courier services, especially in cities with a high density of stops [2]. As an alternative for delivery vans, cargo bikes like the *ONO* cargo bike (figure 4) are a potential alternative on the last mile and are also increasingly used.

In order to support the delivery person, the aim of the research project *EAASY System* is to automate the *ONO* cargo bike and develop a *Come-With-Me* function (*CWM*). The use case is shown in figure 1.

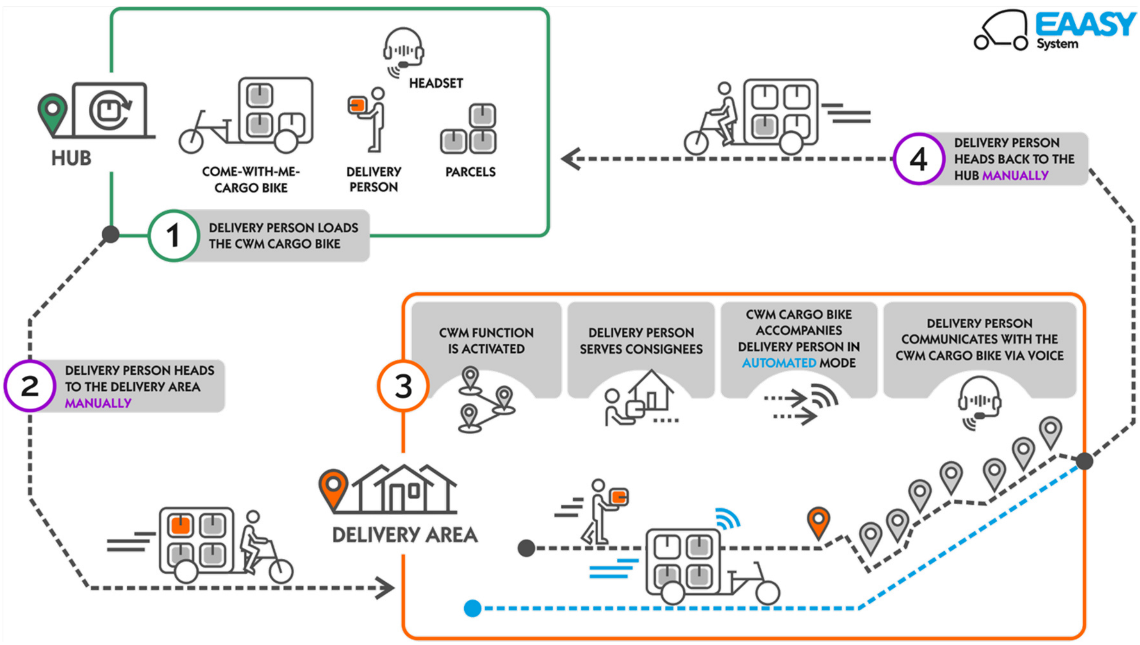

Figure 1. The use case of the *ONO* cargo bike of the *Eaasy System* Project with Come-With-Me function

In the delivery area the deliverer activates the come-with-me function. While consignees are served, the *CWM* cargo bike accompanies automatedly. Accordingly, there is no need for the delivery person to get on and off the cargo bike between the stops. While using the *CWM* function, the deliverer communicates with the system by voice. Outside the area, the *ONO* cargo bike is used manually like a pedelec.

While in automated mode (step 3), a safe standstill of the bike is always achieved by the safety function of the control unit. If a safety-critical device no longer functions within its parameters, the system intervenes and brings the cargo bike to a controlled stop using the automated service brake. A failure of this service brake or the power supply is problematic. In these cases, other vulnerable road users (*VRU*) like pedestrians can be considerably harmed due to the intrinsic mass of the rolling cargo bike.

To overcome this a risk analysis has been conducted to demonstrate the need for an additional braking system that is independent of the traction battery. Despite the limited maximum speed of the *CWM* function of 6 km/h, the potential hazard of the cargo bike cannot be neglected due to its comparatively high gross weight.

2. Safety management of the automated cargo bike

For the automated *ONO* cargo bike described in the scenario above, the state machine shown in figure 2 has been designed. It represents the modes, which are reached by defined transitions. The *software emergency stop* state is intended to identify all electrically and logically detectable errors and bring the cargo bike to a safe standstill. Possible errors in automated operation are failures of sensors, actuators, or control units, which can be diagnosed via the corresponding, periodic heartbeat on the CAN bus.

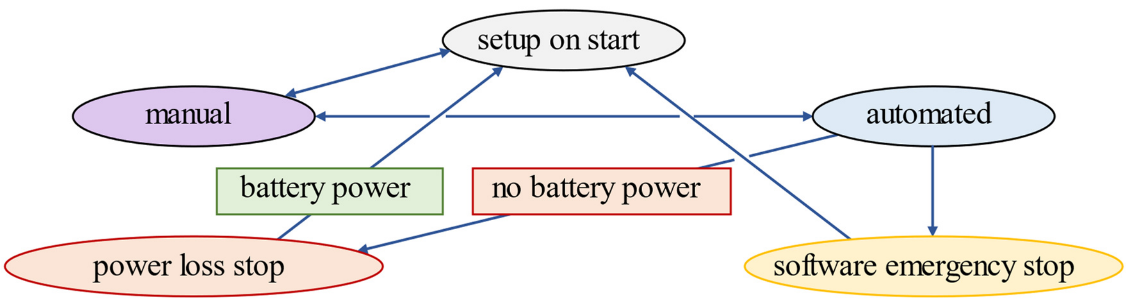

Figure 2. State machine of the automated *ONO* cargo bike

The possibility of a power loss situation while riding should not be neglected. Since there is no redundant safety power supply, the vehicle cannot stop in automated mode using the automated service brake such as the *software emergency stop*. Because the service brake and its control unit are based on the regular traction battery. To prevent serious consequences while power loss, a safe automated standstill must be implemented. The manual driving mode is excluded, as in this mode the deliverer alone is responsible for the longitudinal and lateral guidance. Furthermore, an inadvertent automated triggering of the service brake could seriously injure the rider and must be prevented. This could be done, for example, by an electrical or mechanical locking of this system in manual mode.

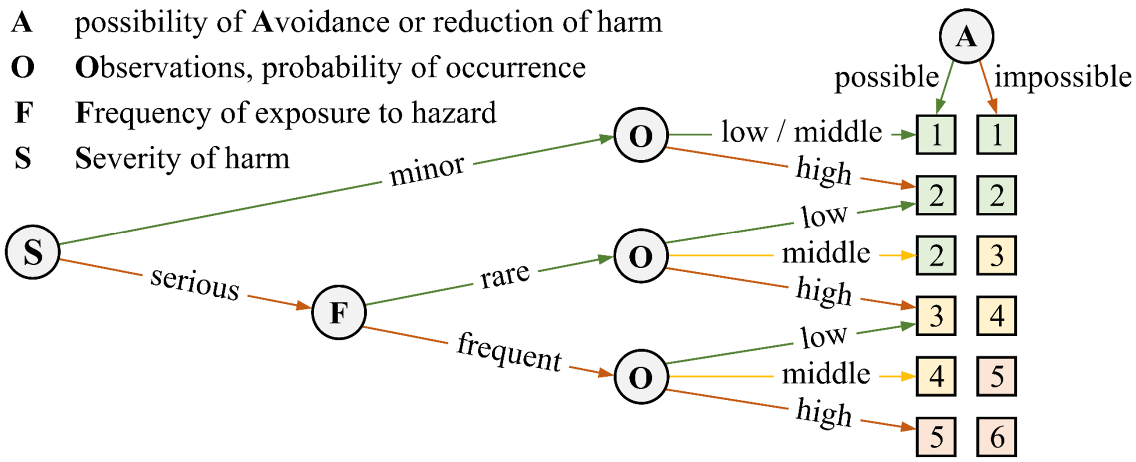

Figure 3. Matrix for determination of risk index in ISO/TR 14121-2 [3]

A risk analysis in accordance with ISO/TR 14121-2 has been carried out for the autonomous operating mode to identify measures in the case of fault [3]. A serious fault occurs due to the failure of the vehicle's braking function. The severity of harm of a service brake failure is classified as *serious* while the frequency due to loss of power is considered as *frequent*. And the probability of occurrence in such cases is rated as *medium*. With these findings, a risk index of *4* is determined (figure 3 and table 1).

This overall classification of risk analysis results in the need for additional protection in form of an energy storage brake. With the presence of an emergency brake as a preventative measure, the frequency of an *exposure to hazard* is reduced to *rare*. Thus, the *risk index* is reduced to *2*. According to ISO 12100, this risk is classified as acceptable in the risk assessment and requires no further reduction measures [4].

Table 1. Excerpt from risk analysis

possible faults	possible consequences	possible causes	stopping action	severity of harm
brake function failure	collision with passers-by or objects	overheating battery, excessive discharge current, overvoltage / undervoltage, vibrations	power loss stop	serious
exposure to hazard	**probability of occurrence**	**avoidance**	**risk index**	**action**
frequent	medium	possible	4	release of an energy storage brake

3. Functional Development

3.1 State of technology

Emergency brake systems work on the fail-safe principle. This means they retain their functionality even if the actuating device or medium fails. For this reason, they can be used not only as an emergency brake but also as a parking brake. The energy required for braking must be stored for those systems. Various forms of energy can be used for this purpose, for example, electrical and potential energy. The latter can be further subdivided into pressure and spring accumulators. The most widely used form of energy in commercial vehicle brakes is tension energy. The spring-loaded brake based on this stored energy consist of a mechanically pre-loaded spring that presses the brake pads against the brake disc or drum. To release the brake, a fluid such as air or mineral oil must be passed into the brake system. The pressure required for this can be held in pneumatic or hydraulic accumulators to implement a combination together with the service brake [5,6].

Spring-loaded brakes are equipped with a release function to allow the vehicle to be moved in the event of a failure. For example, pneumatic truck brakes are released by supplying their brake system with external compressed air. In the event of a leak in the pneumatic system the brake is released manually with the help of integrated lead screws. Hydraulic brake systems used in construction machinery, are equipped with hand pumps to generate the required opening pressure manually [5,7].

Electric brakes that use electromagnets to hold the pretensioned brake system open directly are not implemented in practice. This is because such combined system is only used in commercial vehicles where high holding forces are required. And these are equipped with pneumatic or hydraulic systems either way. There are prototypes of direct-acting electric brakes using actuators to provide the force. These could also be used not only as parking brake but also as service brakes. However, such systems are currently used for hybrid- and fully-electric vehicles and not for bikes. In addition, they have the disadvantage that they also require auxiliary energy to be activated, so that they are only suitable as an independent emergency brake to a limited extent [8,9]. Nevertheless, this approach is well suited for the automated service brake of the *ONO* cargo bike, as this requires a comparatively high braking force due to its high gross weight.

Innovative approaches such as wheel hub brakes have been considered, but due to non-existent market availability or limited manufacturing possibilities, these options have not been considered [10]. New technologies such as cylindrical magneto-rheological fluid brakes have also been investigated. But because of the ongoing research and development and the associated unavailability, these cannot be used either [11,12].

3.2 Selection and positioning of the braking system

Due to the existing hydraulic disc brake systems on both the front and rear axles of the *ONO* cargo bike, possibilities to implement an additional brake are limited. Moreover, the wheel hub motors prevent the use of roller or drum brake on the rear axle. On the front wheel a braking system for manual riding as well as the automated electric service braking system for the *CWM* function is already implemented. A comprehensive market research has shown, that the purchasable brakes for bicycles do not work according to the fail-safe principle. Spring-loaded brakes from the industrial sector would cause an internal development and new design. Furthermore, it would require an additional pneumatic system and compressor, which would take up additional space and add weight to the cargo bike. For this reason, it has been decided to equip the rear wheels with another brake circuit and to develop the corresponding system itself. The advantage of this approach is that only a second brake calliper needs to be fitted. Since these are available for both left- and right-hand mounting, it can be installed symmetrically (figure 5).

Figure 4. *ONO* cargo bike from *ONOMOTION*

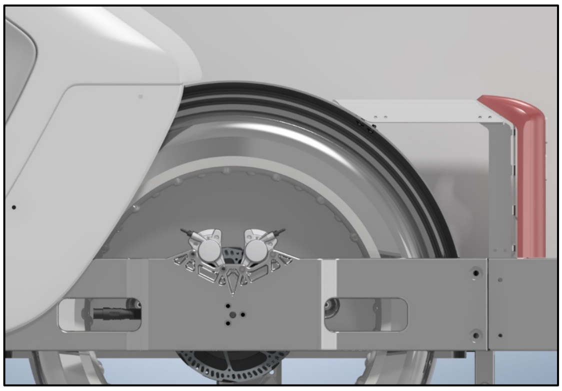

Figure 5. Planned assembly of the second calliper

The main aspect of the technical implementation is not only a small installation space and the lowest possible power consumption, but also a simple brake release function. In the event of a failure the automated cargo bike should be moveable again as quickly as possible so that it can be pushed out of the hazard area. Based on the research, there are three possible functional principles for actuating the disc brake system – electrically operated systems as well as brakes with a pressure or spring accumulator. Irrespective of this, in all variants the pressure transducer, which is normally operated with a hand lever, must be actuated by this auxiliary energy by using a mechanism. To obtain the required brake pressure of 30 bar, a force of approx. 600 N and a stroke of 8 mm is necessary due to the piston size of the master cylinder and the hydraulic transmission. The parameters for the design of the selected hydraulic brake system are based on the requirement of the minimum brake deceleration from DIN 79010, which are listed in table 2. This norm specifies the requirements and test methods for single and multi-track cycles [13].

Table 2. Excerpt from DIN 79010 values for braking [13]

bike type	**condition**	**effective range**	**minimum braking deceleration a_{min}**
cargo bike	dry	one axle	3,4 m/s^2
		each additional axle	2,2 m/s^2
	wet	one axle	2,2 m/s^2
		each additional axle	1,4 m/s^2

Brake tests with the aforementioned *AuRa* test bike, in which both the deceleration and wheel speeds as well as the hydraulic pressure have been measured, serve as basis for the design of the new brake system. With the help of the determined results, the parameters for the dimensioning of the system could be specified [14]. The planned future implementation into the *ONO* cargo bike is shown in figure 5 and 7.

The emergency braking system is designed for a failure of the electrical power supply. Therefore, no electrical systems are used, because these would require another redundant battery and monitoring and could fail analogously. A pressure accumulator system, whether hydraulic or pneumatic, would be suitable, as those in the range between 150 and 250 ml are commercially available. However, a compressor or pump would have to be integrated. The advantage of such systems is the use of simple normally open directional valves. They are closed in the energised state and block the inflow of a pressure accumulator. In this case, the status can be monitored using pressure sensors, so that the automated operation is only enabled when the minimum pressure in the accumulator is achieved. If the power supply fails, the valve opens and activates the brake.

Due to simplicity and the availability of its commercial parts, a spring accumulator is implemented as an emergency braking system. Unlike conventional spring-loaded brakes, the spring force does not have to be compensated by another force to be able to drive. Instead, the spring is installed outside the brake and is held in position by lever mechanisms. This makes it possible to maintain the high spring tension force of 960 N with small solenoids of only 20 N strength. Accordingly, the power consumption of the system can be kept very low in the operational state (figure 10).

4. Design and implementation

4.1 Structure of the spring-loaded brake

The spring-loaded brake consists of five main assemblies: the case, the kinematics (figure 9) and the two mechanism (figure 10) as well as the hydraulic bicycle brake. Sub-assemblies are, for example, the crossbar with the solenoid holders and the limit switch for the case (figure 6) as well as the solenoids for the mechanism (figure 11). The two mechanisms are identical in design except for the conical springs and connectors of different lengths (figure 10). The mechanisms are arranged point-symmetrically to the centre of the tensioned load spring. This results from the fact that the releasing mechanism pulls the fastener against the lock, while the tensioner presses it against the other one.

The basic principle of the kinematics is based on a lead screw with a high pitch per revolution. This represents a compromise between the torque required to tension the spring on the one hand and the risk of self-locking on the other. The lead screw nut moves a sliding element, which is supported on the case due to its square shape and therefore does not follow the lead screw rotation. The moving parts are guided by sliding surfaces made of brass or sleeve bearings made of low-friction plastic (figure 9).

The two sliding elements, which enclose the load spring on both sides, are held in position with the help of holders. The special feature of the lever mechanism is the redirection of the holding force. The clamping force acting axially on the lead screw is distributed in such a way that it is largely supported by the base (figure 10). This makes it possible to realise low holding forces despite the strong tension spring and to use small linear solenoids. Due to the increased loads, these components are made of steel. During the design, care is taken to use similar blanks and materials as far as possible.

The master cylinder is connected via an internally toothed sleeve, which is based on the original bracket for the handlebar. The connection between the brake piston and the slider is made via a coupling. This not only transmits the braking force, but also guides the return spring. To compensate manufacturing tolerances, it is divided into two parts connected with a grub screw. This makes it possible to reduce the idle travel path between the release and the actuation to a minimum with the help of washers (figure 11).

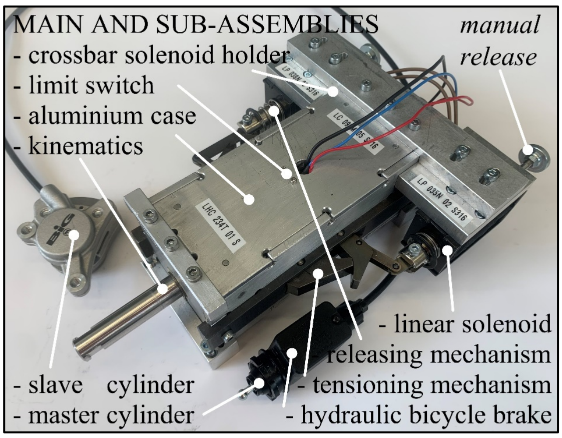

Figure 6. Structure of the spring-loaded brake

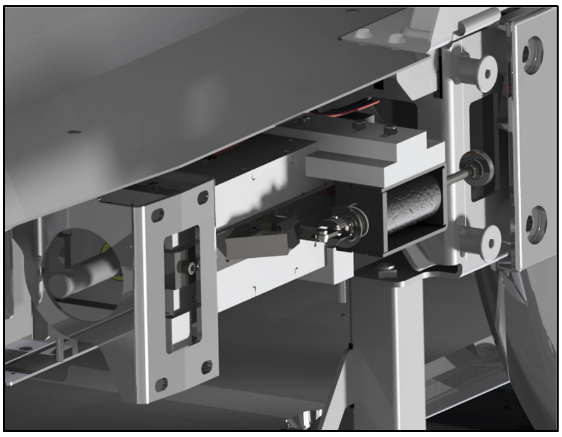

Figure 7. Planned integration into the bicycle frame

4.2 Implementation

Since the *ONO* cargo bike used in *Eaasy System* has not yet been available, the first tests have been carried out with a test bike of the *AuRa* project. This three-wheeled cargo bike also has two separate brakes on the front axle and a hydraulic system on the rear axle. For this reason, adjustments have been made to this bike in order to examine the functional principle and the basic suitability of the spring-loaded emergency brake system.

The planned installation position of the system into the *ONO* cargo bike is shown in figure 7. The housing is designed in such a way that it can be integrated into the existing vehicle frame. The advantage of this is that the frame has relatively large cross-sections due to its lightweight construction. For this reason, the retrofitting of this system is possible. Within the scope of accessibility, inspection flaps must be provided.

Compared to the *AuRa* test vehicle, the *ONO* cargo bike has a total weight that is greater by a factor of two. However, there is the option of equipping both rear wheels with a spring-loaded brake each. This would have the advantage of additional redundancy. The length and constants of the springs used can be varied to match different specifications. For this reason, it is first useful and expedient to validate the basic functioning on the test bike. Further improvements can then be made in the course of the final implementation. For example, it must be evaluated whether a throttling is necessary to limit the pressure increase when the system is released. Additionally, the lead screw, which is currently rotated manually for test purposes, must be equipped with an electric motor.

5. Operating principle and states

In the following section, the functionality of the brake system is explained based on the individual states. In addition, the various components are marked in the illustrations. Figure 7 lists the various springs, while figure 8 to 10 show the components of the kinematics, both holding mechanisms and the linear solenoids respectively. The monitoring of the tensioned state is done with a limit switch. This closes the circuit for activating the automated driving mode. On the one hand, this excludes automated riding with an unready, not tensioned emergency brake on the hardware side. And on the other hand, manual driving with an operational emergency brake system is prevented. This satisfies the requirements of functional safety.

5.1 Zero position state

In this state, the load spring is released to its free length and the movable slider of the tensioning mechanism is force-free. The return spring presses with a spring pre-tension against the locked slider of the releasing mechanism so that the holder is held in position. Mechanical stops in the base plate prevent the holders from assuming an impermissible angular position (figure 9). Both linear solenoids are currentless so that the springs on the solenoid armatures push them out of the coil and the locks release the holders. As shown in figure 8, the armature of the tensioning mechanism is held in position in the retracted state due to the holder. For safe manual operation of the vehicle without any power consumption, brake release in this tension less state is not possible.

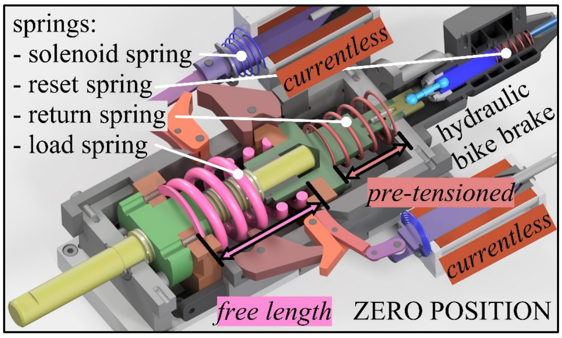

Figure 8. Setup of the *zero position state*

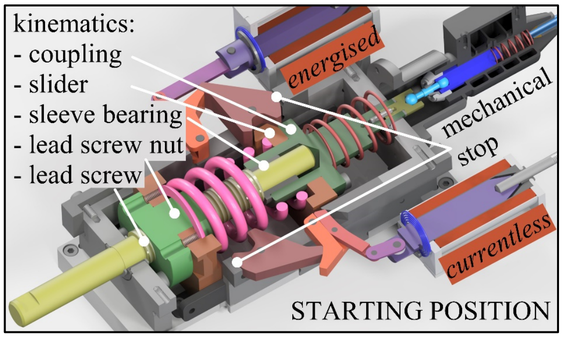

Figure 9. Setup of the *starting position state*

5.2 Starting position state

To tension the system, the solenoid of the releasing mechanism is first energised. The armature is pulled in and compresses the solenoid spring. The connector thereby pulls the fastener and the lock against the holder. As this is pressed against the mechanical stop on the base plate by the return spring, only the bearing friction and the spring force of the solenoid spring must overcome for the adjustment process. This must be considered when dimensioning. Especially since the tensile force of the linear solenoids is non-linear. When the lead screw is turned, the associated lead screw nut is pressed towards the brake connection. Due to the chamfer, the slider straightens up the holder and thus unblocks the lock. The solenoid spring of the tensioning mechanism now pushes the lock towards the holder and prevent the movement. The system is therefore loaded. It is held on one side by the magnetic force and on the other side by the spring force.

5.3 Tense position state

In the tense position, both sliders are locked. The holding forces of the load spring are supported by the lever mechanisms on the base and the solenoids. The redirection and distribution of forces ensures that any impacts do not lead to unintentional release of these mechanisms. The lever arm design and ratio has been evaluated and optimised both mathematically and experimentally. To keep the installation space small, care was taken to ensure that the load spring is compressed to almost block length in this state. Meanwhile, the return spring is still in the pretension state. In order to switch to the automated mode, these positions of the sliders must be detected using the limit switches.

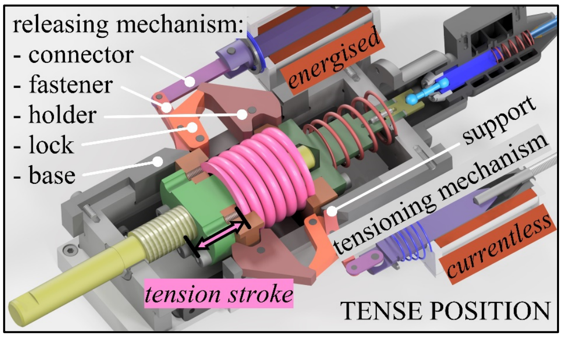

Figure 10. Setup of the *tense position state*

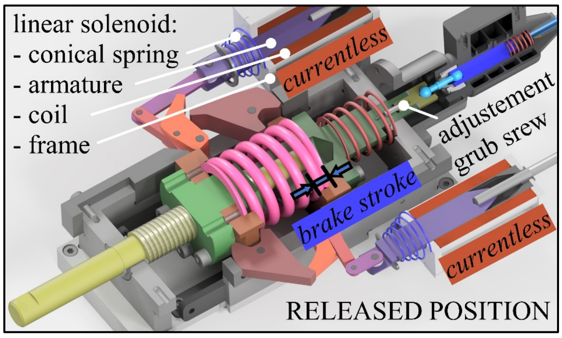

Figure 11. Setup of the *released position state*

5.4 Released position state

Due to the tensioned load spring, the emergency brake is triggered when the current at the holding solenoid is interrupted. The spring expansion and force are transferred to the master cylinder via the coupling and actuates the bicycle brake. The release is triggered by a conical spring on the holding solenoid, which has a force of 7.4 N at block length. This is sufficient to transfer the holding lever from the stable to the unstable state. Thus, due to the stroke, the spring force gradually decreases, but is overcompensated by the resulting force vector of the clamping force. As soon as the lock is released, the holder is pushed away and unblocks the movement of the slider and the coupling to the brake.
Alternatively, the brake can be transferred directly from the zero position to this state. For this purpose, the release mechanism is currentless and the load spring is tensioned. In this case, the brake acts directly as a parking brake. The procedure for locking the lead-screw-side slider is analogous to the locking of the coupling-side slider at starting position.

To release the brake and return it to its tension less position, the solenoid of the tensioning mechanism must be energised. As a result, both the residual tension force of the load spring and return spring ensure that the holding mechanism is released (equivalent to the *tense position state*). The residual tension force of the return spring ensures that the release mechanism is locked, as already explained in *starting position state*. In case of a power failure, the release can also be done manually by pulling the guide rod of the solenoid with the help of a knurled nut (figure 6).

6. Evaluation of the emergency braking system

Experiments are carried out to test the spring-loaded braking system. First, the kinematics and the mechanisms, including the solenoids, are checked. After the basic functions are tested and implemented, the pressure generated at the master cylinder is measured, evaluated, and adjusted by varying the different springs. Afterwards, the braking system is evaluated with help of the aforementioned *AuRa* test bike.

For this purpose, the cargo bike is accelerated to a predefined speed via remote control and then decelerated by the spring-loaded brake. To execute the test, the power supply to the solenoids is manually interrupted with the use of a radio relay to simulate the failure of the electrical system. During the emergency braking, relevant sensor values are recorded with a data logger integrated in the vehicle control unit.

A pressure sensor is installed in the hydraulic circuit of the spring-loaded brake to measure the brake pressure generated. Deceleration is determined both with inertial measurement units as well as with the help of the wheel speeds. The sensor values for a braking process from 15 km/h are shown in figure 12. The measured deceleration is above 2,2 m/s^2 at all braking tests and thus fulfils the required specifications (table 2). The oscillation of the deceleration results from the locking of the rear wheel during the braking, which causes a bouncing of the bicycle and thus an unsteady traction, as well from the inertia of the vehicle itself. However, this does not affect the requirements of the test specification for cargo bikes, that no increased vibrations occur during braking. Furthermore, the emergency brake does not apply when driving over uneven surfaces. And it decelerates the vehicle satisfactorily during all power interruptions carried out. The results thus demonstrate the suitability of this system for the automated cargo bike.

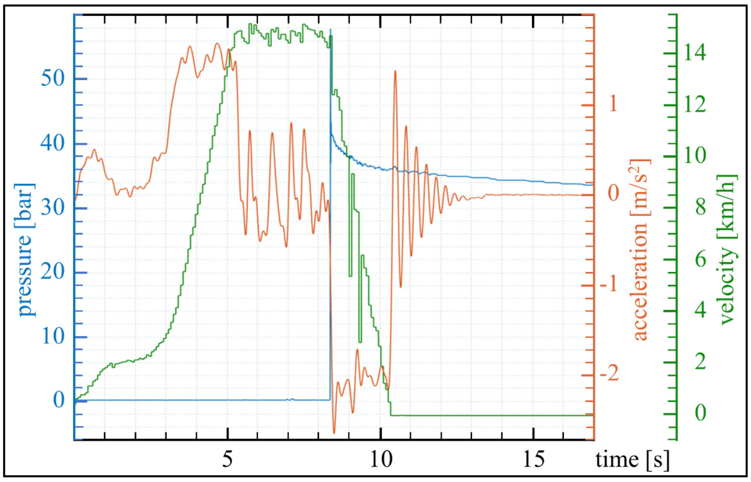

Figure 12. Measurement data of a present driving test

Figure 13. Mounting on test bike

7. Conclusions

The movement of automated cargo bikes in urban areas requires safety systems to bring the vehicles to a safe standstill in the event of system failure to prevent accidents with pedestrians and other road users. For this purpose, a risk analysis has been carried out in which a potential hazard has been assessed and a risk minimisation measure has been identified. This hazard is to be averted by implementing an energy storage brake on the cargo bike. During function development, the requirements of installation space, power consumption and mechanical design are considered and implemented. As a result, a spring-loaded brake has been selected that has a very low power requirement in operational state and, in the event of a power supply failure, brings the vehicle to a safe standstill with the help of an additional brake calliper on the rear brake discs.

The secondary function as a power-less parking brake is also achieved. The ability to unlock the braking system without any auxiliary power and with less efforts exceeds the specifications. Furthermore, simple, and reliable monitoring of the system is possible with less expensive limit switches. To verify the functionality, the developed emergency braking system has been evaluated in driving tests with a test bike and has been adapted to the legal requirements of comparable vehicles. Accordingly, the evaluated emergency brake system can be adapted to the requirements of the *ONO* cargo bike in order to meet the safety requirements of the *Come-With-Me* function. Finally, the spring-loaded brake can be scaled and adapted to other different types of micromobiles.

8. Acknowledgement

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