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DEVELOPMENT OF AN ELECTRIC TRICYCLE FOR SERVICE COMPANIES AND LAST-MILE PARCEL DELIVERY

Summary. In many city centres and some large urban areas, access restrictions are imposed on trucks and vans. On the other hand, the number of e-commerce packages to be delivered daily is increasing rapidly, and service companies of all kinds also have to serve their customers in these areas. The use of cargo bikes is seen as a possible solution. The direct reason for this research is the observation that there is still room for a new type of cargo bike that meets the needs of the outlined target groups. This article summarises how the quality function deployment (QFD) method has been used for the systematic development of an electric cargo tricycle that meets these needs. The developed tricycle distinguishes itself from existing cargo bikes mainly by its loading capacity, stability and manoeuvrability. The prototype tests performed by professional couriers were so positive that a pilot series was built.

1. INTRODUCTION

The accessibility of urbanised areas for conventional trucks and even vans is often restricted. Window times, low emission zones, noise limits, ... are some known restrictions. In a number of historical centres or pedestrian zones, the access of trucks, vans and also passenger cars is even radically prohibited. Such bans pose a problem not only for companies that have to deliver e-commerce parcels but also for service companies that have to deliver spare parts and tools on site. The regulator points, among other things, to bicycles, are seen as solutions to the posed problem [1]. Classic pedal-powered bicycles are suitable for the delivery of light parcels of limited size. The use of electric bicycles (e-bikes) can increase the comfort of the cyclist and the area within which the cyclist can make deliveries. The use of bicycles with a cargo space or a trailer is proposed as a solution for delivering relatively large parcels and for service companies, among others, by the European Commission [2] and in recent research results [3-5]. Research and pilot projects conclude that electric cargo bikes for last-mile delivery improve efficiency, are less polluting, relieve congestion and reduce costs compared to vans [6-8]. The COVID-19 pandemic contributed to an expansion in e-commerce and cargo bike use [9-11]. On the other hand, professional cargo bike couriers point out relevant shortcomings of the bikes they use. Companies that lease and/or maintain cargo bikes for professional users also notice limitations in loading volume, stability, robustness, ..., especially when compared to classic delivery vans. In this research an electric cargo bike is developed. On the one hand, it fits within the mentioned access

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restrictions in urbanised areas. On the other hand, it addresses the primary complaints of professionals who cannot use their classic vans in these areas.

2. LITERATURE RESEARCH

2.1. width of the cargo bike

The majority of current cargo bikes are between 0.8 and 0.9 m [12]. Heavy cargo bikes vary from 0.8-1.2 m. European Regulation limits the maximum width of a bicycle to 1 m [13]. Individual countries can exclude those limitations from their own. For example, in Belgium and the Netherlands, single-track vehicles have a maximum width of 0.75 m, and multitrack vehicles have a maximum width of 2.5 m and 1.5 m, respectively [14, 15]. The maximum width of 2.5 m is extremely wide and is stated in regards to multi-person go-carts or a so-called beer bike. Trailers have a maximum allowed width of 1 m in general and 1.2 m for permitted pilot projects [16]. There is no legislation in place regarding the width of bicycle lanes. There are recommendations stating a minimum width of 1.5 m, taking a 1-m-wide bicycle into account with 0.25 m clearance on both sides [17]. This is currently not the case for all bicycle lanes. Currently, 42% of cyclists are not satisfied with the width of Belgian bicycle lanes, and 31% of current cycle lanes are narrower than the prescribed 1.5 m [18]. Denmark recommends a width of 2.2 m [19]. Greibe et al. recommend a minimum width of 1.95 m for a two-lane cycle track [20]. Cargo bikes with a maximum width of 1 m are allowed to use bicycle lanes [21]. A cargo bike wider than 1 m cannot benefit from the advantages of using bicycle lanes. Belgium, Denmark and the Netherlands are described here since they are part of the top five in terms of Europe's main cargo bikes market [22] and are the top three in private cycling use [23]. Due to financial and political incentives, Belgium emerged as a key cargo bike market in 2021 [24].

2.2. Cargo bike capacity

Fig. 1 shows different types of cargo bikes with their respective payload information and widths [25]. Fig. 2 shows the representation of the types. Overall, 51.2% of the cargo bike sales are three-wheeled cargo bikes, and 48.8% are two-wheeled [26].

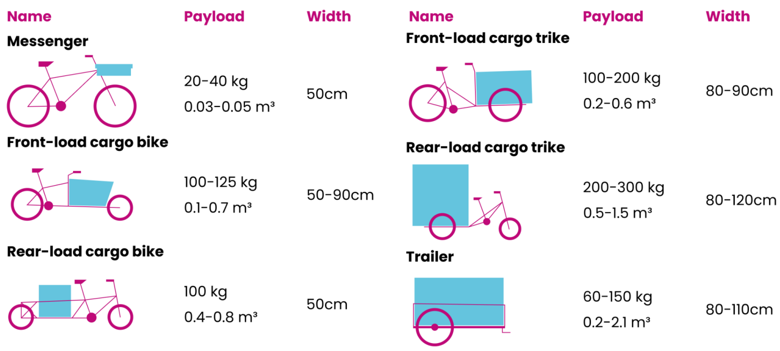

Fig. 1. Cargo bike types [4]

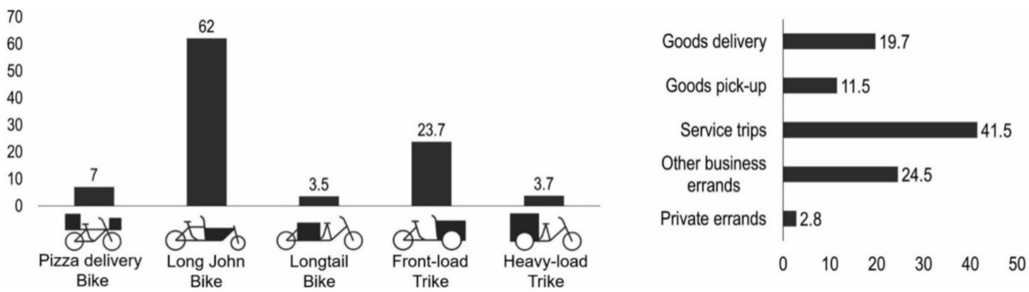

Fig. 2. Representation of cargo bike types [27]

In general, the most common cargo bicycles are front-load cargo bikes, as 62% of cargo bike trips are carried out by front-load cargo bikes [27]. Messenger bikes have a limited cargo capacity but are commonly used for food delivery since they require a low cargo capacity, and due to delivery within one hour, deliveries cannot be combined. Postal services also use this type of bicycle for letter deliveries.

Front-load cargo bikes are the most common cargo bikes for private use. They can transport up to 125 kg, which is perfect for grocery shopping or transporting children. This type is also often used by parcel couriers. The cargo bike has a decent capacity and has similar handling qualities as a traditional bicycle. Bike couriers still complain about the limited volume capacity and often add a trailer to increase the capacity. The full weight capacity is rarely reached due to limited volume and low-density parcels. Research also points to limited capacity as a major shortcoming [28, 29]. Current market trends show an increase in cargo capacity [30]. Rear-load cargo trikes in general have the highest cargo capacity. The extra wheel distributes the load and allows additional cargo capacity. Placing the cargo behind the driver allows for a higher cargo area without obstructing the driver's view. These types are often used by parcel couriers such as UPS, DHL and FedEx [31-33]. However, current rear-load cargo trikes increase the average travel time [34]. This is stated to be due to the extra cargo they can carry.

The specifications in Fig. 1 are the average values for these cargo types. There are extreme versions, such as the Cargo Bike XXL and the Urban Arrow Tender (Fig. 3).

Fig. 3. Ziegler Cargo Bike XXL [35] and Urban Arrow Tender [36]

The Cargo Bike XXL from Ziegler is capable of delivering up to 500 kg with a maximum volume of 4.3 m². Its total length is 6.5 m. Due to the large loading capacity; the cargo bike needs an extra-wide cycle infrastructure. The Urban Arrow Tender is a tadpole tricycle with a payload capacity of 300 kg and 1.2 m³. The vehicle is 1.14 m wide.

2.3. Electrical assistance

E-bikes assist the driver and make it easier to transport high payloads. Electric assistance generally reduces delivery times, especially along routes with elevation differences [34]. Currently, 40% of cargo bikes are electrically assisted. In 2020, 92% and 75.5% of all sold cargo bikes were electric in Europe and Germany, respectively, with the Pedelec25 representing the majority of cases [24, 37]. Pedelec25 assistance is currently limited to 250 W and 25 km/h. These electric cargo bikes are the same type as e-bikes. This, however, provides limited assistance when cycling with a high payload on hilly terrain. The assistance can be increased to 1000 W. These cargo bikes, however, require a licence, insurance and safety equipment, as they fall under other categories and requirements [14].

2.4. Potential to shift

Parcel, express and courier (PEC) is the sector with the highest potential for cycle delivery [38]. Of all deliveries, 85% can be done by cargo bikes [39, 40]. Government incentives and improvements in infrastructure, combined with informing companies about advantages, are major factors in speeding up the transition to cargo bikes [41].

3. SUMMARY OF THE RESEARCH METHODOLOGY AND QUANTIFIED GOALS

In this research, a systematic scientific method has been applied for the development of the cargo bike, namely the quality function deployment (QFD) method [42]. To obtain a full view of the desired features of the vehicle to be developed, representatives of all types of stakeholders were interviewed:

1. experienced bike couriers: couriers transporting light parcels of limited size on a conventional bicycle, couriers using a two-wheel cargo bike, couriers using a tricycle or quadricycle, couriers using a trailer
2. operators of a fleet of bicycles and tricycles, including cargo bikes
3. cargo bike distributors
4. manufacturers of cargo bikes
5. those responsible for mobility and logistics at local authorities
6. operators of an urban distribution centre
7. classic courier services using mostly or exclusively vans and trucks
8. service companies located in an urban environment with access restrictions
9. service companies located in rural areas but with customers in urbanised areas
10. shopkeepers in urbanised areas.

The desired features of a cargo bike detected during the interviews are summarised as follows:

1. highly manoeuvrable
2. robust in the sense of being able to withstand daily use by non-owners of the bike
3. allowed by legislation on bicycle paths
4. low wind resistance
5. loading floor at least suitable for a euro pallet (80 x 120 cm)
6. able to transport long pieces
7. stable at all times, even with loads of 150 or 200 kg
8. can be parked without external support
9. secured against theft
10. safe at all times, even when driving downhill fully loaded
11. battery rechargeable in 15 minutes or replaceable
12. complies with relevant legislation
13. easily repairable
14. intuitive to use
15. cheap to build in small series

The abovementioned features desired by stakeholders are put in the house of quality matrix according to the QFD method. The matrix structures the desired features and distinguishes between requirements and wishes; if the cargo bike under development does not comply with the requirements, it will not be accepted by the market. The wishes are rather desirable features. According to the QFD method, the final classification as "requirement" or "wish" is done by the team of developers using the details of the wording by the interviewees. In this phase of the development – which took place in 2019 – over 300 types of existing cargo bikes are checked with the stakeholder requirements, and it is concluded that not a single type of existing cargo bike complies with all requirements. Therefore, the development process is continued by creating a list of engineering requirements:

1. the cyclist has a free view of the road
2. maximum total load (cargo + cyclist) of 275 kg or more
3. maximum cargo payload of 200 kg or more
4. maximum total payload of each wheel of 110 kg or more
5. maintenance free for 1000 driving hours at maximum load
6. maximum width of 1 m
7. S-turn of two times 180° and a radius of 4 m at a speed of 15 km/h or more;
8. all wheels diameter of 20" or more
9. minimum ground clearance under the loading floor of 14 cm or more
10. stability is an intrinsic property of the bike
11. loading floor of 81 x 121 cm or more, with a pallet edge of 5-15 cm high on four sides;

12. possibility of mounting a ladder-shaped front wall on the loading floor for transporting long pieces protruding above the cyclist
13. vehicle speed can be limited to 25 km/h
14. can be homologated as an L1eA or L1eB vehicle [43], or the maximum rated output power of the motors is limited to 250 W
15. replaceable battery with a capacity of 400 Wh and space for a second identical battery
16. parking using a mechanical brake or active position control using the motor
17. automatic support leg in case of a two-wheel bike, slide in and out within 0.3 s
18. hidden built-in tracing system operational over 200 km
19. automatic quality lighting with EN number
20. conventional brake levers for bicycles (on the right-hand side for rear brake control, on the left-hand side for front brake control)
21. proportional regenerative brakes operated by a conventional brake lever
22. braking deceleration better than $5 m/s^2$ on (clean) asphalt or concrete roads
23. assembly and maintenance can be done using readily available tools only
24. use of parts that are commercially available except for the frame
25. tuned to a cyclist of 1.8 m and adaptable for cyclists between 1.7 and 1.9 m.

The above list of engineering requirements, referred to as ER1 to ER25, is to be considered as a checklist during the next development phases, namely the creative conceptual design and detailed engineering phases.

4. CONCEPTUAL DESIGN

A number of concepts for new types of cargo bikes have been generated. Their potential to meet the engineering requirements has been evaluated, and the most promising concept has been selected. It is schematically represented in Fig. 4.

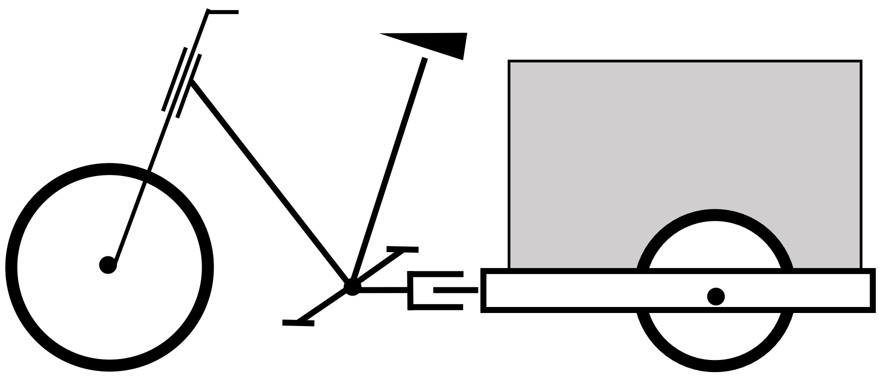

Fig. 4. Concept of the new type of cargo bike

This cargo bike can be classified as a rear-load cargo tricycle. A rear-load cargo tricycle typically allows a free view on the road (ER1) independent of the dimensions of the cargo. A tricycle is easier to keep stable than a bicycle and can be suitably dimensioned for cargo of a Euro-pallet size. The specific proposed design consists of a part for the cyclist at the front (cyclist module) and a part for the cargo at the back (cargo module). Both modules are connected by a hinge.

The cyclist module consists mainly of a front wheel with a fork and handlebars, a saddle, a pair of pedals mounted on an electric mid-drive motor and a frame. For the front wheel, a conventional 26" or 28" spoked wheel is chosen, of which numerous variants are commercially available with matching tires (ER24). The fork and handlebars are also parts for which numerous variants are commercially offered. The saddle is longitudinal and height adjustable (ER25). The frame is a conventionally welded tubular frame commonly used in cargo bikes. The pedals and handlebars are conventionally commercially available components. The pedal rods are mounted on a conventional mid-drive motor for an e-bike. However, this motor is used as a generator by installing purpose made software on the motor controller. The front wheel is equipped with a conventional hydraulic brake to meet legal and engineering requirements. This front wheel brake is considered an emergency brake and should not be used often, as it is the most wear-sensitive part of the tricycle.

The cargo module consists mainly of a U-shaped frame. A wheel motor is mounted on each leg of the U, and the loading floor is situated between both legs. The width of each leg is limited to 9.5 cm to allow for a width of 81 cm for the loading floor (ER11) within the maximum total width of 100 cm (ER6). The ground clearance under the loading floor can be chosen to comply with the engineering requirements (ER9) since it is not determined by the diameter of the wheels. The U-frame is composed of sheet metal parts connected by structural rivets (ER23). This construction method avoids the use of moulds and dies, allows the strength (ER2-ER3) and stiffness to be maximised by means of computer simulations, avoids the use of specifically trained personnel for welding (ER23) and ensures fast assembly. Furthermore, well-shielded compartments for electronics (ER18), batteries (ER15) and cables can be integrated inside the U-shaped frame owing to the sheet metal-based concept. A ladder-shaped front wall (ER12) and high-quality lighting (ER19) are also included.

The cyclist module and the cargo module are hinged so that the cyclist module can rotate around an almost horizontal longitudinal axis in relation to the cargo module. This enables the driver to lean when taking corners, enhancing the stability of the tricycle (ER10). The exact choice, location and orientation of the hinge have been experimentally researched and are discussed below.

The loading floor is surrounded on three sides by the U-shaped frame. At the backside, there is a robust door that can be folded down around horizontal hinges. When folded down, this door supports the loading module so that the tricycle cannot tip over backwards when loaded. Loading can be done from above with an overhead crane, from behind with a pallet truck or completely manually from the side. Most likely, a service company will mount a fixed box of suitable height on the loading floor. Couriers are expected to prefer to load a single case or two stacked cases containing the parcels to be delivered. Foldable cases can be used to minimise wind resistance.

All engineering requirements not yet mentioned in this paragraph – except for the manoeuvrability (as quantified in ER7) and stability requirements – can be dealt with in the detailed engineering phase. Further research was focused on these features, as they are crucial for couriers in urban areas.

5. STABILITY AND MANOEUVRABILITY

As the main dimensions of the tricycle are determined by the need to transport cargo the size of a Euro pallet, the stability and manoeuvrability depend mainly on the complex mechanical drive system, the control software and the proper features of the hinged connection between both modules.

5.1. Drive system

The propulsion system of the proposed tricycle consists of a wheel motor in each of the rear wheels, a generator mounted between the pedal rods, one or more battery packs, control electronics with the necessary software and controls on the handlebars. The wheel motors can provide torque for driving or braking and a holding torque when parked.

A permanent magnet brushless DC (BLDC) motor with coils on the stator and magnets on the rotor has been chosen as a wheel motor. Two flanges are mounted on the rotor. They support the wheel rim on which pneumatic tires are mounted. 20" tires (ER8) with a payload of 140 kg are commercially available (ER4). Three hall sensors are fitted between the stator coils to determine the speed and direction of rotation. The power cable and signal cable are routed outward along the axis. The stator can be powered by a 24V, 36V or 48V DC power source according to the desired maximum speed. A direct drive BLDC motor is chosen instead of the more widely available geared motor because such a direct drive motor can be adapted to the very small width that is available. The direct drive motor, including a stator shaft, rotor flanges and a rim, forms a single unit with a drop-out size of 70 mm. It can be fitted within the width of 95 mm of the leg of the U-shaped frame. The wheel motors propel and stop the vehicle using regenerative braking, increasing the range as recommended by previous research [44].

A mid drive motor of a conventional e-bike is mounted on the cyclist module. It is driven by the cyclist using the pedals, and it serves as a generator. It is connected to the battery pack that powers the wheel motors, thus increasing the range by the energy supplied by the cyclist. This series hybrid system was studied in detail by [45, 46].

Numerous user control features are implemented to enable the smooth operation of this drive system:

1. an on/off key interrupting the connection to the main power source; only the tracer (ER19) remains powered.
2. an "intention" multi-position switch
   - Parking: the wheel motors are energised and controlled to a position. This prevents the tricycle from spontaneously moving on a slope. (ER16)
   - Driving: the wheel motors are energised depending on the movement of the pedals. Up to a speed of 5 km/h, the wheel motors can be driven proportional to the position of a throttle, serving as a walking function.
   - Reverse: similar to the walking function but backwards.
3. an "assistance" multi-position switch to select the level of assistance by the tricycle rear wheel motors. The switch position mainly determines a multiplication factor to calculate the torque of the motors, starting from the torque of the cyclist on the pedal rods mounted on the generator.
4. a "throttle" to control the power of the wheel motors up to 5 km/h forwards and backwards.
5. a brake lever on the right side of the handlebars that, when operated, immediately interrupts the propulsion by the wheel motors, causing the tricycle to coast. When the brake lever is pressed further, the regenerative braking action of the motors is activated. The position of the brake lever determines the power in braking mode (ER21).
6. a hydraulic brake on the front wheel of the tricycle (ER20). It is activated by a brake lever on the left side of the handlebars. A brake switch is integrated into this brake lever. When operated, it immediately interrupts the propulsion by the wheel motors and sets a fixed braking current. When the brake lever on the right-hand side is also pressed, this brake lever determines the power in braking mode. The hydraulic brake can also be used as a parking brake on the front wheel.
7. a display providing information to the cyclist, such as speed, distance travelled, battery charge, ...
8. two batteries mounted inside the frame of the cargo module. Each battery is equipped with its own battery management system. They are used sequentially. The battery used to power the wheel motors is also charged by the generator and the regenerative braking system.
9. a brake resistor mounted in the frame. It dissipates energy from the generator when the batteries are fully charged and limits the energy to the battery from regenerative braking in order to maintain the health of the battery.
10. an electronics box, which includes a double driver for both wheel motors, a driver for the generator, a data processor and a data storage module. The data storage function was used intensively to gather data for the ongoing research. Performance data can be visualised on the display, while more detailed and historical data can be visualised on a smartphone over a link such as Bluetooth.

The handlebar of the tricycle is shown in Fig. 5.

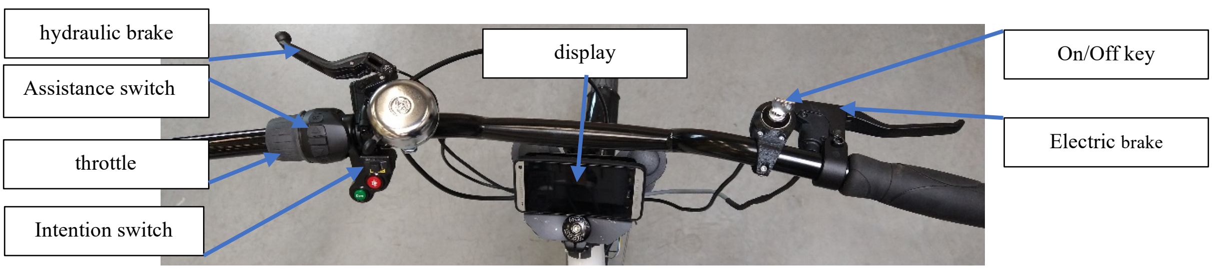

Fig. 5. Handlebar of the tricycle

5.2. Software

The software used to run the tricycle mainly consists of modules for the wheel drives, the generator, battery management and user interaction. This research focused on the software for the wheel drives and the generator.

The drive of the wheel motors controls the torque exerted on the rotor of each motor. When driving straight ahead with equal load and tire pressure on both wheels, this torque should be identical for both motors. As soon as the handlebars are turned when entering a bend, the resistance on the wheel on the inside of the bend increases, and the resistance on the wheel on the outside of the bend decreases. The speed of the motor on the outside of the bend increases while the opposite occurs for the motor on the inside of the bend, thus helping the bicycle turn corners. The individual control of both wheel motors increases the manoeuvrability of the tricycle considerably in a way comparable to the electric stability control (ESC) implemented in conventional cars.

Furthermore, this drive reads the inputs of the intention switch, assistance switch, throttle and both brake levers mounted on the handlebars. As mentioned before, the brake lever on the right-hand side is used to control the level of regenerative braking by both wheel motors. Apart from the advantage of energy recuperation, using the wheel motors as primary braking also activates a software-implemented anti-lock braking system (ABS) without requiring extra components. The rotational speed of the wheel motors is constantly monitored using three Hall sensors. A measured decrease in the rotational speed of a wheel motor is interpreted by the software to identify the slipping of the wheel. In that case, regenerative braking is interrupted immediately until the wheel regains traction. Then, braking is reactivated as before. This procedure is repeated as long as the wheel tends to slip. As a consequence, the maximum vehicle deceleration mainly depends on the coefficient of friction between the tires and the road. This coefficient is beyond 0.5 anyway, thus allowing a deceleration above 5 m/s² (ER22).

This drive also determines the maximum speed at which the motors still provide assistance. This switch-off speed depends on several parameters. Local legislation can limit this switch-off speed (often to 25 km/h). In practice, the voltage supplied by the battery varies depending on the state of charge (SOC). For a nominal voltage of 48V – as used in the tricycle described in the current work – the actual voltage varies between 39V (0% SOC) and 54.6V (100% SOC). Battery life can be prolonged by keeping the SOC between 20% and 80% [47]. Other research [48] shows that the efficiency of a BLDC motor may diminish consistently when operated in the top 10% of its rotational speed, thus draining the battery very quickly. Therefore, the motor's switch-off speed is made variable depending on the actual voltage of the battery. The switch-off speed is within the limit implied by legislation as long as the battery voltage is more than 42V (ER13). As soon as the battery voltage drops below this value, the switch-off speed is reduced to avoid operation in the inefficient speed zone. The software of this drive can also limit the output power of the wheel motors. According to European regulations, the average power output of the propulsion of an e-bike – either a bicycle or tricycle – is limited to 250 W [43]. If not, homologation as a light electric vehicle category L1eA or L1eB is required. The technical guidelines state that the power measurement may be carried out for half an hour, which means that the peak power consumption may be significantly higher than indicated in these guidelines. In concrete terms, this means that the power consumption when driving up a slope can be significantly higher than 250 W as long as it is largely reduced when driving down the slope immediately afterwards. The software manages this power consumption, taking into account energy recuperation during braking on some downhill roads. The drive of the generator creates resistive torque on the bottom bracket. A safe and comfortable feeling during cycling is related to the course of this torque as a function of the position of the pedal rods. Prior tests reveal that a constant resistive torque is very uncomfortable for the cyclist [49]; in the dead points at the upper and lower positions of the pedal rods, a resistive torque from the generator is very difficult to overcome. In conventional bicycles these dead points are bridged by the inertia of the moving bicycle. This is not the case for a tricycle carrying a heavy load starting at a standstill. Further, at higher speeds, the resistance must be limited in the dead points to maintain safety. Preferably, the resistance on the pedals also depends on the physical resistance of the loaded tricycle (i.e. the rolling and air resistance). Since there is no mechanical linkage to the rear wheel motors, a digital linkage is established to create the feeling of the physical resistance of the tricycle. The actual electrical current and the actual rotational speed of the wheel motors are indicative of this physical resistance. Therefore, the generator drive uses this current and speed as input values. The resistive torque on the bottom bracket created by the generator depends upon several factors:

- the rotational speed of the generator
- the rotational speed of the wheel motors
- the actual current of the wheel motors
- the actual position of the pedal rods

Moreover, this digital linkage serves as a continuous variable transmission (CVT): a constant pedalling speed is created to maximise the comfort of the cyclist.

5.3. Hinged connection

The hinge consists of a shaft that rotates in a housing. It resists forces in all directions perpendicular to the shaft, forces in both senses parallel to the shaft and bending moments in both senses around all transverse directions. The longitudinal direction of the shaft largely coincides with the longitudinal direction of the tricycle. However, it can be tilted slightly up or down at the front to improve manoeuvrability. Moreover, the hinge can be mounted at a higher or lower position between both modules of the tricycle. A design of experiments has been set up to determine the ideal tilt angle and installation height.

The prototype tricycle used for these experiments is shown in
Fig. 6. Numerous geometrical parameters of this tricycle influence its manoeuvrability and stability. Since the design of experiments focuses on the height and tilt angle of the hinge, these geometric parameters are copied from a rigid cargo bicycle. The design of experiments includes three different heights (220 mm, 360 mm and 500 mm above ground level) at three different tilt angles (10° upwards, horizontal and 10° downwards) with an empty load and the maximum load on the loading floor.

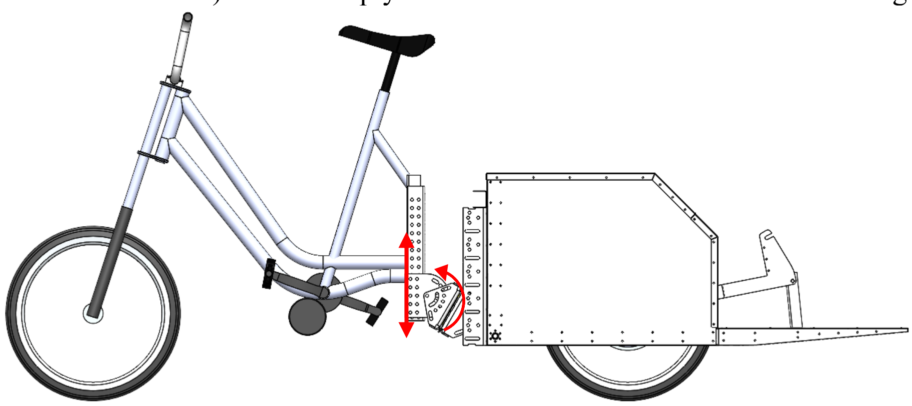

Fig. 6. Prototype with adjustable hinge

Cyclists conducted an obstacle course at different speeds (below 10 km/h, 10-15 km/h, 15-20 km/h and above 20 km/h). The specified combinations of heights and tilt angles were evaluated by questioning the cyclists. They were explained that “stable” is to be understood as not likely to fall or tip over, and “manoeuvrable” is to be understood as easy to move and direct as intended. Parallel to the interviews, the stability was evaluated by measuring the steering angle. Frequent small changes in the steering angle indicate poor stability of the cyclist module and, thus, the overall stability of the tricycle.

The experiments show that the height of the hinge position has no impact on the tricycle stability at low speeds. At higher speeds, cyclists reported feelings of instability when entering a corner with the hinge in the highest position. They felt the cyclist module being swept out from under them when tilting the cyclist module to the inside of the turn. As such, the interviewed cyclists unanimously preferred the lowest hinge position.

The orientation of the hinge significantly influences both the stability and the manoeuvrability of the tricycle. Orienting the hinge perfectly horizontally creates a feeling similar to cycling with a conventional two-wheeled bike. By tilting the front of the hinge slightly downwards, the tricycle is less stable but more manoeuvrable. Cornering with a downwards tilted hinge causes a small rotation of the load module towards the outside bend when the cycle module is tilted inwards. This rotates the rear wheels away from the direction the cyclist module is going, creating a smaller turning radius compared to a horizontal orientation of the hinge. The cases of tilted downwards, horizontal and tilted upwards hinge are illustrated in Fig. 7. Unfortunately, a downwards tilted hinge steers the tricycle sideways. This is experienced as instability and causes the cyclist to react. A new user will not expect such instability and, therefore, will feel uncomfortable. After using the tricycle for a couple of hours, this uncomfortable feeling seems to disappear. Orienting the hinge in a slightly upwards position has the opposite effects on manoeuvrability and stability. The cargo module moves in the same direction the cyclist wants to turn, thus enlarging the turning radius and making it more difficult to turn.

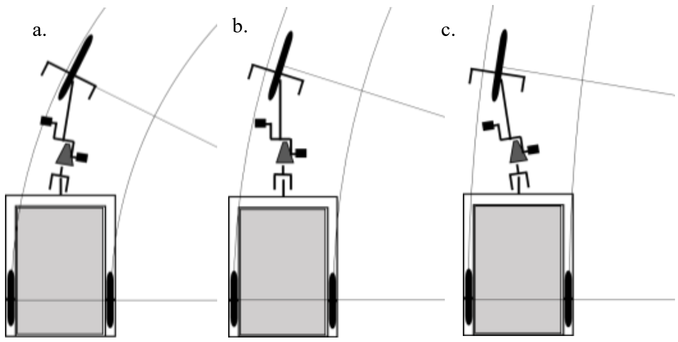

Fig. 7. Turning radius of the vehicle with a. a downwards tilted hinge, b. a horizontal hinge and c. an upwards tilted hinge

These effects are proportional to the tilting angle of the hinge, both for downwards and upwards tilting. A larger inclination has a larger effect on the manoeuvrability and on the stability. Finally, the cyclists preferred a slightly downwards tilted hinge, as the improved ability to make sharp turns outweighs the mild reduction in stability. Probably, the cyclists also took into account that they were used to this instability at the end of the series of tests.

Finally, the hinged tricycle with the hinge in the lowest position and tilted downwards is compared to a fixed frame tricycle. For cycling speeds below 10-15 km/h, the fixed frame tricycle is more stable than the hinged tricycle. The latter requires more steering corrections. For cycling speeds beyond 10-15 km/h, the hinged tricycle is more manoeuvrable than a tricycle with a fixed frame due to the ability of the cyclist to lean into the corners. Stability is comparable for both hinged and fixed frames with an empty load. When transporting goods, a fixed frame tricycle can even tilt over in sharp turns, while a hinged tricycle will show stable behaviour.

The poor stability of the hinged tricycle at low speeds can be eliminated by introducing rotational stiffness into the hinge. This stiffness reduces the tendency of the cyclist to tilt at low speeds. The optimal rotational stiffness depends on the mass and the centre of gravity of the cyclist. Therefore, an adjustable rotational stiffness is recommended.

Lastly, the hinge system also includes a couple of stabilisers that keep the cycling module in a vertical position when parked. The actual hinge and the stabilisers are integrated into the frame to avoid damage by water infiltration.

6. CONCLUSIONS

Existing cargo bikes do not completely meet the expectations of professional users for the last-mile delivery of e-commerce parcels, nor do they meet the requirements of service companies. A novel future-generation tricycle was developed using the QFD method to inventory the requirements of such a cargo bike and to select the most appropriate design concept. The systematic use of design of experiments during the detailed engineering step of the development resulted in an electric cargo tricycle that is very stable and manoeuvrable. The vehicle is able to carry a Euro pallet and has a payload capacity of 200 kg. The series hybrid drivetrain allows a hinged frame while maintaining a low centre of gravity and remaining within width restrictions. The hinge between the driver module and cargo module allows for a nimble and comfortable ride. It complies with all important requirements of all stakeholders detected during the research. The concept corresponds with current trends in the cargo bike market, as seen in Cargo Chariot and Fulpra. A prototype of this tricycle is shown in

Fig. 8. It has been tested intensively on campus and is currently being tested by some major courier companies for parcel delivery in pedestrian areas of city centres.

Fig. 8. Tribike prototype

References

1. Reiter, K. & Wrighton, S. & Rzewnicki, R. Potential to shift goods transport from cars to bicycles in European cities. In: *Moving Europe forward*. 2014.
2. *Sustainable and Smart Mobility Strategy – putting European transport on track for the future.* COM(2020) 789 final. European Commission. 2020.
3. Caggiani, L. & Colovic, A. & Prencipe, L.P. & Ottomanelli, M. A green logistics solution for last-mile deliveries considering e-vans and e-cargo bikes. *Transportation Research Procedia.* Vol. 52. P. 75-82. DOI: https://doi.org/10.1016/j.trpro.2021.01.010.
4. Verlinghieri, E. & Itova, I. & Collignon, N. & Aldred, R. *The Promise of Low-Carbon Freight*. Westminster, 2021.
5. Wrighton, S. & Reiter, K. CycleLogistics – Moving Europe Forward! *Transportation Research Procedia.* Vol. 12. P. 950-958. DOI: https://doi.org/10.1016/j.trpro.2016.02.046.
6. Giglio, C. & Musmanno, R. & Palmieri, R. Cycle logistics projects in Europe: Intertwining bike-related success factors and region-specific public policies with economic results. *Applied sciences.* Vol. 11. No. P. 1-31. 2021. DOI: https://doi.org/10.3390/app11041578.
7. Arnold, F. & Cardenas, I. & Sörensen, K. & Dewulf, W. Simulation of B2C e-commerce distribution in Antwerp using cargo bikes and delivery points. *European Transport Research Review.* Vol. 10. No. 1. P. 2. DOI: https://doi.org/10.1007/s12544-017-0272-6.
8. Nowak, D. *How sustainable is the Pedal Me fleet?* Pedal Me. 2021.
9. Mucowska, M. Trends of Environmentally Sustainable Solutions of Urban Last-Mile Deliveries on the E-Commerce Market – A Literature Review. *Sustainability.* 2021. Vol. 13. No. 11. DOI: https://doi.org/10.3390/su13115894.
10. Clement, J. *Coronavirus impact on retail e-commerce website traffic worldwide as of June 2020, by average monthly visits*. Available at: https://www.statista.com/statistics/111259.
11. Villa, R. & Monzón, A. Mobility Restrictions and E-Commerce: Holistic Balance in Madrid Centre during COVID-19 Lockdown. *Economie.* 2021. Vol. 9. No. 2. DOI: https://doi.org/10.3390/economies9020057.

12. Buch, T.S. & Greibe, P. *Bredde af cykelstier: Analyse af adfærd og kapacitet*. [In Danish: *Width of cycle paths: Analysis of behavior and capacity*]. 2014. Available at: https://www.trafitec.dk/sites/default/files/publications/Bredde%20af%20cykelstier_Analyse%20af%20adf%C3%A6rd%20og%20kapacitet.pdf.
13. *Regulation (EU) No 168/2013 of the European Parliament and of the Council of 15 January 2013 on the approval and market surveillance of two- or three-wheel vehicles and quadricycles (Text with EEA relevance)*.
14. Roetynck, A. Electric Cargo Bikes: Technical Rules & Regulations. In: *ECLF conference*, Vienna, 2017. Available at: https://eclf.bike/presentations17/D1%20Annick%20Roetynck%20ECLF%202017.pdf.
15. de Groot, R. *Ontwerpwijzer fietsverkeer*. [In Dutch: *Design guide for bicycle traffic*]. Ede: CROW. 2016. ISBN: 9789066284692.
16. *Koninklijk besluit houdende algemeen reglement op de politie van het wegverkeer en van het gebruik van de openbare weg*. [In Dutch: *Royal Decree on General Regulations on the Police of Road Traffic and the Use of Public Roads*]. Belgian Official Gazette of 9 December 1975.
17. Vlaanderen, M. *Ontwerpichtljinen voor fietsvoorzieningen*. [In Dutch: Design guidelines for bicycle services]. 2017.
18. *Vademecum fietsvoorzieningen – Minimumbreedte fietspaden*. [In Dutch: *Vademecum bicycle facilities – Minimum width of bicycle paths*]. 2018.
19. *Danish Guidelines for planning and design, Danish Road Directorate*. 2000.
20. Greibe, P. & Buch, T.S. Capacity and Behaviour on One-way Cycle Tracks of Different Widths. *Transportation Research Procedia.* Vol. 15. P. 122-136. DOI: https://doi.org/10.1016/j.trpro.2016.06.011.
21. Fransen, G. *Van bakfietsen tot snelle elektrische fietsen: wie mag er wel op het fietspad en wie niet?* [In Dutch: *From cargo bikes to fast electric bikes: who is allowed on the cycle path and who is not?*]. Het Nieuwsblad, 2020.
22. Behrensen, A. & Sumer, A. *European Cargo Bike Industry Survey Results. City Changer Cargo Bike*. Available at: https://www.cargobike.jetzt/europaeische-marktumfrage-2020/#Ergebnisse.
23. Wens, S. & Vlaanderen, F. *Fiets DNA*. 2018. Available: https://fietsberaad.be/wp-content/uploads/FietsDNA_2018_A5_lwr.pdf.
24. Behrensen, A. *European Cargo Bike Industry Survey. Cyclelogistics*. 2021. Available at: http://cyclelogistics.eu/sites/default/files/downloads/2021-09-20_Summary_CCCB_survey_results.pdf.
25. Farman, G. *Cargo Bike Analysis and Field Testing. Topsector Logistiek.* 2020. Available at: https://www.topsectorlogistiek.nl/wp-content/uploads/2020/11/Cargo-bike-HR-testing-method.pdf.
26. Behrensen, A. & Sumer, A. *First European Cargo Bike Industry Survey Results. City Changer Cargo Bike*. 2020. Available at: https://www.cargobike.jetzt/europaeische-marktumfrage-2020/#Ergebnisse.
27. Narayanan, S. & Gruber, J. & Liedtke, G. & Antoniou, C. Purchase intention and actual purchase of cargo cycles: Influencing factors and policy insights. *Transportation Research Part A: Policy and Practice.* Vol. 155. P. 31-45. DOI: https://doi.org/10.1016/j.tra.2021.10.007.
28. Blazejewski, L. & Sherriff, G. & Davies, N. *Delivering The Last Mile Scoping the Potential for E-cargo Bikes Healthy Active Cities*. 2020.
29. Lenz, B. & Riehle, E. Bikes for urban freight? *Transportation research record.* No. 2379. P. 39-45. 2013. DOI: https://doi.org/10.3141/2379-05.
30. Clements, S. *Cycle Logistics Study*. 2019. Available at: https://crossriverpartnership.org/wp-content/uploads/2019/03/20190520_Element-Energy_Cycling-logistics-study_FINAL-REPORT-1.pdf.
31. Walther Ploos van Amstel. *DHL Netherlands presents their new cargo bike: the Chariot*. City Logistics. 2021.
32. UPS. *Lessons from our e-bike journey*. 2020.
33. FED-ex, FedEx Express Continues Journey Towards Zero Emissions Delivery, as Edinburgh, Glasgow and Cambridge Become the Next UK Cities to Welcome E-cargo Bikes. 2021.

34. Gruber, J. & Narayanan, S. Travel Time Differences between Cargo Cycles and Cars in Commercial Transport Operations. *Transportation research record.* 2019. Vol. 2673. No. 8. P. 623-637. DOI: https://doi.org/10.1177/0361198119843088.
35. Ziegler Group Services. Cargo Bike Ziegler. *A revolutionary, eco-friendly freight solution for Brussels*. 2022.
36. Urban Arrow. *The Tender will handle everything you throw at it*. Available at: https://urbanarrow.com/business-bikes/tender/tender-2500/.
37. Brust, E. *Zweirad-Industrie-Verband (ZIV) Wirtschaftspressekonferenz.* [In German: *Bicycle Industry Association (ZIV) Business Press Conference*]. Berlin, 2021.
38. Orchard, K. & Cluzel, C. *Cycle Freight Study. An independent study commissioned by Transport for London*. Element Energy Ltd. 2018.
39. Gruber, J. *Ergebnisse des größten Lastenradtests Europas Umweltfreundlich und effizient: Lastenräder im dienstlichen und gewerblichen Einsatz*. [In German: *Results of the largest cargo bike test in Europe Environmentally friendly and efficient: cargo bikes in official and commercial use*]. 2021.
40. Ferguson, J. C*argo Bike Crazy: The Potential of Delivering Goods By Bike*. Available at: https://ecf.com/news-and-events/news/cargo-bike-crazy-potential-delivering-goods-bike-0.
41. Cairns, S. & Sloman, L. *Potential for e-cargo bikes to reduce congestion and pollution from vans in cities.* Transport for Quality of Life Ltd. 2019.
42. Maritan, D. *Practical Manual of Quality Function Deployment*. Cham: Springer International Publishing AG, 2014.
43. *Cycles - Electrically powere assisted cycles - EPAC Bicycles EN 15194:2017*.
44. Bahrami, M. & Mokhtari, H. & Dindar, A. Energy regeneration technique for electric vehicles driven by a brushless DC motor. *IET Power Electronics.* Vol. 12. No. 13. P. 3397-3402. DOI: https://doi.org/10.1049/iet-pel.2019.0024.
45. Tournon, E. & Venet, P. & Barbedette, B. & Lelievre, A. & Aubry, J. & Sari, A. Efficiency Comparison between Series Hybrid Bike and Traditional Bike. In: *Fourteenth International Conference on Ecological Vehicles and Renewable Energies (EVER).* Monaco, Monte-Carlo. 2019. IEEE. P. 1-7. DOI: https://doi.org/10.1109/EVER.2019.8813618.
46. Zawirski, K., Nowopolski, K., Wicher, B., Janiszewski, D., Fabiański, B., Siembab, K. Gearless Pedaling Electric Driven Tricycle. In: Gołębiowski, L., Mazur, D. (eds.) *Analysis and Simulation of Electrical and Computer Systems. Lecture Notes in Electrical Engineering.* Vol 324. Springer, Cham. DOI: https://doi.org/10.1007/978-3-319-11248-0_34. 2015.
47. Song, C. & Shao, Y. & Song, S. & Peng, S. & Xiao, F. A Novel Electric Bicycle Battery Monitoring System Based on Android Client. *Journal of engineering (Cairo, Egypt).* 2017. Vol. 2017. P. 1-11. DOI: https://doi.org/10.1155/2017/2579084.
48. Ustun, O. & Tanc, G. & Kivanc, O.C. & Tosun, G. In pursuit of proper BLDC motor design for electric bicycles. In: *2016 XXII International Conference on Electrical Machines (ICEM)*. 4-7 Sept, 2016. P. 1808-1814. DOI: https://doi.org/10.1109/ICELMACH.2016.7732769.
49. Dieltiens, S. & D'Hondt, J. & Juwet, M. & Versteyhe, M. Development of a low-cost measurement system to determine 3-dimensional pedal loads during in-situ cycling. *Transport Problems.* 2019. Vol. 14. No. 4. P. 151-159. DOI: https://doi.org/10.20858/tp.2019.14.4.13.

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