Design, Analysis and Manufacturing of E-Cargo with Digital Drive

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Abstract: In developing nations like India, where technological advancements drive economic growth, the logistics of goods transportation faces persistent challenges. Conventional cargo cycles, though cost-effective, demand substantial human effort and have limited load-carrying capacity, particularly on inclined terrains. E-cargo vehicles, as a sustainable alternative, promise to address these gaps but are constrained by limitations in range, power, and cost-efficiency. Siemens NX was employed to develop a detailed model, while Finite Element Analysis was utilized to establish a virtual testing environment for comprehensive design evaluation. These advanced tools provided critical insights into necessary modifications and optimizations during the initial design phase of the cargo cycle, ensuring quality enhancements and superior design performance. AISI 1020 material was used to manufacture a cargo chassis frame with a minimum safety factor of 1.58 at the rear wheel bearing housing. This paper presents the development of an innovative E-cargo vehicle that incorporates a regenerative drive system to enhance energy efficiency and operational range. Additionally, a chainless drive mechanism is introduced to minimize torque demand and reduce rider effort, ensuring a smoother and more effortless driving experience, especially on uneven or sloped surfaces. The study also investigates various critical factors in designing and manufacturing E-vehicles, including vehicle ergonomics, rider comfort, energy efficiency, manufacturing feasibility, and structural safety checked by using numerical structural analysis in Ansys. Special emphasis is placed on designing a robust yet lightweight frame structure to optimize safety and performance. The software tool used for 3-D CAD simulation is Siemens NX. By addressing these multifaceted challenges, this research contributes to the evolution of cost-effective, sustainable, and user-friendly solutions for cargo transportation, aligning with the global transition towards green technology and efficient logistics systems.

Keywords: E-Vehicle, Cargo Cycle, Design and Analysis, Vehicle Efficiency, Digital Drive, Kinematics and Dynamics, Manufacturing, Fabrication.

INTRODUCTION

In the ever-evolving landscape of urban logistics, cargo cycles have emerged as a transformative force, blending innovation and sustainability to tackle the challenges of last-mile delivery. These vehicles represent a sustainable and efficient alternative to conventional delivery methods, aligning with the global push toward greener and more cost-effective logistics solutions. The journey of cargo cycles spans from their modest origins as human-powered carriers to the sophisticated electric-assisted freight bikes of today, showcasing their adaptability in meeting the dynamic needs of urban transportation.

Despite their advantages, conventional mechanical cargo cycles face significant challenges that limit their applicability. Issues such as restricted load capacity, physical strain on riders, vulnerability to weather conditions, and inefficiency on hilly terrains hinder their widespread adoption. These limitations necessitate innovative approaches to enhance their functionality and usability. [1]

The digital drive concept can be a solution to address these challenges. Assisting riders with power and torque helps increase load capacity. [2], reduce physical effort, extend range, and improve adaptability across varied terrains. Additionally, they contribute to environmental sustainability by reducing reliance on fossil fuels and minimizing noise pollution in urban settings. This offers long-term cost savings through lower operational expenses and reduced maintenance. [3]

Schaeffler has developed this concept for transportation purposes of utility goods across cities. Schaeffler has been partnering with 2-wheeler electric drive specialist Heinzmann GmbH & Co. KG to develop a cutting-edge chainless drive system or as they call it a FREE DRIVE. No former research has been done on this system till now so there is very little information that checks its feasibility. [4]

Designing chassis for cargo cycles, emphasizing the evaluation of loads, potential failure modes, and critical considerations such as material selection and cross-sectional design. Consideration of a range of materials including AISI 1018, AISI 4130, Aluminum Alloy T6061, and DOCOL R8, utilizing Material Selection Chart for preliminary screening and employing digital logic methods for detailed assessment. The findings identified AISI 1020 as the most suitable material. [5], with AISI 4130 steel as a close alternative, primarily based on superior strength characteristics and overall suitability for chassis applications.

To enhance efficiency, durability, range, and affordability, 18-gauge (1.2 mm) mild steel is sufficient to achieve a robust and durable design of the mini cargo cycle body structure, selected for its effectiveness in resisting impacts and absorbing shocks efficiently. [6] For the frame, hollow circular steel pipes were employed, chosen for their structural integrity and ability to withstand the operational stresses associated with cargo transportation, ensuring reliability and longevity in performance. [7]

This research presents a comprehensive methodology for designing a frame structure that integrates human comfort with enhanced ergonomics. The design emphasizes effortless driving, ease of manufacturing, maintenance-free operation, and cost-effectiveness, ensuring its feasibility for widespread adoption. Special attention is given to aligning electrical components, ensuring proper integration while prioritizing safety against fouls and fire hazards. By combining electrical and mechanical elements, this study aims to achieve great efficiency, offering a holistic solution for sustainable and reliable urban logistics.

Digital Drive concept

In contrast to conventional e-cycles, where the rider can power the bike either manually through pedalling or electronically via a throttle, e-cycles equipped with a digital drive system utilize a more advanced approach. In these systems, the rider's pedalling effort directly powers a generator through a pedal-crank arrangement, eliminating the need for a traditional chain mechanism. The generated power drives an electric motor connected to the rear wheels, enabling seamless electronic propulsion.

The digital drive system offers distinct advantages for cargo cycles, particularly in handling additional weight. Unlike traditional setups, pedalling cadence remains uniform and consistent, reducing rider fatigue.

A key benefit of the digital drive system is its ability to optimize human energy output. The human body operates most efficiently under consistent load conditions, which the system achieves by negating the need for manual gear selection. Regardless of the torque demand—such as when starting a heavily loaded cargo bike—the rider experiences a constant pedalling resistance. This feature ensures efficient power generation with minimal physical strain, significantly reducing rider fatigue and improving overall ergonomics.

Additionally, the digital drive system enhances energy efficiency by enabling regenerative charging. While stationary, such as at traffic lights or halts, the pedalling effort is diverted to charge the battery instead of powering the motor.

Advantages of Digital Drive

One key benefit is the uniformity and consistency of pedalling cadence, which significantly improves energy efficiency. The integrated electrical generator can detect and compensate for imbalances in leg muscle power, such as a weaker left leg, by adjusting the resistance on the respective crank. This ensures smoother pedalling dynamics and reduces strain on the rider, leveraging the human body's optimal performance under consistent and uniform muscular effort.

The absence of mechanical drivetrain components, such as chains and sprockets, makes digital drive e-bikes particularly well-suited for adverse weather conditions, as they are less prone to wear, contamination, and maintenance issues. Furthermore, the system's compatibility with regenerative braking enhances energy efficiency, particularly in urban environments with frequent stops, such as during city commuting and delivery operations. [3]

Digital drive technology also presents unique opportunities for specialized applications, such as physical rehabilitation. By allowing precise adjustment of pedalling resistance, the system provides tailored support regardless of terrain, enabling riders to recondition their physical strength effectively and comfortably. [8]

Over time, production costs for digital drive e-bikes are expected to decrease due to the reduced number of mechanical parts and economies of scale in manufacturing.

Cargo frame design

The frame design was developed to accommodate a maximum load capacity of 250 kg, excluding the driver and vehicle weight, resulting in a total weight of 375 kg under fully loaded conditions, including electric components. The CAD modelling and structural design were executed using Siemens NX software.

The frame structure and mounting configurations were finalised to ensure compatibility with Indian transportation requirements and to facilitate ease of manufacturing [7]. The design was optimised to achieve a uniform distribution of static and dynamic loads across the frame, enhancing structural integrity and performance. Bends in the frame were carefully analyzed and optimized to minimize stress concentrations while adhering to the guidelines outlined in the SAE Vehicle Design Rulebook. [9]

Various materials and pipe cross-sections were evaluated during the initial design phase, including MS (Mild Steel), AISI 4130, AISI 1018, AISI 1020, and aluminium alloys. The materials were analyzed for pipe diameters of 25.4 mm and 31.8 mm with wall thicknesses of 1 mm, 1.5 mm, and 2 mm. Based on detailed calculations and performance assessments, AISI 1020 was selected as the optimal material for the frame structure, offering a favourable balance of strength, durability, and manufacturability suitable for the intended application.

Tractive force calculation

For the calculation of tractive force, the total weight of the cargo cycle is considered as 375 kg, comprising the following components: an 80 kg driver, a 13 kg frame structure, a 250 kg payload, 22 kg allocated for electrical components, and approximately 10 kg for mechanical parts.

The analysis assumes the cargo cycle will accelerate to a speed of 25 km/h within 10 seconds under these conditions. This assumption provides the basis for determining the required tractive force, accounting for factors such as inertia, rolling resistance, and aerodynamic drag.

Crank length of pedal (l) = 170mm;

- Wheel radius (r) = 330 mm
  Frictional force (Fs): -

To move the cycle, it requires to overcome static frictional force

$Fs = \mu N$
$= \mu(m)(g)$
$= 0.7*375*9.81$
$= 2575$ N

(μ = frictional coefficient (for asphalt and tyre is 0.7)
N = normal force)

- Rolling resistance (Fr): -

In running condition of the cycle, frictional force acting between the road and tyre is

$Fr = Cr*N$
$= 0.015*375*9.81$
$= 55.18$ N

(Cr = rolling coefficient (for asphalt and tyre is 0.015))

- Aerodynamic resistance (Fd):-

Resistance force acting due to air in dynamic condition

$Fd = Cd*(1/2)*\rho*v^2*A$
$= 0.9*(1/2)*1.2*(25*1000/3600)^2*0.86715$
$= 22.58$ N

(Cd = drag coefficient
ρ = density of air
v = velocity of cycle
A = frontal area of cycle)

- Acceleration force (Fa):-

The force required to accelerate the cycle, considering the cycle starts running from 0 to 25km/h in 10s;

$a = (V-V_0)/t$
$= (25-0)/20*(1000/3600)$
$= 0.7 m/s^2$

$Fa = m*a$
$= 375*0.7$
$= 262.5$ N

- Static condition:

Required Force (F) = Fs
=2575 N

Required torque (τ_s) = F*r
= 2575*0.33
= 849.75 Nm

- Dynamic condition:

Tractive force (Ft) = Rolling Resistance + Aerodynamic Resistance + Acceleration Force
= Fr + Fd + Fa
=55.18 + 22.58 + 262.5
= 340.26 N (At 0° Inclination)

Required torque (τ_d) = Ft*r
= 340.26* 0.33
= 112.28 Nm

In fully loaded condition $\tau_s > \tau_d$
The required torque to move the cycle from rest is 849.75 Nm but the peak torque of the selected motor is 30 Nm. Hence, speed reduction is required.

Required gear ratio (G) = τ_s / τ_p
= 849.75/30
= 28.32
= 29 (approx.)

Rotation of shaft (N_s) = N/G
= 2000/29
= 69 rpm

Calculated top speed = N_s*2*pi*r
= 2000*2*3.14*0.33
= 8.57 kmph

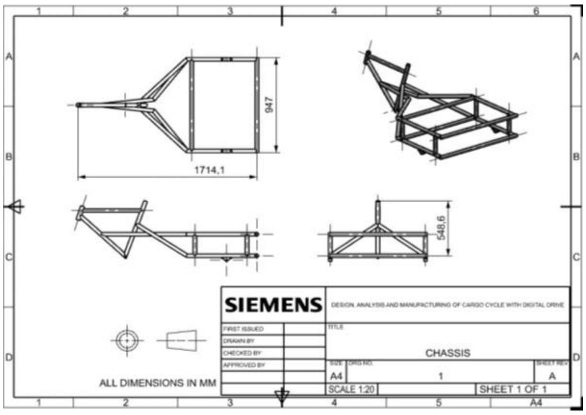

Figure 1: frame structure

Static structure analysis
Here, static structure analysis was conducted for a roll cage, analysing results under all relevant conditions. [10] Pipes are considered to be made from AISI 1020 with a material thickness of 1.5 mm. The

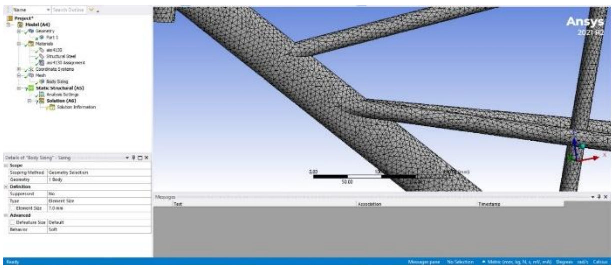

Figure 4: surface mashing

- Gradeability:

The torque provided by the motor in dynamic condition = τ_m*G

= 10*29

= 290 Nm

Force Applied by the motor in dynamic condition = 290/0.33

= 878 N

Grade Force = Applied Force – Rolling Resistance – Air Resistance – Acc. Force
= 878 - 55.18 - 22.58 - 262.5
m*g*sinϴ = 538.52 N
ϴ = 8.41°

CAD model of the cargo cycle


Figure 2: rendered cargo cycle image

mass of the roll cage is around 13 kg. Element size was finalized at 7mm for this test. To analysis the structure deformation, the Live load of the Rider on the seat, the Dead load of the cargo on the pillow bearing, Self-weight of the frame on the bearing loads are considered and applied.

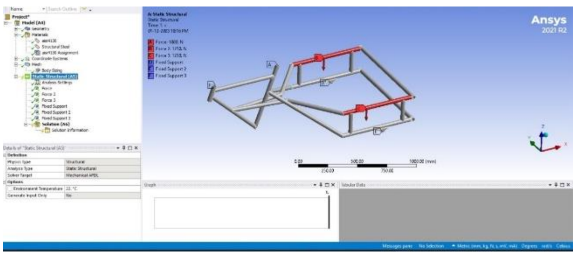

Figure 3: applied loads

ANALYSIS RESULTS AND DISCUSSION

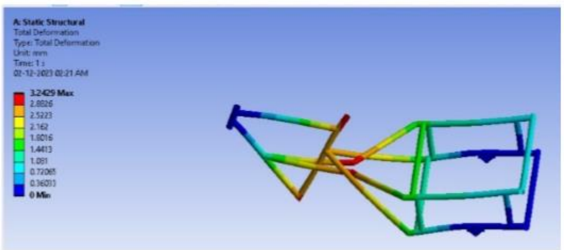

Figure 5: total deformation

Using AISI 1020, which has a yield strength of 710 MPa, the chassis design demonstrates a maximum total deformation of 3.5 mm, as depicted in Figure 5. This deformation is minimal and deemed negligible, as it does not compromise the structural integrity or functional performance of the chassis. The low deformation levels confirm the material's suitability and robustness for the intended application, ensuring reliable operation under the specified load conditions.

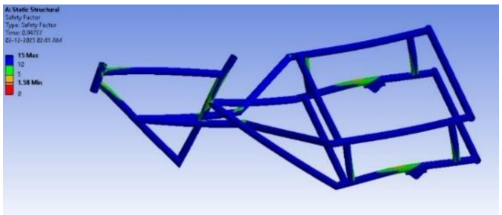

Figure 6: factor of safety

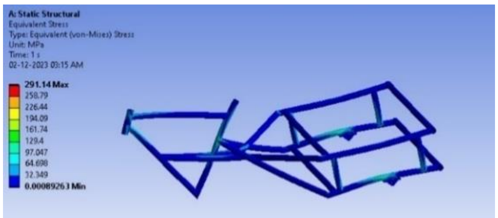

Figure 5: Von mises stress

Figure 6 illustrates the von Mises stress distribution under full load conditions, with the maximum stress of approximately 291 MPa occurring at the rear wheel bearing bracket. This stress level is within the safe limits for AISI 1020, ensuring structural reliability.
Figure 7 depicts the overall factor of safety (FOS) for the structure, with an average FOS of 14 and a minimum FOS of 1.58 observed at the welded joint. Hence, the structure is not only safe but also optimized for lightweight and durable performance, making it well-suited for cargo applications.

Fabrication and manufacturing of cargo cycle

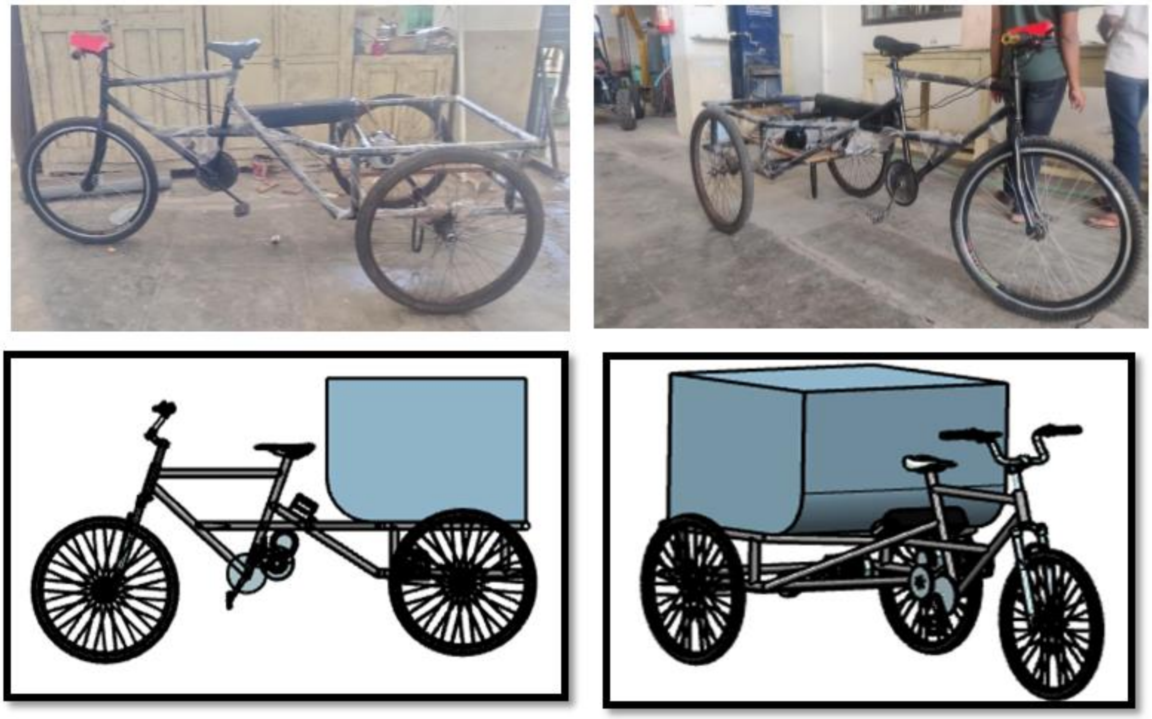

Figure 8: CAD model and fabricated chassis (work in progress)

A set of well-defined constraints guides the fabrication and manufacturing of the cargo cycle frame to ensure optimal performance, safety, and durability while maintaining cost-effectiveness. Weight optimization is achieved by utilizing hollow pipe sections and ensuring uniform weight distribution to enhance handling and performance. The design emphasizes manufacturing feasibility, simplifying the structure to minimize complex bends and welds, and standardizing components to reduce production costs and simplify maintenance. The manufacturing process adheres to environmental regulations for material usage, waste management, and emissions, while the frame design complies with SAE or equivalent standards for cargo cycles.

AISI 1020 steel has been selected for the frame due to its superior combination of strength, machinability, and weldability, meeting industry standards with a yield strength of 350 MPa and tensile strength of 420 MPa. Dimensional parameters include pipe diameters of 31.8 mm and 25.4 mm, with a wall thickness of 1.5 mm, optimized for structural strength and weight reduction. The frame is designed to uniformly distribute a maximum load of 375 kg, including a 250 kg payload, driver weight, and additional components, with a minimum factor of safety (FOS) of 1.5 for all load-bearing sections, particularly at joints and mounting brackets.

CONCLUSION

This paper presents an innovative concept design for a cargo cycle, introducing the digital drive system to enhance vehicle efficiency and rider comfort, particularly in challenging terrains. The integration of an electric generator, which also functions as a flywheel, effectively minimizes torque variations within the system. By eliminating the direct connection of the pedals to the drive mechanism, the design significantly reduces mechanical losses due to the decreased number of moving parts. However, electrical losses are introduced, which represents a key research gap for future exploration.

The design phase is critical in the manufacturing process. Finite element analysis (FEA) conducted in ANSYS demonstrated a maximum deformation of 3.5 mm, well within permissible limits, and a minimum factor of safety of 1.56 under full load conditions. The design considers a safe working load of 375 kg, including a 250 kg cargo capacity. Iterative calculations identified AISI 1020 as the most suitable material for the frame, utilizing pipes with a diameter of 25.4 mm and a wall thickness of 1.5 mm. This material selection ensures an optimal balance of lightweight construction, sufficient strength, and cost-effectiveness, making it ideal for this low-speed vehicle application.

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