

Article

Finite Element Assessment of Single-Track E-Cargo Bike Frames Under Standard-Inspired Fatigue and Impact Loading Conditions

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Abstract

E-cargo bikes have emerged as a promising solution for sustainable urban mobility and last-mile logistics. However, their structural design must ensure durability and safety under demanding cargo transport and daily operating conditions. This study evaluates the structural performance of three single-track E-cargo bike frame typologies, Urban, Long John and Long Tail, using finite element analysis under fatigue and impact loading conditions derived from EN 15194:2020 and EN 17860-2:2024. Numerical models of aluminum 6061-T6 frames were developed to simulate cyclic pedaling, horizontal, seat-post and vertical cargo loading forces, together with falling-frame and falling-mass impact tests. Structural performance was assessed through fatigue life, stress distribution, damage initiation, plastic strain and permanent wheelbase deformation. The Urban and Long John frames satisfied the adopted fatigue-life requirements, whereas the Long Tail frame failed the vertical loading-area fatigue test with a predicted fatigue life of 5.22×10^4 cycles, below the required 2×10^5 cycles. The maximum von Mises stresses during the falling-frame impact test reached 384 MPa, 326 MPa and 356 MPa for the Urban, Long John and Long Tail frames, respectively, while the corresponding permanent wheelbase deformations remained limited to 2.07 mm, 1.97 mm, and 1.43 mm, all below the acceptance criterion. These results highlight the influence of frame geometry and cargo location on structural behavior and support future frame optimization.

Keywords: E-cargo bike; FEA; frame design; urban mobility; bike-sharing; last-mile logistics

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1. Introduction

The popularity of E-cargo bikes in contemporary cities has increased significantly over recent years, primarily as a response to the environmental, spatial, and operational limits of traditional urban transport. These boundaries have been threatened by the rapid growth of e-commerce and the recent concern for sustainability. In the context of transport, sustainability is defined as the safe and efficient satisfaction of mobility needs while minimizing negative impacts, such as excessive resource consumption and

pollution [1,2]. Currently, urban areas contribute to more than 60% of global greenhouse emissions and account for 78% of the world's energy consumption [3]. This poses a substantial threat to climate stability, resulting in an evident necessity for a transition to greener urban environments [4]. Governments have directed efforts towards improving mobility sustainability through incentives for the adoption of zero-emission vehicles [5], aiming to move away from the historical dominance of automobility within urban centers [6] and its long-standing negative impacts [7].

Urban planning models, such as the 15-min city model proposed by Carlos Moreno in 2016, target the environmental fragilities of currently implemented models and provide a structural framework capable of supporting decarbonization agendas [8,9], such as the net-zero commitments by 2050 called for during COP26 [10]. This emerging model promotes sustainable living, social inclusivity and public health [11] by introducing a paradigm shift in urban planning known as “chrono-urbanism”. The core of this philosophy affirms that urban quality of life is inversely proportional to commuting times. Therefore, in a well-planned urban area, all six essential functions (living, working, supplying, caring, learning, and enjoying) are within a 15-min walk or bike ride [12–14]. Reducing travel distances and concentrating local services enhances the feasibility and efficiency of urban transport systems such as last-mile delivery and bike-sharing, allowing them to seamlessly integrate into urban planning [9,15].

Last-mile logistics comprise the final stage of the supply chain, serving as the connection between the final distribution center and the end recipient [16,17]. Factors such as increased urbanization, population growth [18], the expansion of e-commerce [17,19–21], changing consumer expectations [19], continuous innovation in logistics systems [22] and a growing focus on sustainability [19,23] have collectively contributed to the acceptance of last-mile systems as a viable option. Boyer et al. [24] identified the last mile as one of the most expensive, inefficient, and polluting segments of the supply chain, typically characterized by short routes, low average speeds and frequent starts and stops. This leads to a high cost-per-kilometer ratio, accounting for up to 75% of total supply chain costs [25]. Consequently, the efficiency of last-mile systems is sensitive to external variables such as customer density [26], traffic conditions [27] and parcel characteristics [28], resulting in a highly context-dependent system performance [26]. In fact, the randomness of urban dynamics presents a constant challenge to these systems, as last-mile delivery depends on urban traffic dynamics, requiring careful coordination to minimize congestion [29]. Conventional trucks and delivery vans face several constraints such as restricted street accessibility and a deficit of on-street loading zones (OLZs) [30]. The deployment of E-cargo bikes eliminates the majority of these performance barriers while simultaneously addressing the sector's contributions to greenhouse gas emissions [29], air pollution [19] and noise pollution [23]. In the last-mile logistics context, E-cargo bikes significantly outperform conventional delivery means [31] due to their ability to operate in restricted zones, navigate narrow streets, and utilize pedestrian or cycling infrastructure to bypass congestion [25,32–34]. Research indicates that over 40% of all urban deliveries could be executed via E-cargo bikes [35] and that 20% of freight demand can be delivered using E-cargo bike exclusive distribution schemes [36]. This transition results in faster service along with a more positive perception from modern clients who prioritize the adoption of environmentally friendly transportation modes that reduce emissions, noise and vibration [25]. Despite these advantages, perceived limitations such as load capacity and speed are often cited as impediments to adoption. However, recent studies, such as [37], concluded that reduced speed is not an operational impediment in urban areas and identified a 200 kg maximum load cargo bike as the optimal vehicle for these requirements, outperforming both small vans and several other bicycle configurations.

The necessity for high-capacity E-cargo bikes extends significantly beyond commercial logistics. Addressing urban car dependency is a fundamental theme in sustainable development. In this context, a primary barrier to car disposal is the superior cargo-carrying capacity of private vehicles, which remains unmatched by conventional bicycles or public transport [38]. Private car owners often have the necessity to transport children, groceries and varied goods [39,40]. In practice, urban mobility is characterized by “trip chains” such as leaving the kids in school before commuting to the workplace and grocery shopping when returning. To effectively incentivize a reduction in car use, a sustainable alternative must fulfil every purpose within these mobility chains [38]. Bike-sharing systems are network-based shared mobility services that provide short-term access to bicycles, promoting sustainable transport and contributing to improved urban mobility [41]. Within proximity-based urban planning, bike-sharing systems offer a highly viable alternative for short urban trips, providing easy access to various bike typologies without the need for ownership, while contributing to the reduction in private automobile reliance for such journeys [15,33,42]. The integration of electric and cargo bikes has significantly increased the attractiveness of these systems [43,44], presenting an alternative for light freight transport [45]. E-cargo bike sharing addresses a specific void in urban mobility by allowing transportation of heavy or bulky loads. As these transport needs are often occasional, this aligns closely with the operational logic of bike-sharing systems, which are most convenient for users who do not require a specific transport mode on a daily basis [33,42]. Furthermore, it enables individuals without a driving license to move heavy loads independently [33]. Additionally, the reduced prices of shared systems make utility transportation accessible across all socio-economic classes [46].

During the development of bicycles, finite element analysis has become one of the primary tools for evaluating frame structural performance during the design stage, allowing engineers to investigate stress distributions, deformation patterns, fatigue resistance and weight reduction before prototype manufacturing. Despite these advances, few studies have focused specifically on single-track e-cargo bicycles.

This study evaluates the structural performance of three single-track E-cargo bike frame typologies under EN 15194:2020 [47] and EN 17860-2:2024 [48] inspired fatigue and impact loading conditions using finite element analysis, identifying critical load cases, typology-dependent stress concentrations, and design implications for last-mile logistics and shared urban mobility applications.

2. Materials and Methods

The objective of this study was to evaluate and compare the structural performance of three single-track E-cargo bike frame typologies under loading conditions derived from single-track cycle standards. To achieve this, numerical simulations were conducted using finite element analysis to assess the response of Urban, Long John and Long Tail frame configurations under both fatigue and impact loading scenarios. This section first presents cargo-bike typologies and the requirements established in the standard. Subsequently, the material properties, geometric simplifications and finite element modelling procedures adopted for the numerical analyses are described. The fatigue and impact simulation methodologies are then detailed, followed by the evaluation criteria used to assess numerical compliance with the standard and the mesh sensitivity study performed to verify the numerical models.

2.1. Frame Typologies and Geometrical Assumptions

When developing a new bike prototype, one of the most critical components to address is the frame. It is typically described as the main component of the bicycle, determining its size, strength, and capacity to integrate other components while ensuring safety

during use [49,50]. It also has a significant impact on the comfort of the rider as it determines the riding position [51], an attribute highly important in the context of prolonged rides such as in the case of last-mile delivery.

E-cargo bike frames feature various configurations designed for distinct purposes and to accommodate diverse contexts. These variations exist mainly due to factors such as cargo weight and volume, urban topography, and the intended use of the vehicle [52] which translates into differences in the number of wheels, overall width and cargo capacity [53,54]. Resulting from the different contexts and requirements, E-cargo bikes have several distinct typologies. They are commonly categorized as Urban (Messenger), Long John (front-load cargo bicycle), Long Tail (rear-load cargo bicycle), and trikes (front- or rear-load cargo tricycles) [34]. Recently, and with the aim of increasing maximum cargo capacity and efficiency, categories such as quads (quadracycles) have emerged. Figure 1 displays some of the most widely used cargo bicycle typologies as well as their typical cargo allocation areas and drive systems.

Urban or messenger bikes are two-wheeled bicycles featuring a frame geometry similar to conventional electric models equipped with accessories that enable cargo transport. Cargo racks are typically mounted on the head tube of the bike and/or behind the saddle and on top of the rear wheel. Their maximum cargo capacity is generally limited 40 to 70 kg when loaded [55], which can compromise stability, especially at low speeds [56].

Long Tail bikes are two-wheelers with a similar geometry to Urban bikes but with longer stays. This extension serves to accommodate the cargo, which is fitted between the rider and the rear wheel. They are indicated for the transport of children and non-voluminous cargo [53,54] and have a cargo payload of around 50 kg of cargo [56]. The placement of the cargo results in a relatively high and closer to the rear axle center of gravity (COG).

Long John bikes, similarly to the Long Tail typology, are two-wheelers in which the cargo area is located between the rider and the front wheel [56]. They are ideal for the transport of children and moderately sized cargo given their large cargo area [53,54]. These vehicles are the most adopted cargo-specific typology in both private use and parcel delivery operations [30]. They can usually carry up to 120 kg of cargo [56], but some models can accommodate up to 150 kg [57,58]. Its weight distribution allows for a low COG situated closer to the front axle, alongside a longer wheelbase [59].

Trikes are three-wheelers that offer increased stability and cargo capacity, making them suitable for the transport of heavier and bulkier cargo [34]. They are available in two main configurations: front-loading (tadpole) and rear-loading (delta) [59]. Rear-loading configurations typically allow for greater payload volume and weight, while also preserving the rider's field of view compared to front-loading designs [30,56]. Due to their enhanced stability and ability to accommodate Euro-pallet-sized cargo, trikes are particularly well-suited for last-mile logistics applications [30].

Quads are four-wheelers designed for specific urban contexts. Although they hold great potential for sustainable urban mobility, especially in last-mile logistics, they are still uncommon in urban centers [60] as they have only recently been introduced to the market [56]. Their size can make them unviable for certain operational scenarios, yet they remain a highly sustainable alternative for last-mile delivery, particularly for heavy and bulky parcels.

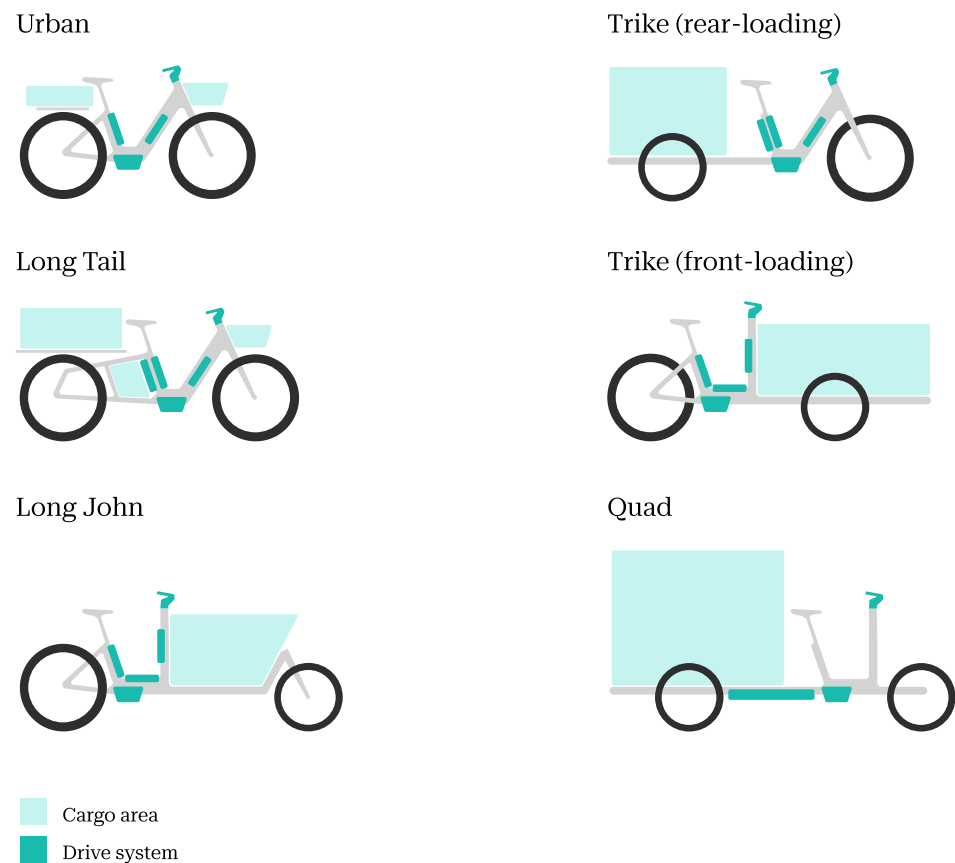


Figure 1. Cargo bike typologies representation.

When discussing the safety of cargo bikes, several cargo-related concerns arise, especially when considering single-track vehicles, such as Urban, Long Tail and Long John typologies. Cargo bikes, with or without a load, should be easily controllable and safe so that riders can focus on their surroundings [61]. Key safety indices include low-speed stability, hard braking, acceleration, maneuvering and obstacle impact response [59,62]. The greatest impacts on the vehicle's performance in these metrics depend on the frame geometry, cargo position, wheelbase and wheel size, which collectively dictate the position of COG.

Low-speed stability refers to the lowest speed a bicycle must maintain in a straight line in order to remain stable. An unstable bike can be perceived as twitchy and nervous, where any small disturbance to the front of the bike can easily be amplified [63]. In their study, ref. [59] found that larger wheels lead to a lower minimum speed for self-stability. They concluded Long Tail bikes are the better performers in this metric and Long Johns the worst, thereby suggesting that the wheelbase has no relation to low-speed stability.

The effects of hard braking and acceleration are very similar, albeit mirrored. Acceleration shifts weight towards the rear wheel, while deceleration shifts weight towards the front wheel. Both reactions are highly dependent on the weight distribution of the cargo bike. Excessive braking or acceleration can cause a wheel to lose traction and potentially lead to an accident. The general consensus is that a longer wheelbase results in better performance across both metrics. Additionally, a lower center of mass is preferred in both cases. A front-leaning COG prevents rotation around the rear axle during acceleration, whereas a rear-leaning COG prevents rotation around the front axle upon sudden braking. Conversely, opposite effects are noted in opposing configurations. Unloaded Long Johns excel across these metrics given their longer wheelbase and their low, relatively longitudinally centered COG. The addition of cargo further lowers the position of the COG and in consequence improves even further the performance in braking and accelerating. In contrast, the addition

of cargo on Long Tails and potential rear racks on Urbans acts negatively on acceleration, as it shifts the COG to the rear [59]. A high acceleration capacity is beneficial for self-stability as it allows for a higher speed to be achieved more easily [64].

Maneuvering is defined as the ease with which a rider can control and execute turns with the bike during steady-state turning. During cornering, dynamics differ significantly from linear dynamics. For instance, handlebar torque is one of the main results of turning. Higher handlebar torque increases the minimum radius required for stable turning. A smaller wheelbase and lower overall weight greatly reduce handlebar torque and therefore result in superior turning performance [62]. Handlebar torque depends on the front wheel size, overall weight distribution, head-tube angle and trail length [65]. Long John bikes perform poorly in such tests, especially with the addition of cargo, which can be explained by the smaller front wheel. Long Tail bikes yield relatively good results, even when loaded, yet remain far from the agility provided by Urban bikes, making them great options when maneuvering through narrow or crowded streets [59].

When riding, cyclists often encounter obstacles. Any obstacle can potentially destabilize the bike as the front wheel starts to roll over it. An impact with a pothole, road hump or step can exert immense force on the frame and consequently the rider [59,66]. A significant number of cycling accidents occur due to obstacle collisions [67]. Smaller wheels are detrimental in this regard, as they demand a substantially higher force to overcome such obstacles. Therefore, Long Johns and small-wheeled Urbans tend to perform poorly in these scenarios. The addition of cargo tends to further intensify the effects of such impacts, especially on Long Johns [59]. It is important that an E-cargo bike is designed with its operational context in mind and that rider safety and comfort are prioritized. Cargo allocation is also a critical factor, since it significantly increases the vehicles' weight and greatly affects its overall performance.

2.2. EN 15194:2020 and EN 17860-2:2024 Loading Cases

In order to properly evaluate a frame's viability for the market, it must undergo a standardization process. Standards such as EN 15194:2020 [47] and EN 17860-2:2024 [48] provide requirements and test methods for the various mechanical, functional and operational aspects of single-track cycles. These tests are designed to simulate as closely as possible the real-world use scenarios that the vehicle might encounter. For the frame specifically, these procedures simulate critical operational conditions. Some of these evaluate high-impact force situations, such as hitting a wall, hitting a curb or dropping off a curb, while others simulate the long-term fatigue effects of regular operation, such as pedaling and hitting small bumps. Additionally, multi-track vehicles are tested for their likelihood of overturning. This study focuses on the standards directed towards single-track vehicles, specifically Urban, Long John and Long Tail typologies.

Different typologies exhibit different operational contexts and specific dynamics and therefore require different test methods. However, some aspects of frame testing remain consistent across most bicycles, resulting in standardized testing methods across different categories. This is the case for four of the six tests explored in this study, while the remaining two are distinguished by being exclusive to Urban and Cargo models, respectively. Table 1 shows the test distribution.

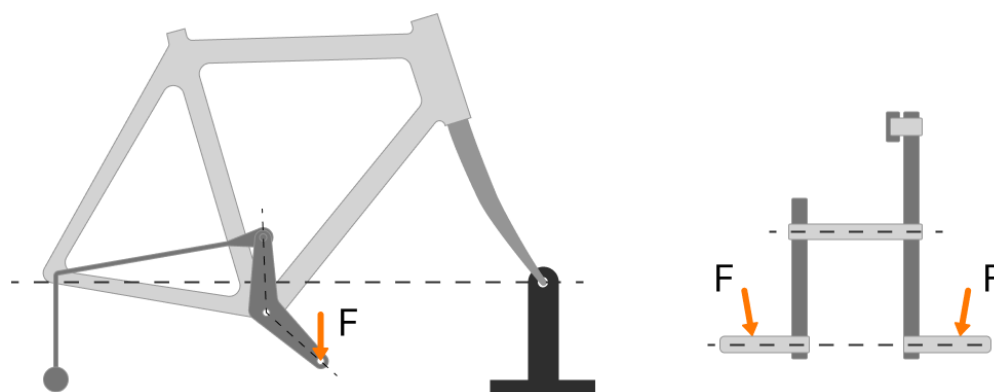
Table 1. Distribution of fatigue and impact tests among the Urban, Long John and Long Tail frame typologies according to the standards.

Test Title	Urban	Long John/Long Tail
Dynamic test with pedaling forces	Yes	Yes
Dynamic test with horizontal forces	Yes	Yes
Dynamic test with vertical forces onto the seat-post	Yes	Yes
Dynamic test with vertical forces onto the loading area ¹	No	Yes
Impact test (falling frame)	Yes	Yes
Impact test (falling mass) ²	Yes	No

¹ Long John and Long Tail specific; ² Urban specific.

2.2.1. Dynamic Test with Pedaling Forces

This test configuration simulates the frame's long-term fatigue induced by the pedaling forces exerted by the rider during regular operation. A cyclic load F , the magnitudes of which are specified in Table 2, is alternately applied to the left and right pedals. To represent the boundary conditions accurately, the rear axle is constrained via a ball joint feature, while the front axle is restricted to rotational freedom about its own axis. Its preparation is similar for all cycle types, adhering to the standardized methodology illustrated in Figure 2.

**Figure 2.** Dynamic test with pedaling forces methodology representation.**Table 2.** Load values according to the standard—Pedaling forces.

	Urban	Long John	Long Tail
Load (N)	1000	1200	1200

To satisfy the requirements of the standard, the frame must withstand 200,000 loading cycles, with no visible cracks or structural failures permitted upon inspection.

2.2.2. Dynamic Test with Horizontal Forces

This test configuration simulates the long-term structural fatigue accumulated over the frame's lifespan due to repetitive, weak front wheel impacts. An alternating horizontal load, F , the magnitudes of which are detailed in Table 3, is applied to the front axle. Regarding the boundary conditions, the rear axle is constrained to allow rotational freedom exclusively about its own axis, whereas the front axle is restricted to horizontal movement. The setup process is identical for all cycle typologies, following the specified methodology of the standards shown in Figure 3.

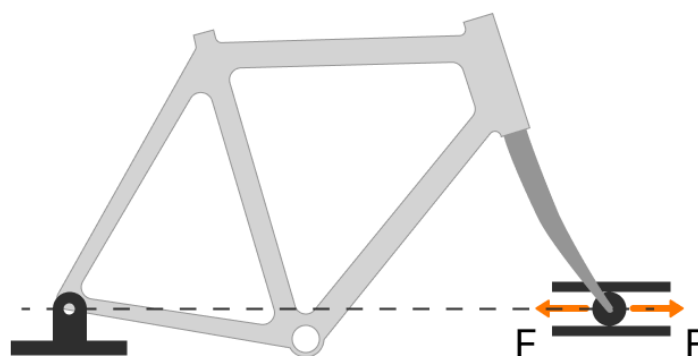


Figure 3. Dynamic test with horizontal force methodology representation.

Table 3. Load values according to the standard—Horizontal forces.

	Urban	Long John *	Long Tail *
Load (N)	500	If $m \leq 120$ kg, $F = \pm 500$ If $m > 120$ kg, $F = \pm \left(\frac{m}{120}\right) \times 500$	If $m \leq 120$ kg: $F = \pm 500$ If $m > 120$ kg: $F = \pm \left(\frac{m}{120}\right) \times 500$

* Vehicles with high/forward COG.

To satisfy the requirements of the standard, the frame must withstand 200,000 loading cycles, with no visible cracks or structural failures permitted upon inspection.

2.2.3. Dynamic Test with a Vertical Force onto the Seat-Post

This test configuration simulates the long-term fatigue of rider and seat interactions on the frame over its lifespan. A cyclic, vertically downward load, F , the magnitudes of which are specified in Table 4, is applied to a dummy seat-post inserted to a depth of 75 mm within the seat tube. Regarding the boundary conditions, the front axle is restricted to horizontal movement. For Urban frames, the rear axle is constrained to permit rotation solely about its own axis; however, for the Long John and Long Tail typologies, the rear axle is fixed utilizing a ball joint. The setup details are illustrated in Figure 4.

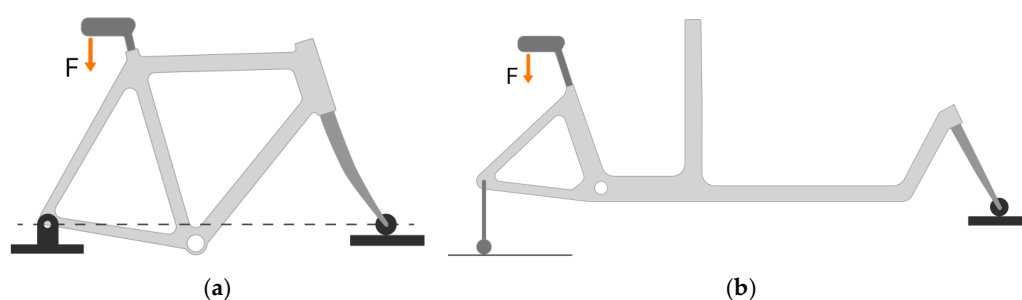


Figure 4. (a) Dynamic test with a vertical force onto the seat-post methodology representation for the Urban typology; (b) Dynamic test with a vertical force onto the seat-post methodology representation for the Long John and Long Tail typology.

Table 4. Load values according to the standard—Vertical forces onto the seat-post.

	Urban	Long John	Long Tail
Load (N)	1100	1200	1200

To satisfy the requirements of the standard, the frame must withstand 100,000 loading cycles, with no visible cracks or structural failures permitted upon inspection.

2.2.4. Dynamic Test with Vertical Forces onto the Loading Area

This test configuration simulates the long-term structural fatigue induced by cargo loading and transport over the frame's operational lifespan. This evaluation is exclusive to the Long John and Long Tail typologies, as the Urban typology does not feature a designated, integrated cargo area. A cyclic load, F , is applied to the frame's cargo platform as central as possible. The load is calculated as shown in Equation (1) and according to the values specified in Table 5.

$$F = 2 \times g \times m_{pl} \quad (1)$$

where F is the applied vertical load (N), m_{pl} is the maximum permissible payload (kg), and g is the gravitational acceleration, 9.81 m/s².

Table 5. Maximum permissible payload specified by the manufacturer.

	Urban	Long John	Long Tail
m_{pl} (kg)	90	175	230

Regarding the boundary conditions, the rear axle is constrained utilizing a ball joint, whereas the front axle is restricted to horizontal displacement. The testing setup and loading configuration adhere to the standardized methodology illustrated in Figure 5.

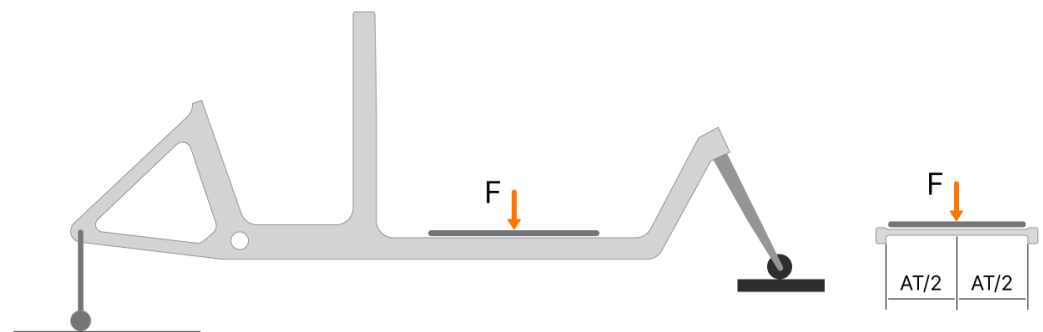


Figure 5. Dynamic test with vertical forces onto the loading area methodology representation.

To satisfy the requirements of the standard, the frame must withstand 200,000 loading cycles, with no visible cracks or structural failures permitted upon inspection.

2.2.5. Impact Test (Falling Frame)

This test evaluates permanent structural deformation of the frame resulting from the drop of the frame when loaded with rider and cargo equivalent masses. The frame is equipped with a fork and a roller and masses are coupled to the structure at designated positions to simulate operational loading. Prior to testing, the wheelbase dimension is recorded. The assembly is then elevated to a specified drop height and released for n consecutive drops. Following the completion of all impact cycles, the wheelbase is re-measured to determine its deformation relative to its initial value. The testing setup and loading configuration adhere to the standardized methodology illustrated in Figure 6 and the specific parameters and evaluation criteria for this test methodology are detailed in Tables 6 and 7.

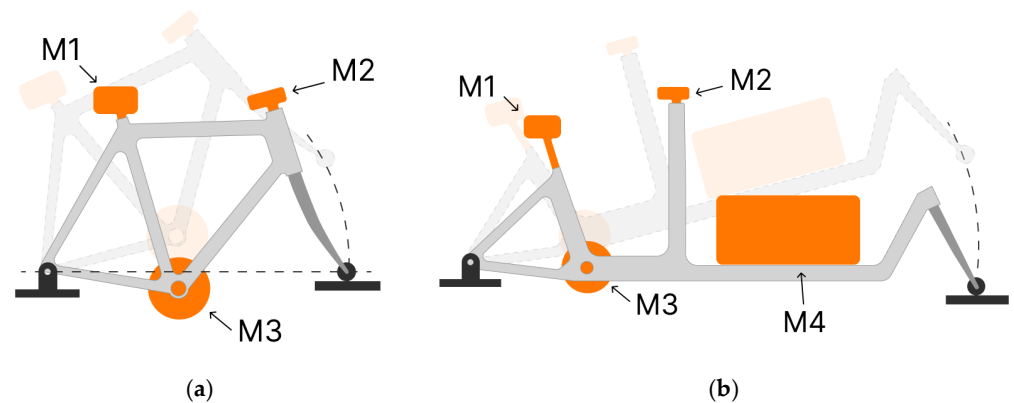


Figure 6. (a) Impact test of a falling frame's methodology representation for the Urban typology; (b) Impact test of a falling frame's methodology representation for the Long John and Long Tail typology.

Table 6. Impact test definition—Falling frame.

	Urban	Long John	Long Tail
Drop height (mm)	300	150	150
number of drops (n)	2	3	3
Maximum wheelbase deformation (mm) *	10	100	100

* With a dummy fork.

Table 7. Added masses according to the standard.

	Urban	Long John	Long Tail
M1 (kg)	30	30	30
M2 (kg)	10	2 × 10	2 × 10
M3 (kg)	50	50	50
M4 (kg)	n/a	Manufacturer value	Manufacturer value

2.2.6. Impact Test (Falling Mass)

This Urban-specific test evaluates the permanent structural deformation of the frame resulting from a falling mass impact, which simulates a hard shock to the front wheel. The frame is equipped with a fork and a roller and is mounted vertically with the rear axle constrained to permit rotation exclusively. Initially, a mass is positioned on the roller to record the starting wheelbase. Subsequently, the mass is elevated to a specified drop height and released onto the roller. Following the impact, the wheelbase is re-measured and in order to comply with the requirements of the standard, the wheelbase deformation must not exceed 10 mm when utilizing a dummy fork. The testing setup and loading configuration adhere to the standardized methodology illustrated in Figure 7 and the specific parameters and evaluation criteria for this test methodology are detailed in Table 8.

Table 8. Load values according to the standard—Falling mass.

	Urban
Mass (kg)	22.5
Drop height (mm)	360
Maximum wheelbase deformation (mm) *	10

* With a dummy fork.

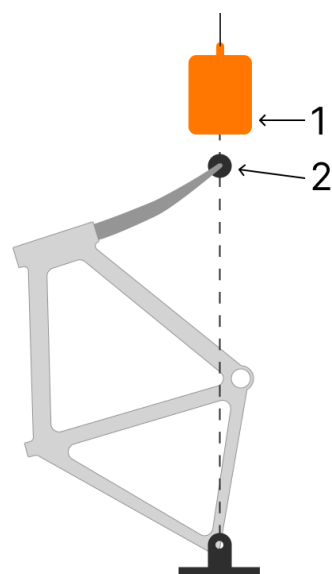


Figure 7. Impact test of a falling mass's methodology representation.

2.3. Material Model and Weld Assumptions

The evaluated frames are projected to be manufactured from Aluminum 6061-T6 alloy. During manufacturing, the individual tubular components are joined by welding using a compatible filler material. Welding locally alters the microstructure of the base material through the formation of heat-affected zones (HAZ), while the weld geometry introduces stress concentrations that may reduce fatigue resistance. In the present study, the completed frames were assumed to undergo post-weld heat treatment to recover the bulk mechanical properties of the 6061-T6 alloy. Consequently, the numerical models were simplified as continuous solid bodies with homogeneous material properties, neglecting the local geometric effects of weld toes and weld roots as well as residual stresses generated during welding.

This modelling approach may overestimate the absolute fatigue life because welded joints introduce local stress concentrations that promote fatigue crack initiation. According to the IIW Recommendations for Fatigue Design of Welded Joints and Components [68], welded joints generally exhibit lower fatigue resistance than unwelded base material due to local notch effects and residual stresses. Therefore, the fatigue predictions presented in this study should be interpreted as representative of the idealized frame geometry rather than the exact fatigue performance of the manufactured structure. Nevertheless, because of the identical material assumptions, modelling procedures and loading conditions, the comparative assessment between the Urban, Long John and Long Tail configurations is expected to remain valid, although the absolute fatigue lives would likely decrease if weld-specific fatigue assessment methods were employed. Future work should incorporate weld modelling and experimental validation to quantify these effects.

The material's elastic properties are displayed in Table 9.

Table 9. Aluminum 6061-T6 elastic properties.

Property	Definition
Density	2700 kg/m ³
Yield stress	275 MPa
Ultimate tensile strength	310 MPa
Young's Modulus	69 GPa
Poisson's Ratio	0.33

For the plastic behavior definition, von Mises yield criterion was used along with a Tabular isotropic hardening plasticity model. The plastic curve was defined using true stress and equivalent plastic strain, as required by Abaqus 2025. Therefore, the tabulated stress values are not directly comparable with the ultimate tensile strength reported in Table 10.

Table 10. Aluminum 6061-T6 alloy plastic behavior.

Yield Stress (MPa)	Plastic Strain
275	0
275.8	0.006
277.2	0.011
282.7	0.016
296.5	0.026
310.3	0.035
324.1	0.055
344.7	0.075
355.8	0.085

The fatigue analysis was performed using the Brown–Miller strain-based critical plane algorithm with Morrow mean stress correction. The fatigue parameters used for Aluminum 6061-T6 were taken from the 3DEXPERIENCE/SIMULIA DS-ElasticFatigue AL 6061-T6 Extrude material definition available in the Material Browser and are listed in Table 11. Since these parameters correspond to software-supplied material data, they were used as input values for comparative numerical assessment and should not be interpreted as experimentally measured properties of the specific frames analyzed in this study.

Table 11. Aluminum 6061-T6 alloy fatigue properties.

Property	Definition
Cyclic strain hardening coefficient (K')	311.5 MPa
Cyclic strain hardening exponent (n')	0.03
Constant amplitude endurance limit reversals ($2n_f$)	2×10^8
Fatigue ductility coefficient (E_f')	12.243
Coffin–Manson fatigue ductility exponent (c)	−1.164
Fatigue strength coefficient (S_f')	802.9 MPa
Basquin’s fatigue strength exponent (b)	−0.13

Additionally, the Roller and Ground objects have different materials, S235 and AISI 1035, respectively. The Ground object is deformable while the Roller was deemed as rigid. The materials’ elastic properties are displayed in Table 12.

Table 12. S235 and AISI 1035 elastic properties.

Property	S235	AISI 1035
Density	7850 kg/m ³	7870 kg/m ³
Yield stress	235 MPa	370 MPa
Ultimate tensile strength	360 MPa	585 MPa
Young’s Modulus	210 GPa	210 GPa
Poisson’s Ratio	0.3	0.3

2.4. Finite Element Model

To enhance frame performance and reliability while maintaining a relatively low weight, it is essential to conduct a structural evaluation using Finite Element Analysis (FEA). This numerical method enables the approximation and analysis of complex

physical systems by subdividing them into smaller subdomains [69]. Through this approach, highly complex engineering problems can be resolved, being limited primarily by the available computational capacity [70]. Several studies have addressed optimization techniques to achieve better performance of bicycle frames [71,72].

The simulations in this study were conducted using 3DEXPERIENCE's platform version HotFix 3.26. The initial 3D models of the frames were provided by LightMobie and subsequently prepared for numerical analysis in SOLIDWORK's platform version 2024. To minimize both preprocessing time and computational runtime, several geometric simplifications were implemented.

A range of 5 to 7 evaluation points were selected across identical locations on each frame to extract relevant stress values. These points correspond to the common high-stress zones identified throughout the testing configurations and are illustrated in Figure 8.

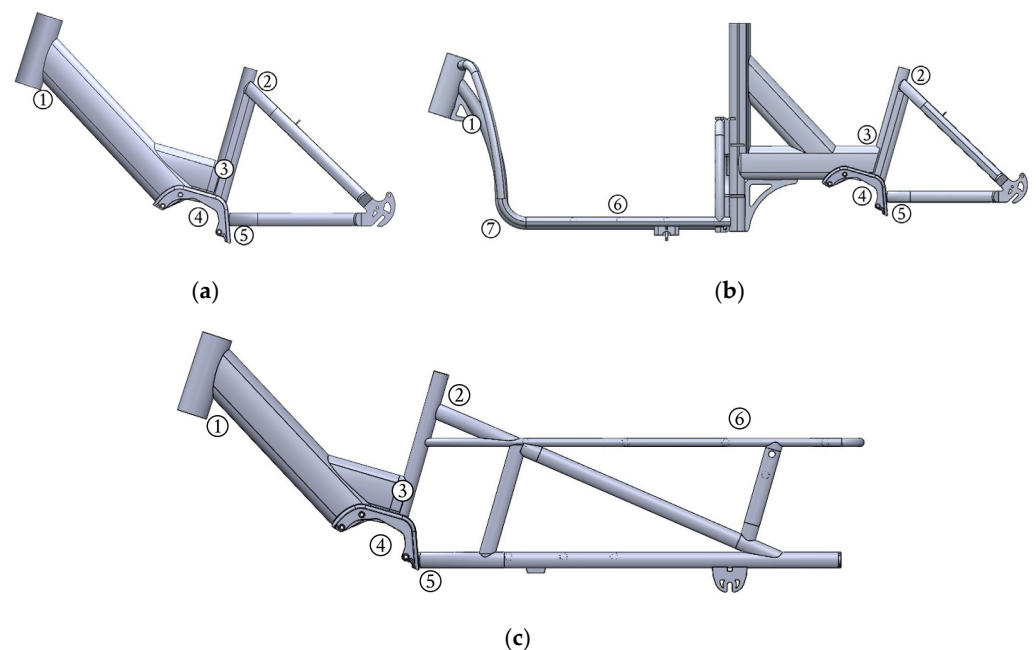


Figure 8. (a) Urban common high-stress zones; (b) Long John common high-stress zones; (c) Long Tail common high-stress zones.

2.5. Fatigue Analysis Procedure

For the static simulation configurations, the assemblies comprised exclusively the frame and the fork. The fork was constrained in position to remain centered relative to the head tube and oriented directly forward. Additionally, the models incorporated 2D and 3D reference sketches to define force application points and key geometries. These marked positions include the rear wheel ground contact point, the rear and front axle centers, the electric motor center, the pedal location, the seat location and the handlebar connection point. Figure 9 illustrates the geometric models developed for the static simulations.

Using the 3DEXPERIENCE plugin within SolidWorks 2024, the assemblies were exported to the platform, where a new project was initiated within the Mechanical Scenario Creation application where the tests are developed and simulated using the Abaqus 2025 solver.

After project initiation, the primary step consisted of generating finite element meshes for each individual component and assigning their respective section and material properties. The specific parameters of the meshes are detailed in Table 13.

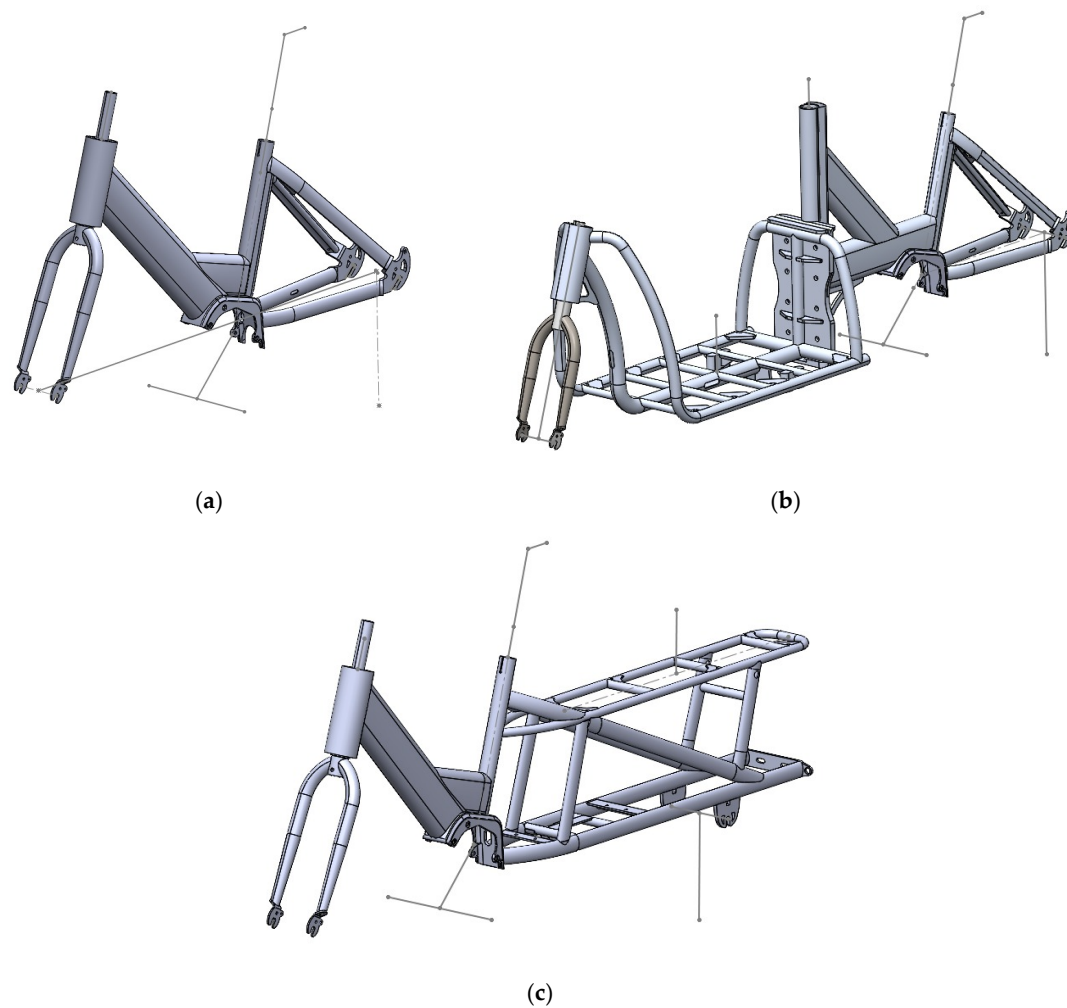


Figure 9. (a) Urban model developed for the static tests; (b) Long John model developed for the static tests; (c) Long Tail model developed for the static tests.

Table 13. Static simulation model's mesh and section characteristics.

Part	Element Type	Element Size	Material
Frame	C3D4	3 mm, 1.75 mm and 1.25 mm	Al 6061-T6
Fork	C3D4	5 mm	Al 6061-T6

Following mesh generation, a coupling tool was utilized to establish a rigid connection between the fork and the head tube. Finally, the dummy fork object was defined as a rigid to ensure the accurate transmission of test effects directly onto the frame.

To simulate the dynamic test with pedaling forces, two distinct general analysis cases and corresponding static steps were established, each representing the force exerted on an individual pedal. In each case, a remote load was applied in accordance with the standard's specifications. Regarding boundary conditions, the rear axles were constrained using ball joint features, whereas the front axles were restricted to rotation about their respective axes using fixed displacement constraints. Figure 10 presents the load cases developed for the Urban typology.

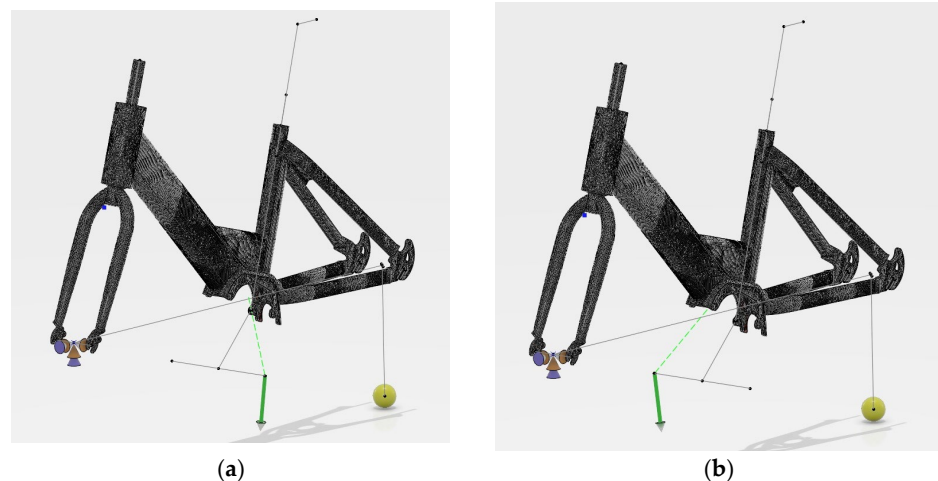


Figure 10. (a) Left pedal case; (b) Right pedal case.

Following the configuration of these static load cases, a Durability Case was established to evaluate the fatigue performance of the structure under cyclic loading. The fatigue loading feature was used to construct the alternating stress cycles, sequencing between the left and right pedal steps.

2.6. Explicit Dynamic Impact Analysis

The impact tests required a distinct methodology due to the inherent complexity of accurately replicating impact phenomena within static simulations. When preparing the 3D models for these simulations, additional parts such as a roller and a ground plane were incorporated into the assembly. Similarly to the static configuration, 2D and 3D reference sketches were integrated to identify mass application points and key geometries. These include the rear wheel ground contact point, the rear and front axle centers, the electric motor center, the pedal location, the seat position and the handlebar connection point. Furthermore, the assembly was configured such that the simulation initiated immediately prior to contact, thereby reducing simulation runtime. Figure 11 illustrates the geometric models developed for the dynamic simulations.

After exporting the 3D models, a separate project was initiated within the Mechanical Scenario Creation application. The finite element mesh was similarly configured to the static test setup, with the specific parameters detailed in Table 14. Four-node linear tetrahedral (C3D4) elements were adopted for the frame models because they provide a robust and computationally efficient discretization for the complex frame geometries evaluated in this study. During preliminary model development, robust convergence could not be consistently achieved with higher-order tetrahedral formulations, particularly in the explicit impact simulations. Therefore, C3D4 elements were selected to ensure stable solution convergence while maintaining a consistent modelling strategy for all frame typologies. To reduce the influence of the lower-order formulation on stress predictions, a mesh convergence study was performed and local mesh refinement was applied in regions exhibiting high stress gradients.

The roller and ground were introduced exclusively to reproduce the standardized impact configuration. Although nominal steel materials (S235 and AISI 1035) were assigned during model preparation, these components were not the objects of the structural assessment, which focused exclusively on the bicycle frame.

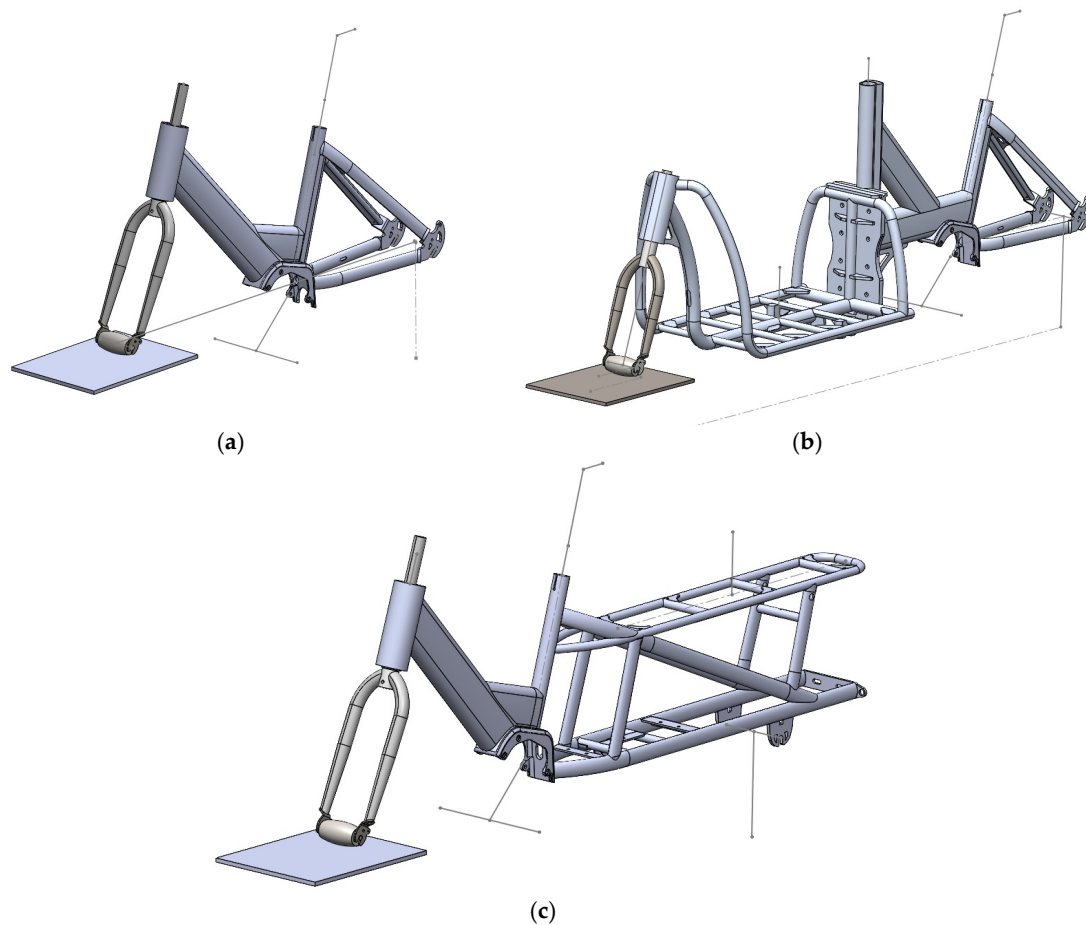


Figure 11. (a) Urban model developed for the dynamic tests; (b) Long John model developed for the dynamic tests; (c) Long Tail model developed for the dynamic tests.

Table 14. Dynamic simulation model's mesh and section characteristics.

Part	Element Type	Element Size	Material
Frame	C3D4	3 mm, 1.75 mm and 1.25 mm	Al 6061-T6
Fork	C3D4	5 mm	Al 6061-T6
Roller	C3D4	5 mm	S235
Ground	C3D4	10 mm	AISI 1035

Following mesh generation, a coupling tool was utilized to establish rigid connections between the elements specified in Table 15. Finally, both the dummy fork and the roller were defined as rigid bodies to ensure the accurate transmission of the impact forces directly onto the frame.

Table 15. Coupling parts and type.

Part 1	Part 2	Coupling Type
Frame	Fork	Distributing
Fork	Roller	Distributing
Handlebar mass point	Frame	Distributing
Seat mass point	Frame	Distributing
Motor mass point	Frame	Distributing
Cargo mass point *	Frame	Distributing

* Long John and Long Tail.

For this simulation, a general analysis case was created utilizing an explicit dynamic step. Given that the simulation was initialized immediately prior to the instant of impact, an initial velocity was applied to all components with the exception of the ground plane. These rotational velocities, the values of which are presented in Table 16, were determined by resolving the total momentum of the assembly at its COG to calculate the pre-impact velocity, which was subsequently converted into an angular velocity around the rear. Point inertias were utilized to replicate the additional loads distributed across the frame. These were applied at the handlebar, seat, electric motor and cargo mass reference points and rigidly coupled to the adequate frame faces. The boundary conditions comprised a hinge constraint at the rear axle and a clamp constraint applied to the bottom face of the ground plane to restrict movement and rotation while permitting contact interactions and localized deformation. Gravitational acceleration was also incorporated to replicate real-world conditions accurately.

Contact was defined with a friction coefficient of $\mu = 0.05$ and a damping coefficient of 1×10^{-6} . These values were adopted to ensure stable contact interactions during the explicit analysis. The low friction coefficient represents a nearly frictionless contact interface, providing smooth contact enforcement while avoiding the numerical instabilities that may arise from a perfectly frictionless formulation. In addition, this simplification facilitates the interaction between the roller and the ground by allowing the roller to slide rather than roll, thereby avoiding the need to model rolling kinematics while preserving the intended impact loading transferred to the bicycle frame. The small damping coefficient was introduced solely to suppress high-frequency numerical oscillations associated with the contact algorithm, improving solution stability without significantly influencing the global structural response. Finally, mass scaling was employed to increase the stable time increment and reduce the computational cost of the explicit dynamic analysis. The applied mass scaling was selected conservatively to improve computational efficiency while minimizing artificial changes to the inertial response of the model. Since the objective of this study is to evaluate the comparative structural response of the bicycle frame configurations under impact loading, rather than to reproduce the detailed contact and post-impact dynamics of the roller, the adopted values for the friction coefficient, numerical damping coefficient, and mass scaling were regarded as modelling simplifications intended to improve computational robustness and efficiency, while their influence on the predicted structural response was considered negligible. The reliability of these modelling assumptions was verified through the energy balance of the explicit analysis. The total energy remained nearly constant throughout the simulation, exhibiting a variation of less than 1%, while the kinetic energy was progressively converted into internal energy as the impact energy was absorbed by the frame. Furthermore, the artificial energy remained equal to zero during the entire simulation, indicating that the adopted numerical parameters did not introduce significant numerical artifacts or adversely affect the predicted structural response. Figures 12 and 13 expose the total energy and the internal energy plots over time of the Urban typology. The remaining typologies presented similar behaviors.

Figure 14 illustrates the scenario developed for the Long John typology and Table 16 presents the details of the tests.

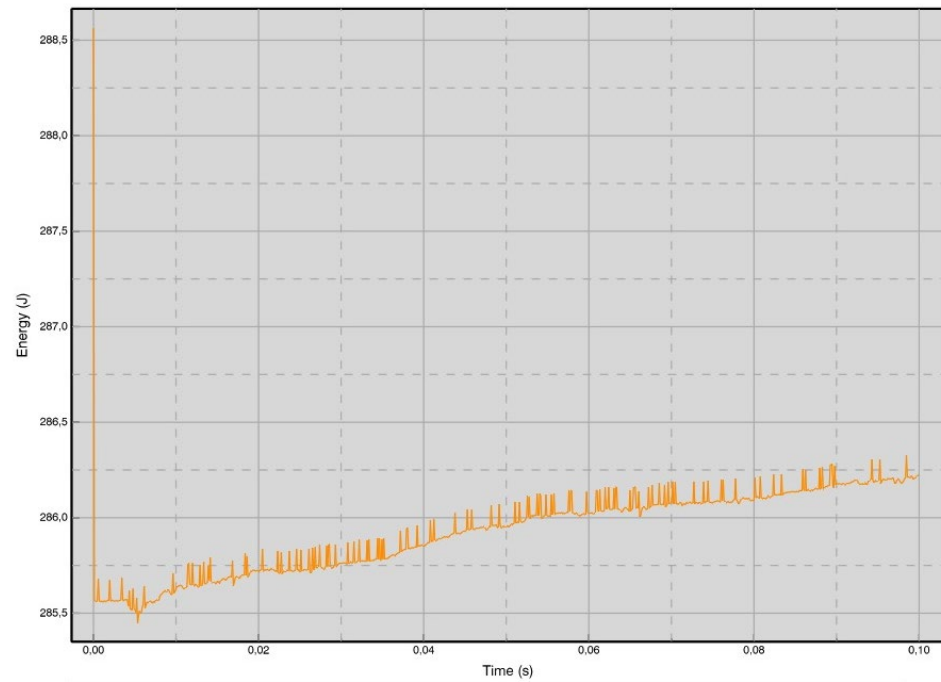


Figure 12. Total energy/time plot.

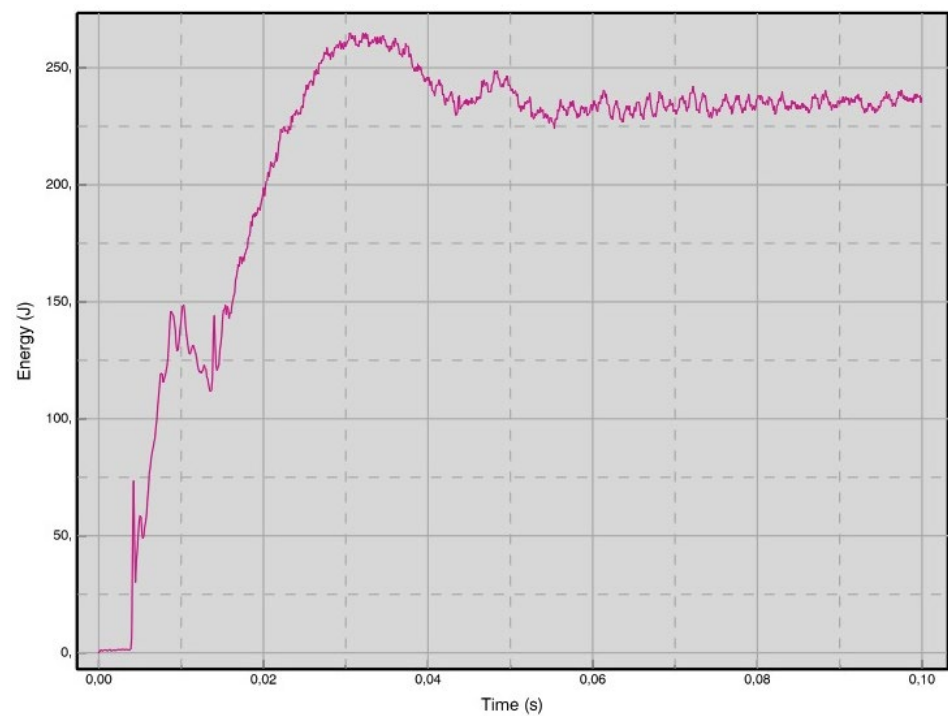


Figure 13. Internal energy/time plot.

Table 16. Cargo payload and angular velocity values utilized in dynamic simulations.

	Urban	Long John	Long Tail
Cargo payload	n/a	75 kg *	130 kg *
Angular velocity	2.39 rad/s	1.02 rad/s	0.24 rad/s

* According to the manufacturer's maximum admissible payload.

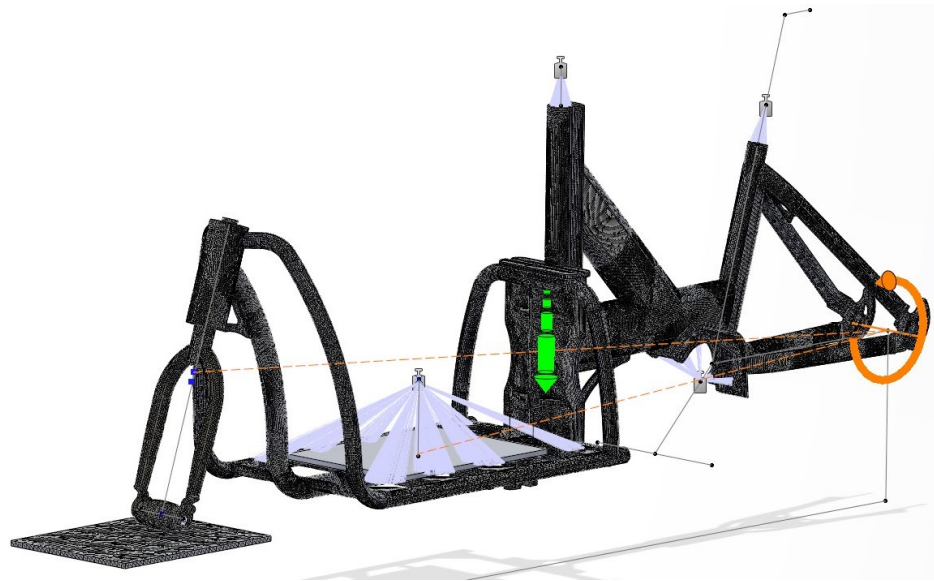


Figure 14. Long John falling frame explicit dynamic simulation scenario.

2.7. Evaluation Criteria and Numerical Compliance Metrics

The numerical results were evaluated according to the acceptance criteria established in the standards for single-track cargo cycles. Since the standard defines minimum fatigue-life requirements and maximum admissible permanent deformations for each test configuration, different performance indicators were adopted for fatigue and impact simulations.

For the fatigue loading cases, three output parameters were analyzed: predicted fatigue life, damage distribution and maximum equivalent stress (Largest Smax). Fatigue life represents the estimated number of cycles that the structure can withstand before failure initiation. The predicted life was directly compared with the minimum cycle requirements specified by the standard, namely 200,000 cycles for the dynamic tests with pedaling forces, horizontal forces and vertical forces onto the loading area, and 100,000 cycles for the dynamic test with vertical forces onto the seat-post. Damage plots were used to identify regions susceptible to fatigue crack initiation, while Largest Smax values were employed to locate critical stress concentrations and compare the relative severity of the different loading cases.

For the impact loading cases, the structural response was assessed using the maximum von Mises stress, the distribution of plastic strain and the permanent wheelbase deformation. Von Mises stress was used to identify regions where yielding could occur, whereas plastic strain was employed to evaluate the extent and location of permanent structural deformation. Numerical compliance with the standard was determined primarily through the wheelbase deformation criterion, which specifies the maximum allowable permanent geometric distortion after impact.

2.8. Mesh Sensitivity and Model Verification

To determine an efficient meshing strategy while maintaining result accuracy, a mesh convergence study was conducted. All static load cases were selected for evaluation, including the two pedaling force load cases, the vertical force onto the seat-post load case, the two horizontal force load cases and the vertical force onto the cargo area load case. For each loading case, the maximum von Mises stress obtained with a given mesh size was normalized by dividing it by the corresponding maximum stress obtained using the 1 mm mesh, which was adopted as the reference solution. Therefore, a normalized value of 1 represents the reference solution, while values below or above 1 indicate under- or over-prediction relative to the reference mesh. The resulting convergence curves are presented

in Figures 15–17. Most load cases exhibited the expected convergence behavior, with the maximum stress approaching a stable value as the mesh was refined; however, the vertical force load case generally showed a delayed convergence trend, with significant changes in the predicted stress persisting until a mesh size of approximately 1.25 mm. Based on the convergence analysis, a non-uniform meshing strategy was adopted to balance computational cost and solution accuracy. A global mesh size of 3 mm was selected for the frame, complemented by local refinements of 1.75 mm and 1.25 mm in regions exhibiting high stress gradients. The locations of these refined areas on the Urban are shown in Figure 18.

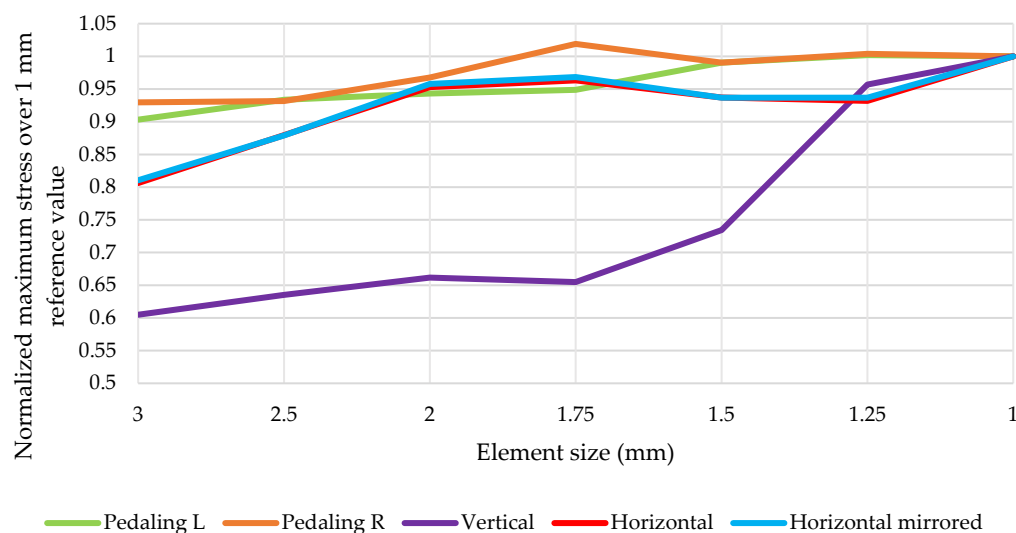


Figure 15. Urban's normalized maximum stress values for different mesh sizes, using the 1 mm mesh as the reference.

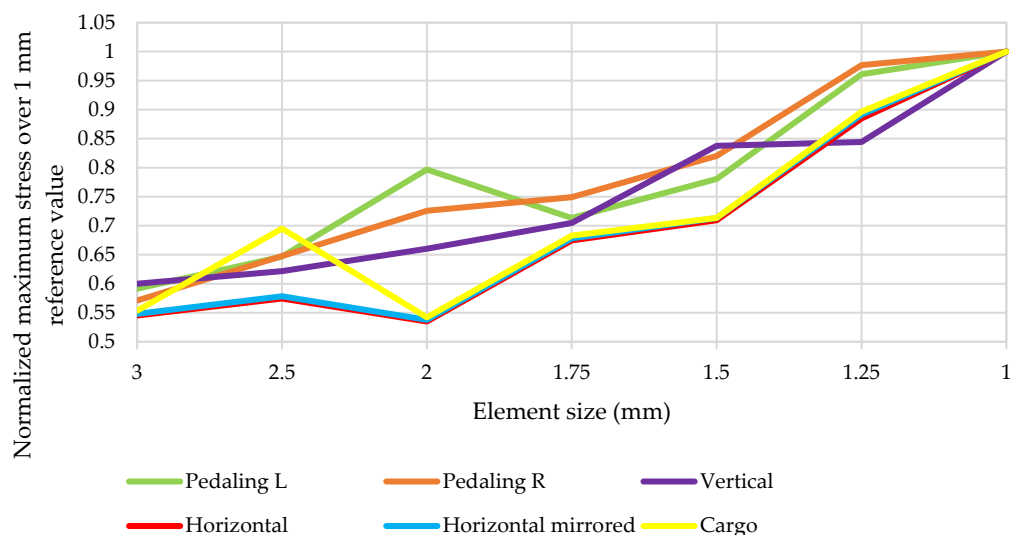


Figure 16. Long John's normalized maximum stress values for different mesh sizes, using the 1 mm mesh as the reference.

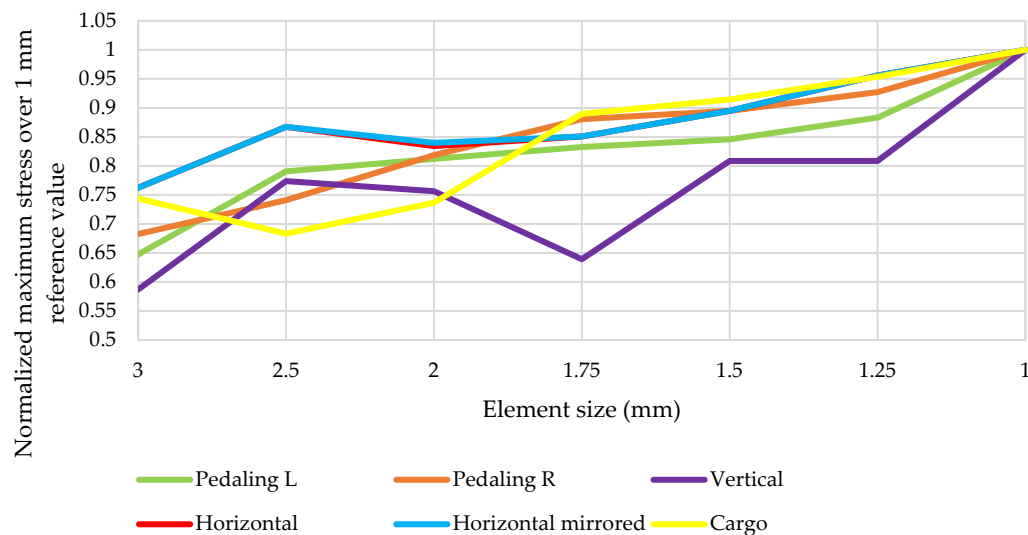


Figure 17. Long Tail's normalized maximum stress values for different mesh sizes, using the 1 mm mesh as the reference.



Figure 18. (a) Refinement areas with 1.75 mm mesh size on the Urban; (b) Refinement areas with 1.25 mm mesh size on the Urban.

3. Results

This section presents the numerical results obtained from the finite element simulations performed on the Urban, Long John and Long Tail frame typologies. The fatigue simulations were evaluated in terms of fatigue life, damage initiation and maximum equivalent stress, while the impact simulations were assessed through von Mises stress, plastic strain and permanent wheelbase deformation.

3.1. Fatigue Loading Cases

Post-simulation, three output metrics were analyzed: Life, Damage and Largest Smax, representing the predicted number of cycles prior to fatigue failure, the specific geometric regions susceptible to structural degradation and the peak stress magnitude registered across the loading cycles, respectively. The results of Largest Smax are presented in Figure 19.

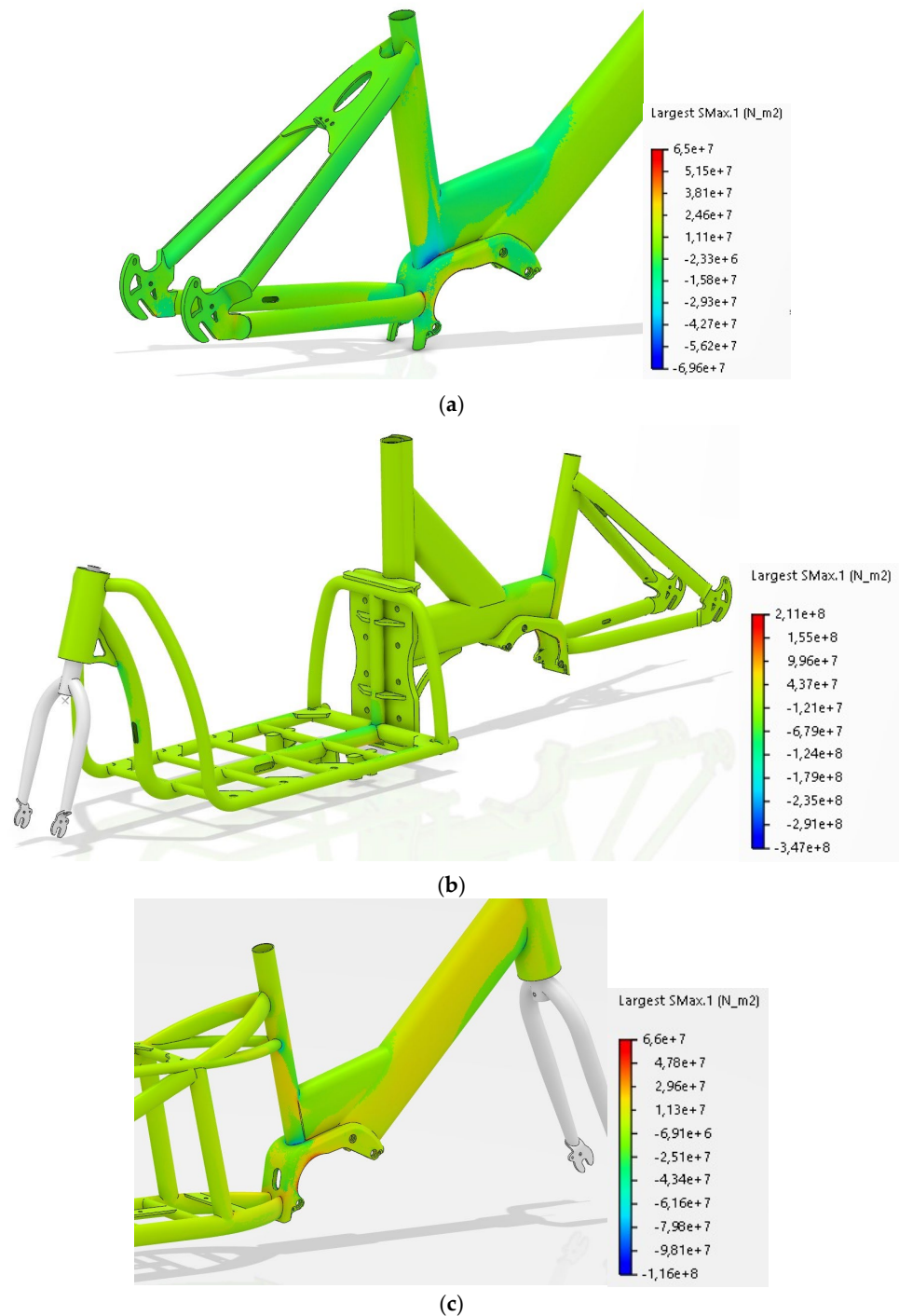


Figure 19. (a) Urban's Largest Smax results; (b) Long John's Largest Smax results; (c) Long Tail's Largest Smax results. Values are in N/m².

In addition to the results shown in this study, all other standard's tests were developed and the results are displayed in Table 17.

Table 17. Life, damage locations and Smax values.

Test Title	Frame Typology	Life (Cycles)	Damage Location	Largest Smax (Absolute Value MPa)
Dynamic test with pedaling forces	Urban	1×10^8	No damage	69.6
	Long John	1.6×10^6	(1)	347
	Long Tail	2.47×10^7	(3)	116

Dynamic test with horizontal forces	Urban	1×10^8	No damage	25
	Long John	1×10^8	No damage	1.53
	Long Tail	1×10^8	No damage	27.1
Dynamic test with vertical forces onto the seat-post	Urban	1×10^8	No damage	151
	Long John	1×10^8	No damage	182
	Long Tail	1.19×10^6	(2)	318
Dynamic test with vertical forces onto the loading area	Urban	n/a	n/a	n/a
	Long John	6.23×10^6	(1)	283
	Long Tail	5.22×10^4	(6)	353

3.2. Impact Loading Cases

Post-simulation, three outputs were analyzed: von Mises stress, plastic strain and the final deformed geometry, representing the stress distribution and magnitude, regions of permanent structural deformation and wheelbase variation, respectively. The corresponding results of the von Mises stress plot at the moment of greatest deflection are presented in Figure 20.

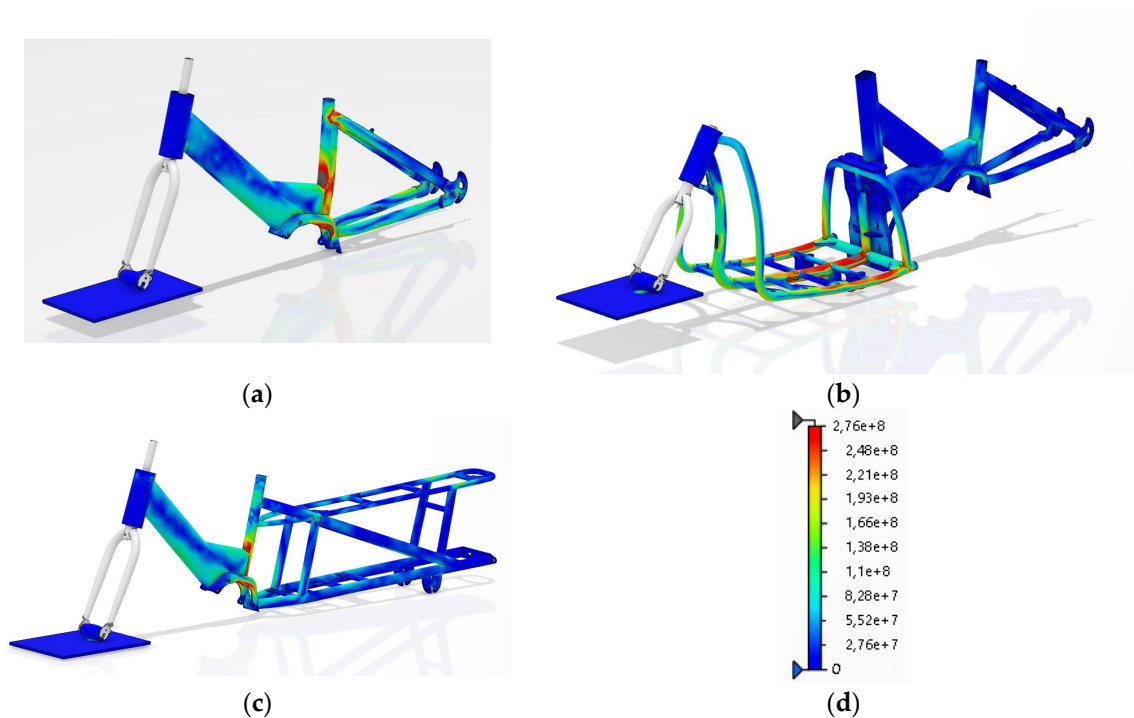


Figure 20. (a) Results of Urban's von Mises stress plot at the moment of greatest deflection; (b) Results of Long John's von Mises stress plot at the moment of greatest deflection; (c) Results of Long Tail's von Mises stress plot at the moment of greatest deflection; (d) Von Mises stress scale for all typologies. Values greater than the material's yield stress (276 MPa) are shown with grey color.

Additionally, the impact test (falling mass) test was developed, and the results are displayed in Table 18.

Table 18. Maximum von Mises stress, plastic strain locations and wheelbase deformation values.

Test title	Frame Typology	Max von Mises Stress (MPa)	Plastic Strain Location	Wheelbase Displacement (mm)
Impact test (falling frame)	Urban	384	(2), (3), (4), (5)	2.07
	Long John	326	(1), (3), (6)	1.966
	Long Tail	356	(2), (3), (4), (6)	1.433
Impact test (falling mass)	Urban	362	(3), (4), (5)	1
	Long John	n/a	n/a	n/a
	Long Tail	n/a	n/a	n/a

3.3. Numerical Compliance Summary by Typology

The Urban frame demonstrated outstanding structural integrity across all fatigue loading cases, significantly exceeding the minimum fatigue life requirements of 200,000 and 100,000 cycles specified by the standard. Notably, no fatigue damage initiation was predicted across any of the fatigue tests, confirming the excellent fatigue resistance of this frame typology under cyclic loading. In contrast, the impact analyses revealed structural vulnerabilities associated with the severity of the experimental methodologies. In the falling frame impact test, localized structural deformation was observed in several regions, in particular, zone (3) exhibited the most pronounced deformation, which contributed directly to the measured wheelbase displacement of 2.07 mm. Although this value remained within the acceptance limits of the standard, it is noteworthy considering the cumulative nature of the test, in which the frame is subjected to multiple consecutive impacts. The concentration of deformation within a single structural region further emphasizes the significance of zone (3) in the overall impact response of the frame. The falling mass impact test resulted in a comparatively small permanent wheelbase displacement, despite producing relatively high maximum von Mises stresses. The combination of high stress levels and limited wheelbase displacement suggests that the impact energy was effectively distributed throughout the frame, reducing global deformation while maintaining localized structural integrity.

Similarly to the Urban typology, the Long John frame successfully satisfied the fatigue requirements of the horizontal forces test without exhibiting fatigue damage initiation. In the remaining fatigue loading cases, although the predicted fatigue life did not reach the computational limit of 1×10^8 cycles, it remained well above the minimum requirements established by the standard. Specifically, the frame achieved a predicted fatigue life of 1.6×10^6 cycles under pedaling forces, reached the computational limit under vertical seat-post forces and attained 6.23×10^6 cycles under vertical forces applied to the cargo area. Despite exceeding the minimum fatigue life requirements in all loading cases, localized fatigue damage was predicted during the pedaling forces test, with zone (1) identified as the most critical region. During impact testing, the measured permanent wheelbase displacement was 1.966 mm. Plastic deformation was localized in regions (1), (3) and (6). Although region (1) exhibited the highest level of plastic strain, region (6) had the greatest influence on the overall wheelbase displacement. Owing to the frame geometry, relatively small deformations in this region produce comparatively large displacements at the front extremity of the frame. Consequently, the consecutive drops prescribed by the standard testing protocol could result in progressive geometric distortion and an increased permanent wheelbase displacement.

The Long Tail frame also successfully satisfied the fatigue requirements of the horizontal forces fatigue test, exceeding the 200,000-cycle requirement without exhibiting fatigue damage initiation. Under cyclic pedaling forces, the frame exhibited localized fatigue damage initiation in zone (3) but still comfortably exceeded the minimum fatigue life requirement, although its predicted fatigue life did not reach the computational limit.

While the vertical seat-post forces test proved to be more demanding for this typology than for the Urban and Long John configurations, the frame still satisfied the minimum requirement of 100,000 cycles. This result suggests that the unique rear stay geometry can be responsible for the inferior performance. The cargo area vertical forces test, however, represented the most demanding fatigue loading case for the Long Tail frame. In this loading condition, the predicted fatigue life decreased to 5.22×10^4 cycles, falling below the minimum requirement established by the standard. The falling frame test resulted in a wheelbase displacement of 1.433 mm. Although this value remained within the acceptance limits of the standard, it is noteworthy because the prescribed test requires three consecutive drops on the same frame. Since most of the permanent deformation was concentrated in zones (3) and (4), additional drops could lead to a progressive increase in wheelbase deformation and local plastic strain. The poor impact resistance can be attributed to the inherent geometric vulnerabilities of the frame design.

4. Discussion

This section interprets the numerical results, with particular emphasis on the most demanding loading scenarios and the influence of frame geometry on the observed structural behavior. The critical loading cases identified through the numerical analyses are first examined, followed by an assessment of the behavior of each cargo-bike typology in relation to its geometric characteristics and load-carrying configuration. The implications of the findings for frame design and structural optimization are subsequently considered, and the chapter concludes with a discussion of the main limitations associated with the adopted numerical methodology.

4.1. Critical Load Cases

The numerical results revealed significant differences in the severity of the loading cases. While all tests contributed to the overall structural assessment, only some challenged the fatigue life and impact performance of the analyzed frame typologies.

Among the fatigue tests, the dynamic test with horizontal forces consistently produced the lowest stress levels and no fatigue damage initiation in any frame. This indicates that horizontal loading does not represent a critical design condition for the analyzed geometries. In contrast, the dynamic tests with pedaling forces and vertical forces generated substantially higher stress concentrations due to the combined effects of higher bending moments and the associated load-transfer paths within the frame structure.

For the Urban frame, the most demanding fatigue condition was the vertical loading applied at the seat-post, although the maximum stress (S_{max}) remained well below the material yield strength, reaching only 151 MPa. This result confirms the substantial fatigue safety margin provided by the compact frame geometry.

For the Long John configuration, the pedaling fatigue test represented the most demanding fatigue loading case. Although the frame exceeded the minimum numerical compliance threshold, localized damage initiation was predicted in zone (1), indicating that cyclic pedaling loads represent the primary structural challenge for this typology.

The Long Tail frame exhibited the most critical response among all analyzed typologies. The vertical forces onto the loading-area fatigue test produced the shortest predicted fatigue life and was the only case that failed to satisfy the minimum cycle requirement established by the standard. This behavior can be attributed to the rear cargo-carrying architecture, which generates significant bending moments and stress concentrations in the extended rear structure.

Regarding impact performance, all frame typologies experienced localized stress levels exceeding the material yield strength. The Urban frame exhibited the highest peak von Mises stresses observed throughout the study. However, these stresses remained highly

localized and did not compromise the predicted compliance with the standard. Permanent wheelbase deformation varied considerably between configurations, highlighting the strong influence of frame geometry on impact energy absorption and load redistribution mechanisms.

4.2. Typology-Dependent Structural Behavior

4.2.1. Urban

The Urban typology demonstrated the most favorable overall structural performance among the analyzed typologies. This behavior can be primarily attributed to its compact geometry, characterized by a relatively short wheelbase and the absence of dedicated cargo-carrying extensions. As a result, external loads are transferred through shorter load paths, reducing the bending moments developed throughout the frame structure.

All fatigue load cases satisfied the minimum requirements established by the standard without exhibiting damage initiation. Furthermore, the stress levels observed during cyclic loading remained substantially lower than those recorded for the Long John and Long Tail configurations. These results indicate that the compact architecture of the Urban frame effectively limits stress concentrations and improves fatigue resistance under the standardized loading conditions. In contrast, the impact simulations generated localized plastic deformation and the highest stress values observed for this typology. The most critical region was identified as zone (3), corresponding to the junction between the middle tube and the seat tube. This area acted as a primary load-transfer path during impact, concentrating a significant portion of the impact energy and consequently exhibiting localized yielding. The results highlight the structural importance of the middle tube–seat tube connection in Urban-type cargo bikes. While the overall frame geometry provides excellent fatigue performance, this junction appears to play a dominant role in the impact response. This behavior may be associated with the absence of a top tube, a common design feature in conventional bikes that is omitted in step-through frame designs to improve accessibility and ease of use. The absence of this additional load-transfer path may increase the proportion of impact loads transmitted through the middle tube and seat tube connection, thereby increasing the structural demand in this region. Consequently, this area should be considered a priority for local reinforcement or geometric optimization.

4.2.2. Long John

The Long John frame exhibited a balanced structural response across the majority of the loading cases. The cargo-carrying area is positioned between the front wheel and the rider, allowing the COG to be located closer to the middle of the vehicle. This arrangement promotes a more favorable load distribution.

All fatigue loading cases satisfied the minimum requirements established by the standard; however, the pedaling forces test represented the most demanding fatigue condition, producing localized damage initiation in zone (1). This region is located ahead of the cargo-carrying area and is subjected to combined bending and torsional loads. The extended front geometry increases the torsional effects generated by cyclic pedaling forces, resulting in elevated stress concentrations in this region. Although the predicted fatigue life remained well above the minimum requirement, the results suggest that this joint represents the most fatigue-sensitive location within the structure. The Long John frame demonstrated satisfactory impact performance, exhibiting a permanent wheelbase displacement of 1.966 mm following the falling-frame impact test. This result indicates that the frame geometry is effective at redistributing impact loads throughout the structure; however, the plastic deformation observed in zone (1) identifies a localized area of possible structural vulnerability under repeated impact events, particularly considering the multiple-drop sequence required by the standard. Additionally, deformation in zone

(6) may also prove critical due to the significant influence that relatively small local deformations in this region can have on the displacement of the front extremity and, consequently, on the permanent wheelbase displacement. Despite these localized vulnerabilities, the results suggest that the Long John configuration achieves an effective compromise between cargo-carrying capability and structural performance. The centrally positioned cargo area promotes efficient load distribution and good impact resistance, while the extended front structure increases the structural demand on specific load-transfer regions that may benefit from local reinforcement or geometric optimization.

4.2.3. Long Tail

The Long Tail frame exhibited the most critical structural response among the analyzed typologies. Unlike the Urban and Long John configurations, the cargo load is positioned behind the rider and over the rear wheel, creating an extended rear overhang that increases the bending moments acting on the frame.

Although the frame successfully satisfied the fatigue requirements for the pedaling, horizontal and seat-post loading cases, the dynamic test with vertical forces applied to the loading area represented the most demanding fatigue condition. In this configuration, the predicted fatigue life reached only 5.22×10^4 cycles, falling below the minimum requirement of 200,000 cycles. Furthermore, the highest fatigue stresses of all analyzed fatigue tests were recorded during this loading case, with fatigue damage initiation concentrated in zone (6). These results indicate that the rear cargo-support structure represents the primary fatigue-critical region of the frame. The impact simulations also revealed reduced structural robustness compared with the other typologies. During the falling-frame test, the Long Tail exhibited a lower wheelbase displacement than the Long John frame, despite exhibiting higher maximum von Mises stresses. This behavior is likely associated with the differences in frame geometry and wheelbase length, which influence the distribution of impact loads. Plastic strain developed in zone (4) and more critically in zone (3). The combination of localized yielding and increased global deformation suggests that the geometries of zones (3) and (6) reduce the ability of the frame to efficiently redistribute impact loads throughout the structure. Reinforcement of the rear load-carrying structure and the adjacent frame connections should be considered essential design priorities for improving the fatigue and impact performance of this typology.

4.3. Design Implications

The results suggest that the analyzed Urban frame possesses potential for structural optimization through weight reduction. Since all fatigue loading cases comfortably exceeded the minimum requirements established by the standard, a reduction in tube wall thicknesses could be investigated while maintaining structural integrity. Such modifications could contribute to a lighter frame without compromising compliance with the standard. Particular attention should be given to the junction between the middle tube and the seat tube, where the highest plastic deformation was observed during the impact simulations. This connection represents the primary impact load-transfer region of the frame and may benefit from local reinforcement or geometric optimization. In particular, the angle between the middle tube and the seat tube could be investigated to improve load distribution during impact events.

The results indicate that the Long John frame would benefit from a redesign of the front cargo-support structure. The critical regions identified in zones (1) and (6) suggest that local geometric modifications could reduce both stress concentrations and permanent deformation. In particular, zone (6) represents the greatest opportunity for structural improvement, as its limited bending stiffness allows relatively small local deformations to produce comparatively large displacements at the front extremity of the frame. Increasing

the structural support of the cargo area, for example by introducing additional horizontal members connecting the front and central portions of the frame, could improve structural stiffness and reduce the influence of local deformation on the overall wheelbase displacement. However, such modifications should be carefully balanced against the available cargo volume, as additional structural members may reduce the usable loading space.

The results indicate that the Long Tail frame would benefit from a redesign of the rear cargo-support structure. Additionally, similarly to the Urban configuration, the junction between the middle tube and the seat tube should be further evaluated, as the similar front-frame geometry leads to comparable impact load-transfer mechanisms. The rear structure represents the primary opportunity for improvement. The lower connection between the seat stay and the seat tube generated elevated stress concentrations during both fatigue loading and impact testing. Approximating this connection to the top of the seat tube, similar to the Urban and Long John geometries, may reduce the bending moments acting on this region and improve performance. Furthermore, the overhang of the cargo platform exhibited high stresses and localized deformation. Relocating the support tube and cargo platform connection point closer to the rear end of the cargo platform could improve structural stiffness, reduce stress concentrations and enhance both fatigue and impact performance.

4.4. Limitations of the Simulation Approach

The results presented in this study should be interpreted considering the assumptions and simplifications inherent to the adopted methodology. Although finite element analysis provides a valuable tool for comparative structural assessment, several aspects of the real behavior of the frames could not be fully represented. One of the main limitations concerns the modelling of welded joints. The welds were represented through simplified geometric connections and homogeneous material properties, without explicitly accounting for weld bead geometry, heat-affected zones, residual stresses, or manufacturing defects. Since welded regions are often the primary locations for fatigue crack initiation, these simplifications may affect the predicted stress distributions and fatigue-life estimations. In addition, the material behavior was assumed to be homogeneous, isotropic, and free from manufacturing variability. As a result, potential effects associated with material imperfections, property dispersion, or local variations introduced during fabrication were not considered.

Another limitation of the present study concerns the adopted element formulation. Although first-order tetrahedral (C3D4) elements enabled stable and computationally efficient analyses for all loading cases, higher-order tetrahedral elements, such as C3D10, were not evaluated because preliminary analyses presented numerical convergence difficulties within the adopted nonlinear simulation framework. Consequently, the influence of the element formulation on local stress concentrations was not quantified and should be investigated in future work.

Additional uncertainty may arise from the representation of the loading conditions and boundary constraints. Although the simulations were developed according to the procedures specified in the standards, the simulation setup simplifies the experimental configuration. Differences in fixture stiffness, load introduction, contact conditions, and alignment may affect local stress concentrations and the overall structural response when compared with physical testing. Furthermore, the fork and the roller were modeled as rigid components in the simulations, which differs from the real test conditions. Although a dummy fork and roller could be considered as alternative simplifications, rigid-body properties would not reproduce the actual stiffness of the real dummy objects and could therefore alter the load-transfer path and local stress distribution.

In addition, the present model did not include road-induced vibration loading generated by pavement roughness, curbs, potholes or repeated low-amplitude surface irregularities. Such dynamic inputs may contribute to cumulative fatigue damage in the stress-concentration and fatigue-critical regions identified in this study, while also affecting rider comfort during prolonged urban use. Consequently, the predicted fatigue lives should be interpreted as standard-derived numerical estimates rather than complete representations of long-term operational durability under real urban riding conditions. The influence of vibration loading, including possible mitigation through tire optimization, soft-wheel technologies or wheel-suspension solutions, should therefore be addressed in future work.

Finally, the numerical predictions were not validated through experimental testing. Therefore, the results should be interpreted as a comparative assessment of the structural behavior of different cargo-bike typologies rather than as an exact representation of real-world performance. Future work should include physical testing according to the standard to establish numerical–experimental correlation and further improve the accuracy of the proposed models.

5. Conclusions

This study presented a comparative structural assessment of three single-track E-cargo bike frame typologies, Urban, Long John and Long Tail, under fatigue and impact loading conditions derived from EN 15194:2020 [47] and EN 17860-2:2024 [48]. Finite element analyses were performed to evaluate fatigue life, stress distribution, damage initiation, plastic strain and permanent wheelbase deformation, providing a numerical framework for assessing the structural behavior of cargo-bike frames under standardized loading conditions.

The numerical results demonstrated that frame geometry and cargo location play a decisive role in determining both fatigue and impact performance. The Urban frame exceeded the required fatigue life in every loading case, reaching the computational fatigue limit of 1×10^8 cycles for the horizontal loading condition. During the frame drop impact, the maximum wheelbase deformation was only 2.07 mm, well below the allowable 10 mm. The mass drop impact test resulted in a predicted deformation of the wheelbase of 1 mm. The Long John frame satisfied every numerical acceptance criterion, presenting a minimum fatigue life of 1.6×10^6 cycles under pedaling loads and 6.23×10^6 cycles under cargo loading. Additionally, during impact, the wheelbase deformation was 1.966 mm. The Long Tail frame failed only the vertical loading-area fatigue test, with a predicted fatigue life of 5.22×10^4 cycles, although its maximum permanent wheelbase deformation remained limited to 1.43 mm during impact. Overall, the Urban and Long John frames satisfied all numerical acceptance criteria, whereas the Long Tail frame failed only the vertical loading-area fatigue requirement. The analyses identified the most demanding loading conditions and the critical structural regions for each typology. These findings provide valuable insights for frame design, indicating where local reinforcement or geometric modifications may improve structural performance while maintaining compliance with current standards.

Although the numerical models were developed according to standardized testing procedures, experimental validation remains necessary to establish numerical–experimental correlation and further improve prediction accuracy. Future work should therefore include physical testing, more detailed representations of welded joints and manufacturing effects and the evaluation of optimized frame geometries based on the critical regions identified in this study.

Overall, the proposed methodology provides an effective framework for the structural assessment and design optimization of single-track E-cargo bike frames during the early stages of development. By identifying fatigue- and impact-critical regions prior to

prototype manufacturing, the methodology can support more efficient design iterations and contribute to the development of safer, more durable and structurally efficient E-cargo bikes for urban freight transport and last-mile logistics.

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