

## Design and Construction of the Steering System on the Trolley City Three-Wheeled Bicycle Considering Quasi-Dynamics

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### Abstract

*Three-wheeled cargo or city bicycles often experience dynamic instability and risks of tipping during cornering at moderate speeds, yet conventional rigid steering mechanisms fail to accommodate lateral leaning while maintaining structural rigidity under dynamic loads. To address this gap, this study aims to design, analyze, and construct an optimized bracket for a tilting steering system on a trolley city three-wheeled bicycle considering quasi-dynamic loading conditions. Following the VDI 2221 systematic design approach, design concepts were generated and systematically evaluated through alternative functional combinations (AFK) using evaluation criteria based on structural rigidity, manufacturability, safety factor, and weight efficiency. The selected design was fabricated and evaluated using two candidate materials: ST37 structural steel and 3D-printed PLA. Structural behavior was investigated through Finite Element Analysis (FEA) in SolidWorks Simulation to assess stress distributions and safety factors under combined static and quasi-dynamic forces, followed by direct field operational testing. The results demonstrate that the ST37 steel bracket withstood a maximum operational load of 143 kg with a safety factor exceeding 1.5, maintaining structural stability and handling control during turns. In contrast, while PLA is suitable for rapid prototyping and lightweight validation, it exhibited insufficient long-term durability and lower safety margins under real cornering forces. In conclusion, integrating quasi-dynamic considerations with systematic AFK selection yields a reliable tilting steering bracket, providing critical structural and material benchmarks for developing stable urban three-wheeled vehicles.*

**Keywords :** *Quasi-Dynamic Analysis; Tilting Bicycle Steering; Bracket Design; Finite Element Analysis (FEA); Stress Analysis.*

### Abstrak

Sepeda roda tiga perkotaan (*trolley city*) memiliki risiko ketidakstabilan dan terguling saat bermanuver pada kecepatan tertentu, sementara sistem kemudi kaku konvensional belum mampu mengakomodasi kemiringan bodi (*tilting*) secara optimal di bawah beban dinamis. Untuk mengatasi kesenjangan tersebut, penelitian ini bertujuan merancang, menganalisis, dan memvalidasi bracket sistem kemudi miring dengan mempertimbangkan pembebanan kuasi-dinamis dan analisis berbasis computer-aided engineering (CAE). Melalui pendekatan metode perancangan VDI 2221, konsep desain dikembangkan dan diseleksi melalui kombinasi fungsi alternatif (*alternative functional combinations/AFK*) berdasarkan kriteria kekakuan struktur, kemudahan manufaktur, faktor keamanan, dan efisiensi bobot. Konsep terpilih dianalisis menggunakan simulasi *SolidWorks* untuk mengevaluasi distribusi tegangan dan faktor keamanan pada material baja ST37 serta plastik PLA hasil cetak 3D, yang kemudian divalidasi melalui pengujian performa di lapangan. Hasil penelitian menunjukkan bahwa *bracket* berbahan baja ST37 mampu menahan beban maksimum hingga 143 kg dengan faktor keamanan lebih dari 1,5 serta mempertahankan stabilitas belok yang andal. Sebaliknya, material PLA mengalami penurunan kekuatan dan daya tahan jangka panjang, sehingga lebih direkomendasikan untuk purwarupa awal. Dapat disimpulkan bahwa integrasi pertimbangan kuasi-dinamis dan seleksi sistematis AFK menghasilkan desain bracket kemudi miring yang kokoh, stabil, dan aman untuk pengembangan sepeda roda tiga perkotaan.

**Kata Kunci:** Analisis Kuasi-Dinamis; Kemudi Sepeda Miring; Desain Bracket; Kombinasi Fungsi Alternatif; VDI 2221; Analisis Elemen Hingga (FEA); Analisis Tegangan

### 1. Introduction

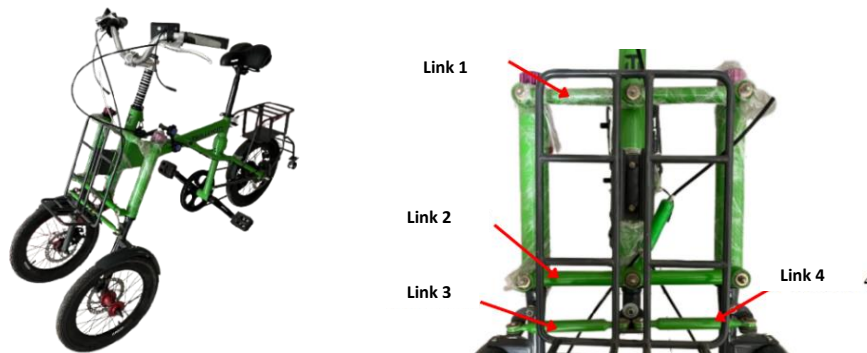
The design of tilting bicycle steering systems has become a rapidly growing area in the bicycle industry, offering significant improvements in stability and maneuverability during turns, particularly for high-performance bicycles [1], [2]. One of the major challenges in the development of such systems is the design of brackets that can withstand dynamic

loads while maintaining the structural stability of the bicycle [3]. The brackets used must consider materials that are strong, lightweight, durable, and have efficient manufacturing processes. With technological advancements, 3D printing offers a promising solution for producing complex bicycle components with high precision, especially for prototyping and component manufacturing [4]. Material selection, such as ST37 steel and PLA plastic, plays a critical role in the strength and durability of the components produced [5], [6]. ST37 steel is well-known for its high tensile strength, while PLA plastic is lighter and easier to print but has limitations in terms of load-bearing capacity under heavy loads [7], [8].

Previous research has developed various methods to analyze and optimize bicycle component designs, including the use of Finite Element Analysis (FEA) to evaluate stress distribution and safety factors on materials and structures [9], [10]. FEA enables more accurate predictions of how components will behave under specific loads, which is crucial for the design of tilting bicycle steering systems [11], [12]. By utilizing FEA, researchers can predict potential component failures before manufacturing begins, thus saving costs and production time [13].

In addition, the concept of quasi-dynamic analysis has been applied in vehicle stability and steering system analysis, taking into account factors such as speed, friction, and load distribution during turns [14], [15]. This method provides a clearer picture of how steering system designs perform under dynamic conditions, which are often overlooked in static analysis.

However, despite the considerable body of research in this field, direct testing and validation of tilting bicycle bracket designs in real-world conditions remain limited. Therefore, this study aims to design and test a bracket that improves bicycle stability during turns, using quasi-dynamic analysis and FEA to evaluate its performance, while comparing the performance of ST37 steel and PLA plastic materials fabricated via 3D printing.



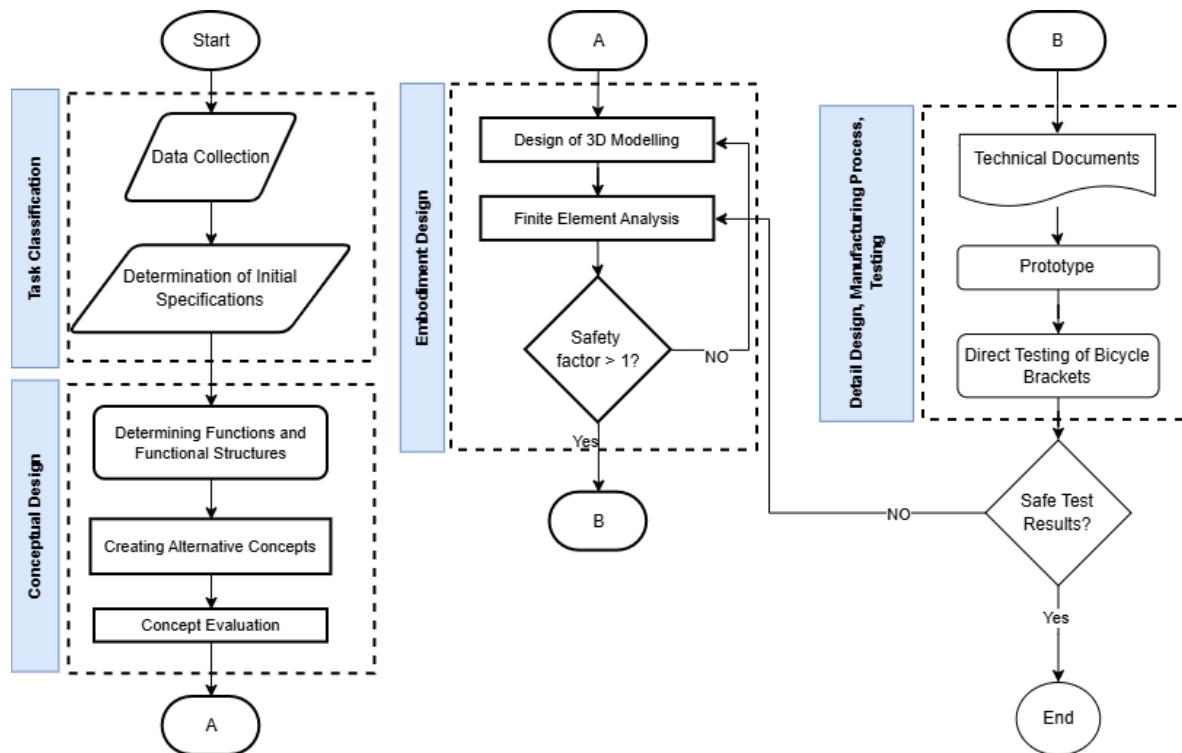
**Figure 1.** City trolley bicycle (left) and steering system on city trolley (right)



**Figure 2.** (a) Side and centre bracket (b) Condition of the bracket when installed

## 2. Material and Method

The methodology used in this study to solve the stability problem of the steering system for the Trolley City three-wheeled bicycle is based on the VDI 2221 design method. This method consists of a series of systematic steps aimed at producing a mechanical design that not only meets functional requirements but also ensures efficiency in production and usage. The overall research framework is structured into four main stages, as illustrated in Figure 3: task clarification, conceptual design, embodiment design, and detailed design coupled with prototype manufacturing and operational testing. Each stage incorporates iterative feedback loops—particularly FEA safety factor criteria and field testing validation—to ensure structural integrity before advancing to subsequent stages.



**Figure 3.** Flowchart of the tilting steering bracket design and testing methodology based on the VDI 2221 approach

### 2.1. Task Classification

In the first stage, the existing problem is analyzed to determine the requirements that must be met by the steering system. These requirements serve as a reference in the design process and the formulation of design specifications. Table 1 presents the list of requirements that must be fulfilled in the design of the three-wheeled bicycle's steering system.

**Table 1.** List of Requirements

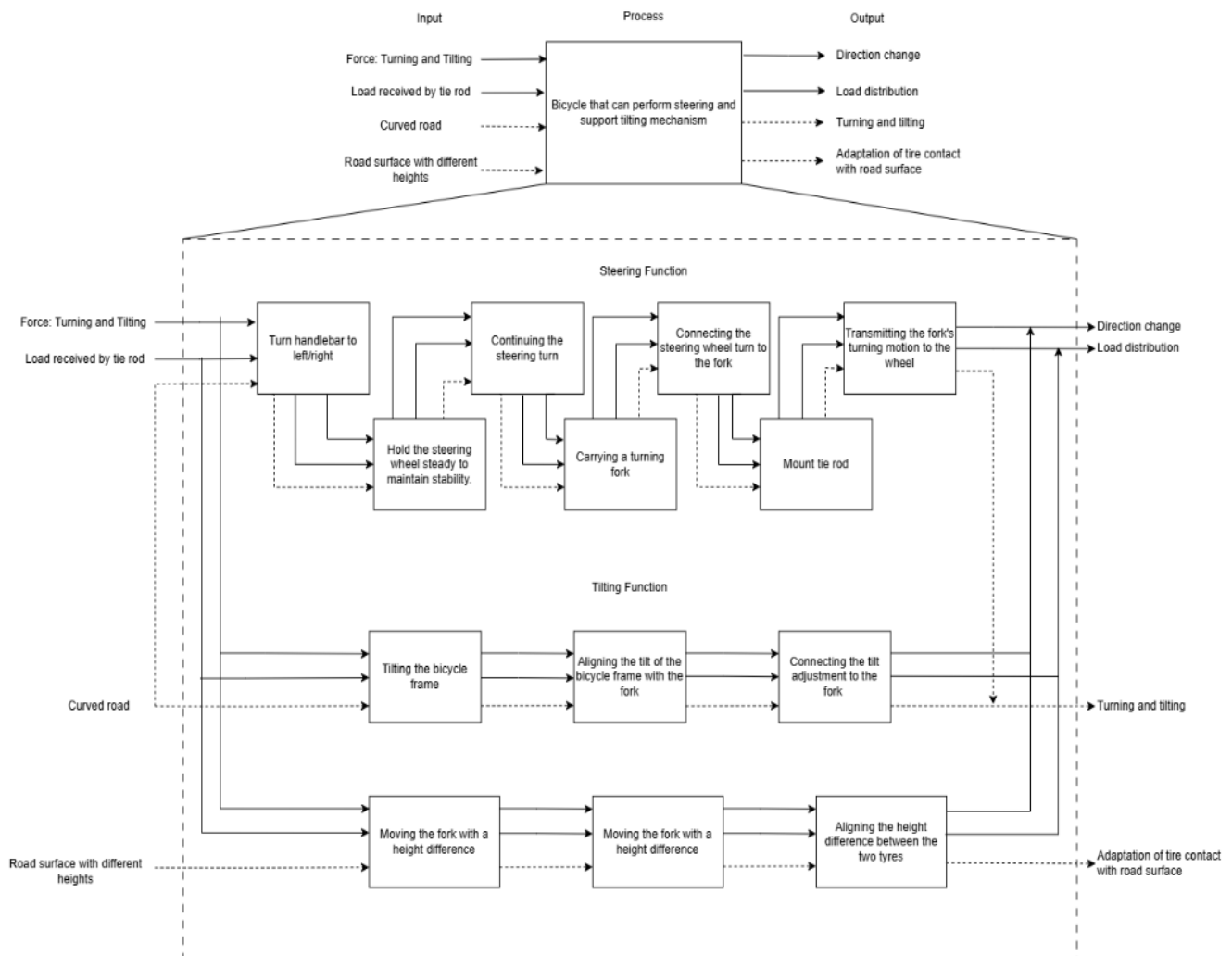
| No                   | Requirement                                                           | Description                 |
|----------------------|-----------------------------------------------------------------------|-----------------------------|
| Primary Requirements |                                                                       |                             |
| 1.                   | Tilting height                                                        | 15 cm                       |
| 2.                   | Tilting angle                                                         | 30°                         |
| 3.                   | Steering turning radius                                               | 25°                         |
| 4.                   | degrees of freedom at the left and right Bracket joints (binary link) | Joint 1: 1 DOF (bearing)    |
|                      |                                                                       | Joint 2: 3 DOF (ball joint) |
| 5.                   | Degrees of freedom at the middle bracket joint (ternary link)         | Joint 1: 1 DOF (bearing)    |
|                      |                                                                       | Joint 2: 3 DOF (ball joint) |

| No                      | Requirement                               | Description                                 |
|-------------------------|-------------------------------------------|---------------------------------------------|
| Secondary Requirements  |                                           | Joint 3: 3 DOF (ball joint)                 |
| 1.                      | Stabilizer                                | Maximum length 200 mm Minimum length 147 mm |
| 2.                      | Load capacity of the entire bicycle frame | Maximum 143 kg (bicycle, rider, cargo)      |
| Additional Requirements |                                           |                                             |
| 1.                      | Manufacturability                         | Easy to manufacture                         |
| 2.                      | Assembly                                  | Easy to assemble                            |

## 2.2. Concept Design

In the conceptual design phase, the functional structure of the mechanism is established to map out the energy, force, and kinematic relationships within the system. As shown in Figure 4, this structure is developed through two complementary representations: the Overall Function (Black Box) and the Sub-Functions (Glass Box).

The black box defines the boundary of the system, transforming primary dynamic and environmental inputs into desired operational outputs. The inputs comprise mechanical driver inputs (Force: Turning and Tilting and Load received by tie rod) and external terrain conditions (Curved road and Road surface with different heights). These are systematically transformed by the mechanism into directional change, effective load distribution across the wheels, coordinated vehicle leaning (Turning and tilting), and continuous tire-road contact adaptation.

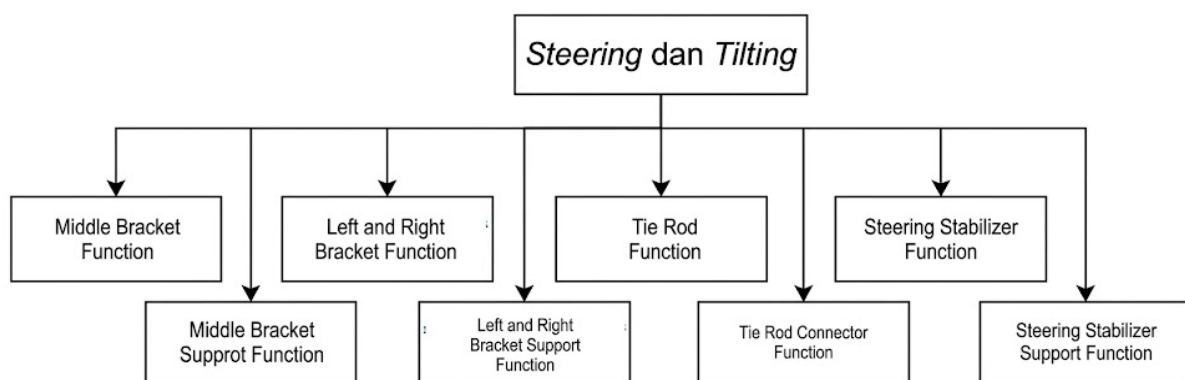


**Figure 4.** Black box and glass box diagram

The glass box decomposes the black box into two synchronized functional branches:

1. **Steering Function:** Governs kinematic directional control and dynamic load distribution. Steering input applied to the handlebar is relayed to stabilize the steering wheel, carried through the fork pivot, connected via tie-rod mounts, and finally transmitted to generate front wheel angular deflection.
2. **Tilting & Surface Adaptation Function:** Manages lateral stability and terrain compliance. Leaning forces induced by cornering are coordinated between the main bicycle frame and front forks to ensure balanced roll angles. Concurrently, uneven ground variations are absorbed through independent vertical fork displacements, equalizing height discrepancies between both front tires to maintain wheel grip.

The interconnections (represented by solid force transmission lines and dashed motion/feedback lines) define how energy and kinematic motions transfer between sub-systems. This functional breakdown directly provides the technical criteria for populating the Morphological Box and selecting specific physical construction alternatives (AFK).

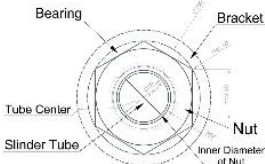
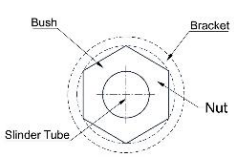
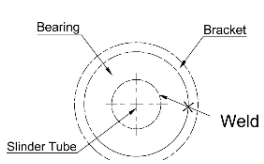
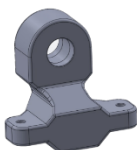
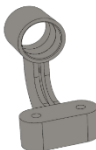


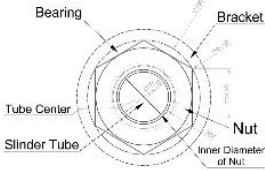
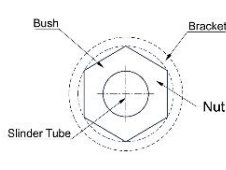
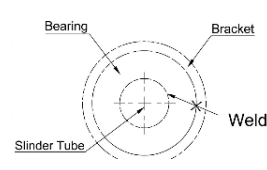
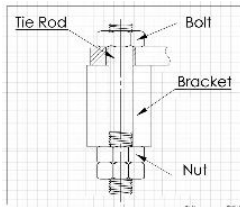
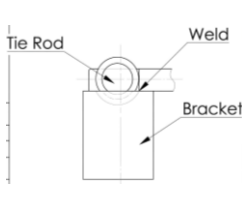
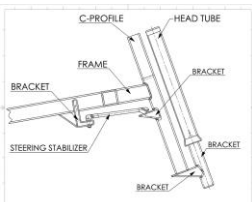
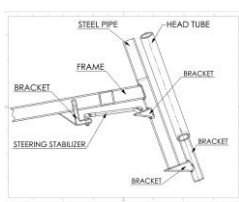
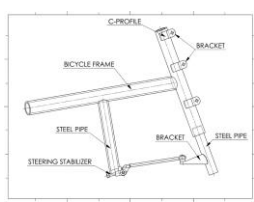
**Figure 5.** Function block diagram of steering and titing

### 2.3. Part Construction Alternatives

In this stage, various construction alternatives for each part of the bicycle are evaluated. Each part of the steering system serves a specific function, which is represented by multiple design alternatives.

**Table 1.** Part construction alternatives

| No | Part Function          | Description                                                                                                          | Alternative 1                                                                       | Alternative 2                                                                        | Alternative 3                                                                         |
|----|------------------------|----------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|
| 1. | Middle Bracket Support | A sturdy support on the head tube to support the middle bracket on the front frame of the bicycle.                   |  |  |  |
| 2. | Middle Bracket         | Connects the turning motion from the head tube to the fork, so the steering movement can be transferred to the fork. |  |  |  |

| No | Part Function                  | Description                                                                                                  | Alternative 1                                                                                       | Alternative 2                                                                                       | Alternative 3                                                                                            |
|----|--------------------------------|--------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------|
| 3. | Left and Right Bracket Support | A sturdy support on the fork to support the left and right brackets on the bicycle frame.                    |                    |                   |                       |
| 4. | Left and Right Bracket         | Connects the steering movement to the fork to allow the front wheel to turn according to the rider's input.  |                    |                   |                       |
| 5. | Tie Rod Locking                | Keeps the tie rod stable and locked in place on the bracket to ensure optimal steering performance.          |                    |                   |                                                                                                          |
| 6. | Tie Rod                        | Connects the middle bracket to the left and right brackets to transmit steering movement to the front wheel. | <br>Sway Bar Link | <br>Tie Rod      |                                                                                                          |
| 7. | Steering Stabilizer            | Maintains bicycle stability while turning and moving straight, improving rider comfort and safety.           | <br>Gas spring   | <br>Coil spring | <br>Steering Damper |
| 8. | Stabilizer Support             | A support to ensure that the stabilizing component can optimally maintain bicycle stability.                 |                  |                 |                     |

## 2.4. Morphological Box

After selecting the construction alternatives, the next step is to combine and assess the pros and cons of each option to generate three alternative functional combinations (AFK). The morphological box helps evaluate the various design alternatives based on the functions that need to be fulfilled.

**Table 3.** Morphological box

| No | Part Function                  | Alternative 1 | Alternative 2 | Alternative 3 |
|----|--------------------------------|---------------|---------------|---------------|
| 1. | Middle Bracket                 | ★ A1          | ◆ A2          | ▲ A3          |
| 2. | Left and Right Bracket         | ★ B1          | ◆ B2          | ▲ B3          |
| 3. | Middle Bracket Support         | ▲ C1          | ★ C2          | ◆ C3          |
| 4. | Left and Right Bracket Support | ▲ D1          | ★ D2          | ◆ D3          |
| 5. | Tie Rod Locking                | ★ E1          | ◆ E2          | ▲ E3          |
| 6. | Tie Rod                        | ◆ F1          | ★ F2          | ▲ F3          |
| 7. | Steering Stabilizer            | ▲ G1          | ★ G2          | ◆ G3          |
| 8. | Stabilizer Support             | ★ H1          | ▲ H2          | ◆ H3          |

In Table 3, each functional row is designated by an alphabetical code (A through H) representing the eight constituent sub-functions of the steering mechanism, while numeric indices (1, 2, and 3) denote specific structural or kinematic solution variants for that sub-function. The sequence of sub-functions is structured systematically based on structural hierarchy and load-transmission priority: starting from the primary chassis-mounting brackets (A–D), progressing to the active steering linkages (E–F), and concluding with the auxiliary damping and stabilizer mounts (G–H). Connecting paths across the morphological matrix yield three complete design variants:

- Concept 1 (★AFK 1): A1-B1-C2-D2-E1-F2-G2-H1
- Concept 2 (◆AFK 2): A2-B2-C3-D3-E2-F1-G3-H3
- Concept 3 (▲AFK 3): A3-B3-C1-D1-E2-F2-G1-H2

## 2.5. Evaluating Functional Combination Alternatives

Concept alternatives are evaluated according to the standards of VDI 2225. This standard evaluates both technical and economic aspects to select the best concept among the available options. The evaluated was based on each concept's ability to fulfil the overall function and sub-functions of the bicycle steering system. Factors such as load distribution on the bracket, resistance to dynamic stress, and efficiency in operation were the main considerations.

**Table 4.** Technical evaluation

| Evaluation Criteria  | Weight [%] | Technical Evaluation of the Concept |    |        |    |      |     | Optimum Score |     |
|----------------------|------------|-------------------------------------|----|--------|----|------|-----|---------------|-----|
|                      |            | AFK 1                               |    | AFK 2  |    | AFK3 |     |               |     |
| Function Achievement | 30         | 3                                   | 90 | 3      | 90 | 4    | 120 | 4             | 120 |
| Construction         | 20         | 3                                   | 60 | 3      | 60 | 4    | 80  | 4             | 80  |
| Manufacturing        | 20         | 4                                   | 80 | 4      | 80 | 4    | 80  | 4             | 80  |
| Assembly             | 20         | 2                                   | 40 | 3      | 60 | 3    | 60  | 4             | 80  |
| Maintenance          | 10         | 3                                   | 30 | 3      | 30 | 4    | 40  | 4             | 40  |
| Total Score          | 100        | 300                                 |    | 320    |    | 380  |     | 400           |     |
| Average              |            | 3.05                                |    | 3.05   |    | 3.4  |     | 4             |     |
| Percentage           |            | 76.25%                              |    | 76.25% |    | 88%  |     | 100%          |     |

Based on the technical and economic evaluation, AFK 3 is selected as the concept to be implemented for the initial construction design and layout.

In addition to technical aspects, economic aspects are also important in evaluating concepts. Manufacturing costs, maintenance costs, and the use of affordable materials (such as PLA for prototypes and ST37 steel for main components) are also taken into consideration to ensure that the selected concept can be produced cost-effectively without compromising quality or performance.

**Table 5.** Economic evaluation

| Evaluation Criteria | Weight [%] | Technical Evaluation of the Concept |     |        |     |      |     | Optimal Score |     |
|---------------------|------------|-------------------------------------|-----|--------|-----|------|-----|---------------|-----|
|                     |            | AFK 1                               |     | AFK 2  |     | AFK3 |     |               |     |
| Manufacturing Cost  | 35         | 4                                   | 140 | 4      | 140 | 4    | 140 | 4             | 140 |
| Maintenance Cost    | 35         | 3                                   | 105 | 3      | 105 | 4    | 140 | 4             | 140 |
| Standard Components | 30         | 2                                   | 60  | 2      | 60  | 3    | 90  | 4             | 120 |
| Total Score         | 100        | 305                                 |     | 305    |     | 340  |     | 400           |     |
| Average             |            | 3.05                                |     | 3.05   |     | 3.4  |     | 4             |     |
| Percentage          |            | 76.25%                              |     | 76.25% |     | 88%  |     | 100%          |     |

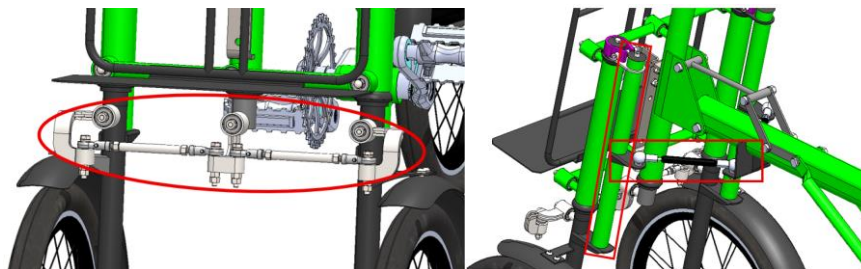
Based on the technical and economic evaluations, AFK 3 was selected as the concept to be applied for the initial construction design and layout.

## 2.6. Initial Design

The initial design phase focuses on the arrangement of the layout using SolidWorks 2020. During this process, changes to dimensions, layout, or components are still possible to adjust to the functional requirements.



**Figure 6.** 3D design trolley city



**Figure 7.** Design bracket (left) and design stabiliser mount (right)

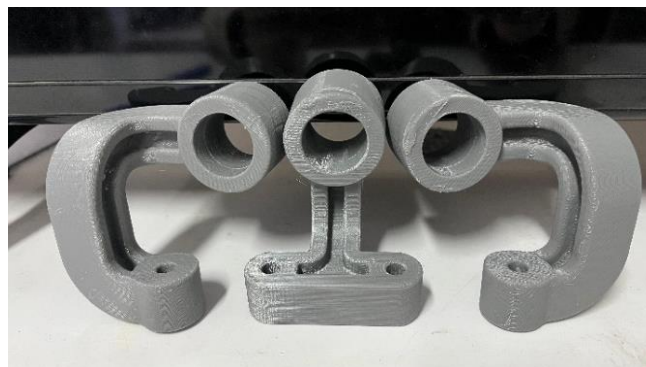
## 2.7. Manufacturing Process

Once the initial design is complete, the next step is fabrication. Two materials, ST37 steel and PLA plastic, are used to fabricate the brackets in order to compare the strength of each material. The realization of the stabilizer prototype could not be completed due to the unavailability of standard gas springs in the market. Additionally, a double link was added to the bracket to stabilize the link's position, ensuring better control of the steering system's movement.

The fabrication of the 3D printed prototype with PLA material aims to gather comparative data on the performance of the bracket through numerical analysis using the finite element method (FEM) and experimental testing. The experimental testing was conducted via functional field trials on the assembled bicycle prototype. Each manufactured bracket—ST37 steel and the two PLA variants (0.8 mm and 3.2 mm wall thickness)—was installed onto the steering system. The bicycle was tested under progressive payload increments up to the design limit of 143 kg during cornering and turning maneuvers at speeds between 10–20 km/h. During testing, critical failure modes, including layer delamination, visible deflection, and structural cracking around the bolt mounting holes, were monitored and recorded to validate the stress distribution and safety factors predicted by the finite element analysis. Therefore, a thorough and objective comparison between the two materials can be analyzed in the context of the bracket application. The 3D-printed brackets have different shell thicknesses of 0.8 mm and 3.2 mm.



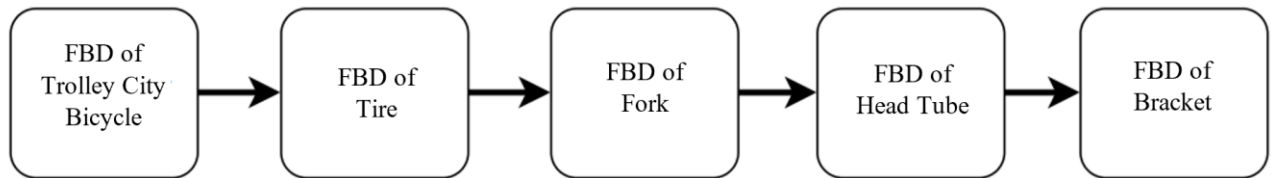
**Figure 8.** Double link on bracket (left) and gas spring mount (right)



**Figure 9.** Bracket with PLA material

## 3. Results and Discussion

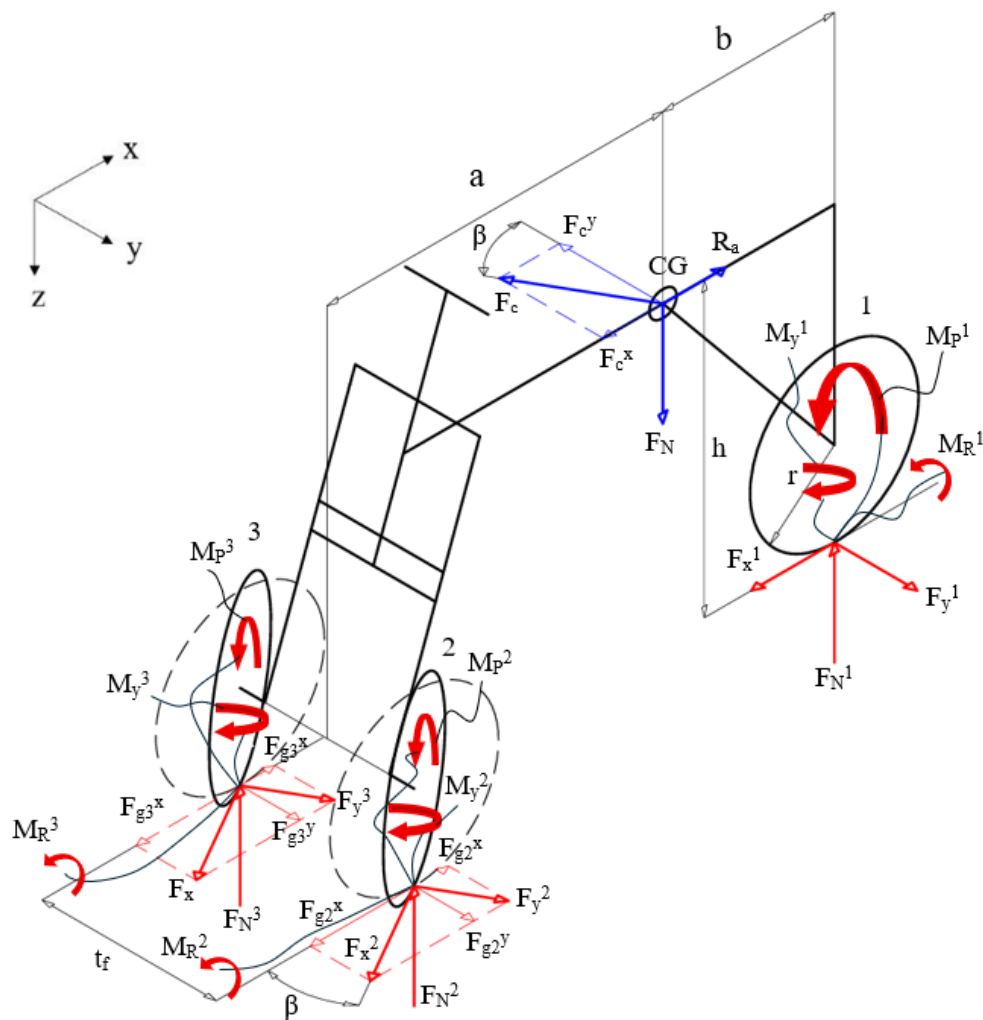
In this study, force analysis was performed to understand the forces acting on the bracket and steering system. The process is illustrated using Free-Body Diagrams (FBD), which provide a visual representation of the forces acting on the system at different stages of the analysis.



**Figure 10.** Stages of FBD calculation

Figure 10 shows the stages involved in calculating the forces acting on the bicycle's steering system. The calculation starts from the FBD of the wheel and progresses to the FBD of the bracket. The forces considered in the analysis include longitudinal forces ( $F_x$ ), lateral forces ( $F_y$ ), and normal forces ( $F_N$ ) that act on the system.

Once the FBD calculations are completed as shown in Figure 11, the FBD on the bracket can be determined, as seen in Figure 12. The applied loading values are shown in Table 6.



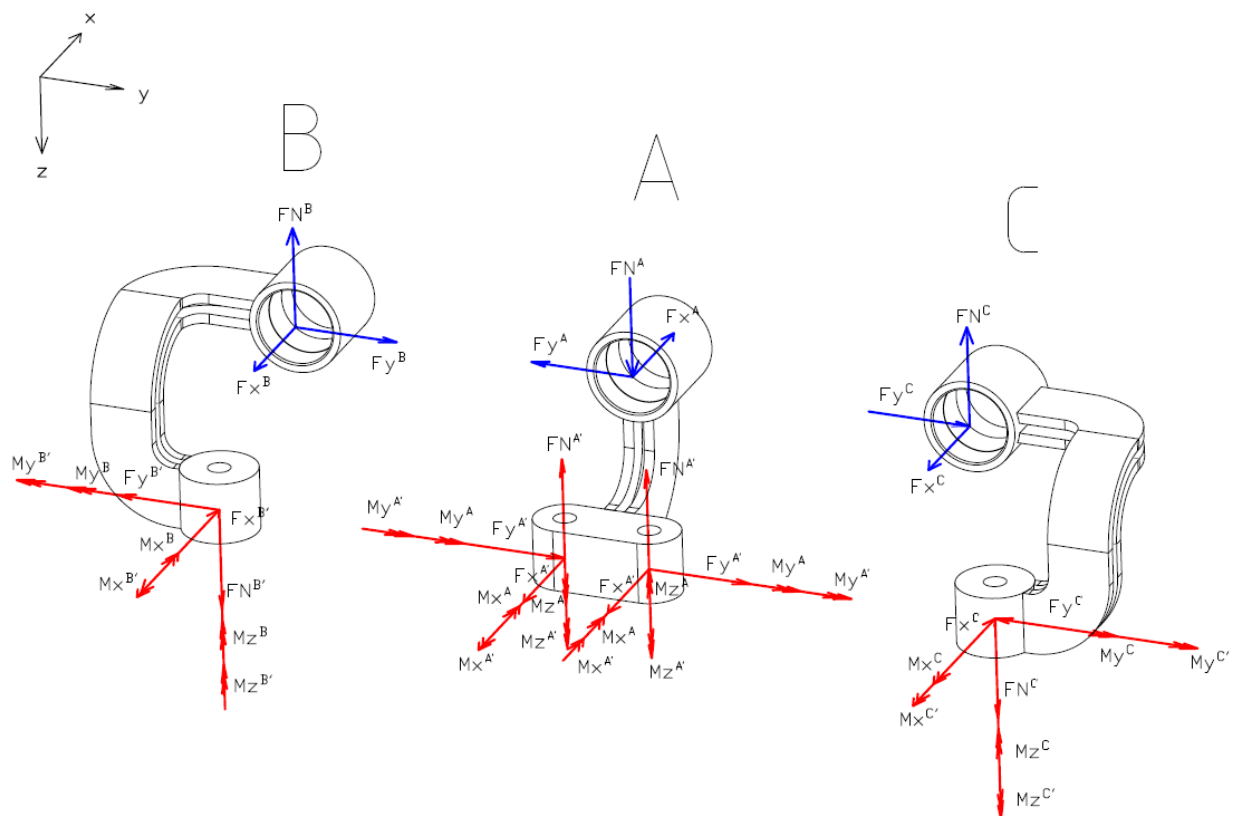
**Figure 11.** Bicycle FBD when turning

Figure 11 presents the FBD of the Trolley City bicycle when it is turning. In this scenario, three main forces act on the center of gravity (CG) of the bicycle. Normal Force ( $F_N$ ) acts vertically to support the weight of the bicycle and rider.

Aerodynamic Force ( $R_a$ ) acts horizontally due to the air resistance as the bicycle moves. Centrifugal Force ( $F_c$ ) acts outward during the turn, creating a force that pulls the bicycle away from the turn's center.

These forces are balanced by reaction forces acting on each wheel, such as  $F_N$ ,  $F_x$ ,  $F_y$ ,  $F_{gx}$ , and  $F_{gy}$ , which are calculated and displayed in the subsequent diagrams.

The quasi-dynamic analysis was used to obtain a clearer picture of the forces during a turning condition, as it involves a more complex combination of forces, including centrifugal forces that are not present when the bicycle is moving straight. This approach allows for a more accurate understanding of how the steering system responds under dynamic conditions.



**Figure 12.** FBD of bracket

Once the forces acting on the bicycle were determined, Figure 12 illustrates the FBD applied to the bracket. The forces acting on the bracket are the result of the forces transmitted through the steering system, with each component of the bracket (middle, left, and right) subjected to different magnitudes and directions of forces.

The FBD of the bracket allows us to visualize how each joint and connection (bearing joints, ball joints) is affected by the forces transmitted from the wheel and steering system. This helps in determining whether the bracket design can withstand the expected loads without failure.

**Table 6.** Loading on the bracket

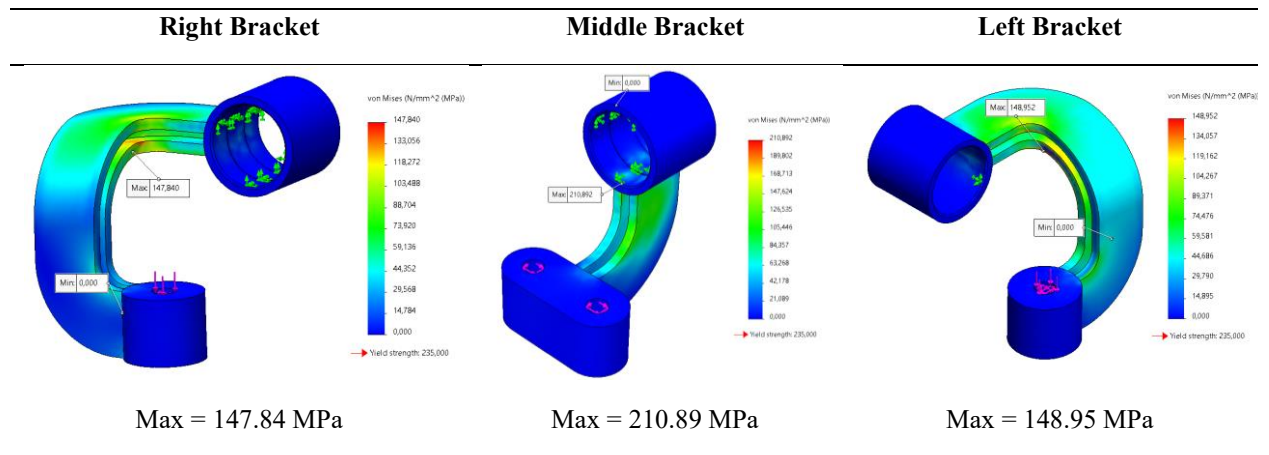
| No                                      | Parameter           | Notation                     | Unit | Value  |
|-----------------------------------------|---------------------|------------------------------|------|--------|
| Actual Total Mass of the Model          |                     |                              |      |        |
| 1                                       | Bicycle system mass | M <sub>system</sub>          | kg   | 43     |
| 2                                       | Rider mass          | M <sub>driver</sub>          | kg   | 80     |
| 3                                       | Cargo mass          | M <sub>load</sub>            | kg   | 20     |
| 4                                       | Total mass          | M <sub>tot</sub>             | kg   | 143    |
| 5                                       | Total weight        | W                            | N    | 1430   |
| Forces Acting on the Middle Bracket (A) |                     |                              |      |        |
| 1                                       | Longitudinal Force  | F <sub>x</sub> <sup>A</sup>  | N    | 82.44  |
|                                         |                     | F <sub>x</sub> <sup>A'</sup> | N    | 41.22  |
| 2                                       | Lateral Force       | F <sub>y</sub> <sup>A</sup>  | N    | 86.6   |
|                                         |                     | F <sub>y</sub> <sup>A'</sup> | N    | 43.3   |
| 3                                       | Normal Force        | F <sub>N</sub> <sup>A</sup>  | N    | 135.79 |
|                                         |                     | F <sub>N</sub> <sup>A'</sup> | N    | 67.89  |
| Forces Acting on the Right Bracket (B)  |                     |                              |      |        |
| 1                                       | Longitudinal Force  | F <sub>x</sub> <sup>B</sup>  | N    | 41.22  |
|                                         |                     | F <sub>x</sub> <sup>B'</sup> | N    | 41.22  |
| 2                                       | Lateral Force       | F <sub>y</sub> <sup>B</sup>  | N    | 86.6   |
|                                         |                     | F <sub>y</sub> <sup>B'</sup> | N    | 86.6   |
| 3                                       | Normal Force        | F <sub>N</sub> <sup>B</sup>  | N    | 67.89  |
|                                         |                     | F <sub>N</sub> <sup>B'</sup> | N    | 67.89  |
| Forces Acting on the Left Bracket (C)   |                     |                              |      |        |
| 1                                       | Longitudinal Force  | F <sub>x</sub> <sup>C</sup>  | N    | 41.22  |
|                                         |                     | F <sub>x</sub> <sup>C'</sup> | N    | 41.22  |
| 2                                       | Lateral Force       | F <sub>y</sub> <sup>C</sup>  | N    | 86.6   |
|                                         |                     | F <sub>y</sub> <sup>C'</sup> | N    | 86.6   |
| 3                                       | Normal Force        | F <sub>N</sub> <sup>C</sup>  | N    | 67.89  |
|                                         |                     | F <sub>N</sub> <sup>C'</sup> | N    | 67.89  |

Based on the FBD analysis, the loading values on the bracket were determined and summarized in Table 6. The table shows the forces acting on the middle, right, and left brackets in terms of longitudinal, lateral, and normal forces.

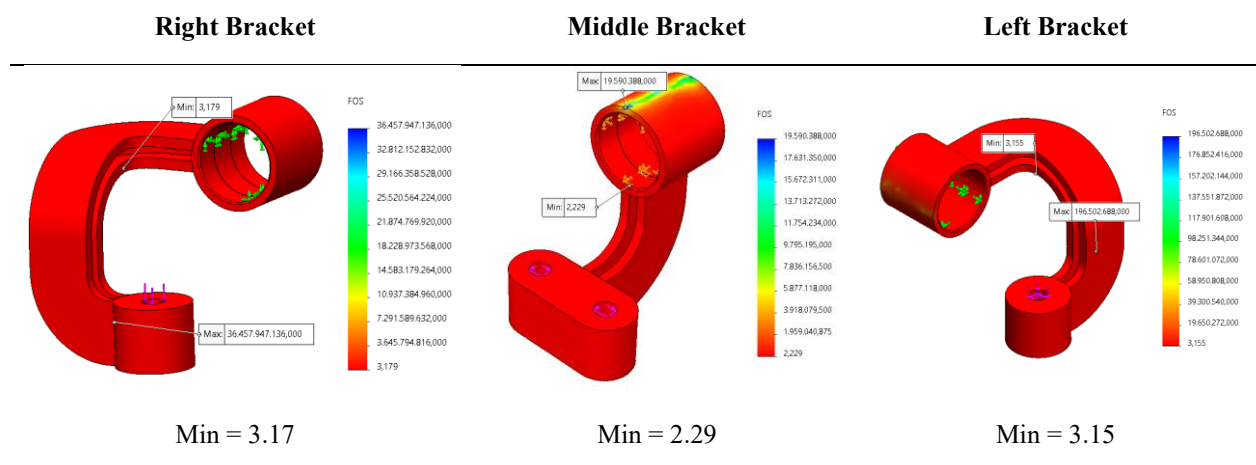
The values obtained from the FBD calculations are essential for the Finite Element Analysis (FEA) simulations, where they are applied to test the bracket's structural integrity and safety under these loading conditions. To ensure the accuracy and reliability of the structural analysis, finite element models were developed in SolidWorks Simulation using linear isotropic elastic material behavior. The mechanical properties assigned for ST37 structural steel were: elastic modulus  $E = 210$  GPa, Poisson's ratio  $\nu = 0.28$ , mass density  $\rho = 7850$  kg/m<sup>3</sup>, and minimum yield strength  $\sigma_y = 235$  MPa. Boundary conditions were established to simulate actual operating constraints: fixed cylindrical supports were applied to the primary pivot sleeve bearing surfaces, while multi-axial reaction forces derived from the FBD accounting for dynamic cornering loads at 143 kg gross vehicle weight were applied at the tie-rod mounting holes. A mesh independence study was performed using solid 10-node quadratic tetrahedral elements. Mesh refinement iterations were conducted with global element sizes ranging from 8 mm down to 2 mm (with local edge refinement at fillet radii). Convergence was achieved

when the variation in peak Von Mises stress between successive refinements fell below 4%. The final discretized model for the middle bracket contained approximately 42,600 elements and 61,800 nodes, ensuring mesh-independent numerical stability and high solution confidence.

**Table 7.** Von mises stress simulation results for ST37 bracket

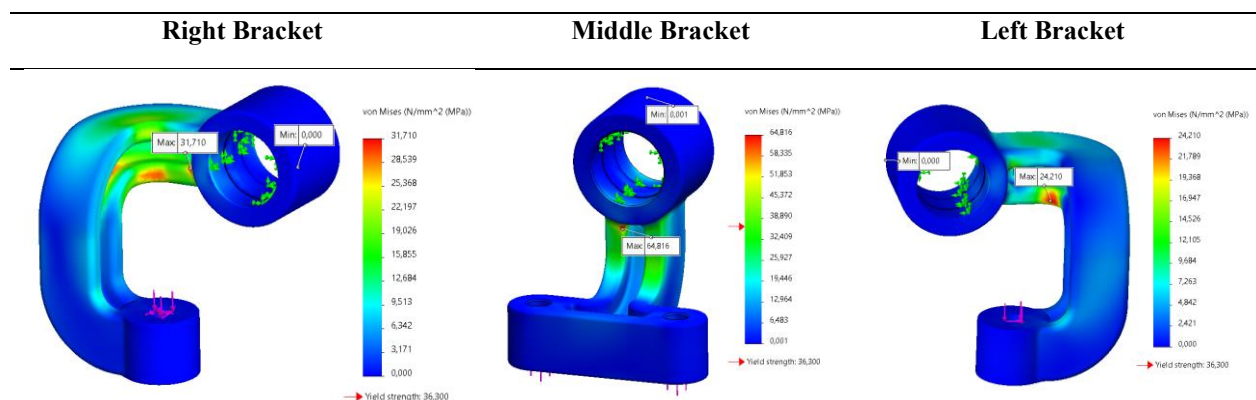


**Table 8.** Safety factor simulation results for ST37 bracket



Based on the simulation results, the ST37 bracket is safe to use, as it has not exceeded the material's yield strength.

**Table 9.** Von mises stress simulation results for PLA bracket

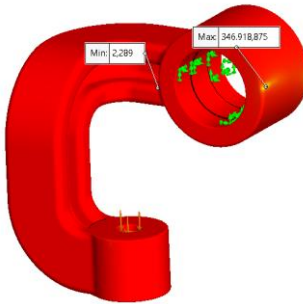
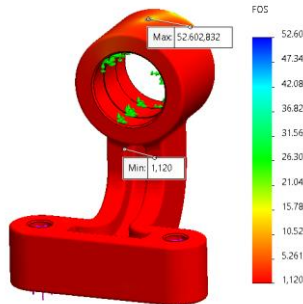
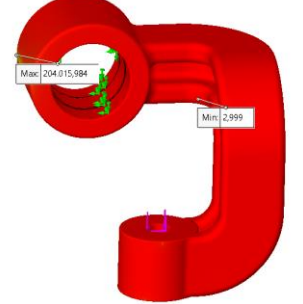


Max = 31.71 MPa

Max = 64.81 MPa

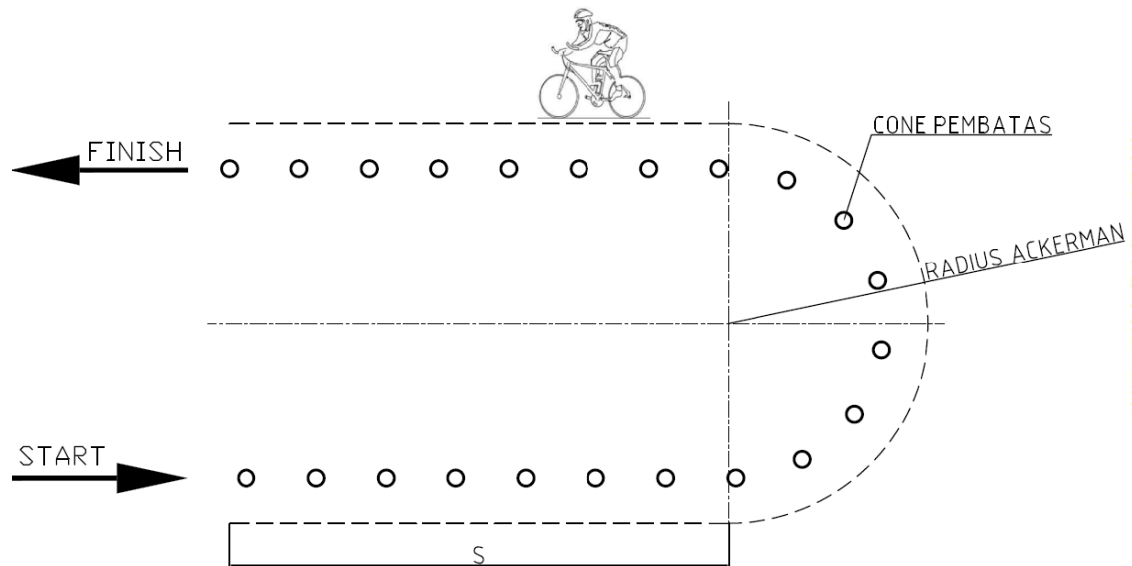
Max = 24.21 MPa

**Table 10.** Safety factor simulation results for PLA bracket

| Right Bracket                                                                                       | Middle Bracket                                                                                      | Left Bracket                                                                                          |
|-----------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------|
|  <p>Min = 2.28</p> |  <p>Min = 1.12</p> |  <p>Min = 2.99</p> |

Based on the simulation results, the PLA bracket shows the possibility of permanent deformation in the middle bracket, as it has exceeded the material's yield strength.

After the analysis, testing was conducted to directly assess the bracket's ability to withstand the stresses occurring in various testing simulation conditions. The tests were conducted using a U-turn track, as shown in Figure 13.



**Figure 13.** Testing scenario

During the tests, the cyclist pedaled a predetermined distance (s) to reach the required speed. The bicycle then turned following the Ackerman radius of 5.95 m, 3.97 m, 2.98 m, and 2.38 m. The table below shows the results of testing the bicycle using the ST37 bracket.

**Table 11.** Bicycle test results

| No | Speed (km/h) | Steering Angle (°) | Ackerman Radius | Remarks |
|----|--------------|--------------------|-----------------|---------|
| 1. | 5 km/h       | 10°                | 5.95 m          | 4       |
|    |              | 15°                | 3.97 m          | 4       |
|    |              | 20°                | 2.98 m          | 4       |
|    |              | 25°                | 2.38 m          | 4       |
| 2. | 10 km/h      | 10°                | 5.95 m          | 4       |
|    |              | 15°                | 3.97 m          | 4       |
|    |              | 20°                | 2.98 m          | 4       |
|    |              | 25°                | 2.38 m          | 4       |
| 3. | 15 km/h      | 10°                | 5.95 m          | 4       |
|    |              | 15°                | 3.97 m          | 4       |
|    |              | 20°                | 2.98 m          | 4       |
|    |              | 25°                | 2.38 m          | 4       |
| 4. | 20 km/h      | 10°                | 5.95 m          | 4       |
|    |              | 15°                | 3.97 m          | 4       |
|    |              | 20°                | 2.98 m          | 4       |
|    |              | 25°                | 2.38 m          | 4       |

Remarks:

1 = fall                      3 = slip

2 = roll                      4 = stable

Based on the test results with varying steering angles (10°, 15°, 20°, and 25°) and speeds (5 km/h, 10 km/h, 15 km/h, and 20 km/h), the bicycle remained in a stable condition (marked as 4). This indicates that the bicycle has a well-designed steering geometry and weight distribution, allowing it to maneuver effectively without experiencing slipping, falling, or rolling, even at the highest speed tested.

Figure 14 shows the fractures that occurred in the middle bracket (left) and the right bracket (right) during the testing phase. These failures provide significant insight into the limitations of the materials used and the overall design.

The fracture in the middle bracket occurred during the test with the PLA material, with a shell thickness of 0.8 mm. The analysis indicates that the failure was due to the high stress concentration at the center of the bracket, especially when the bicycle was moving in a straight line. This high stress was caused by the flexibility of the PLA material under load, which failed to adequately resist the forces acting on the bracket.

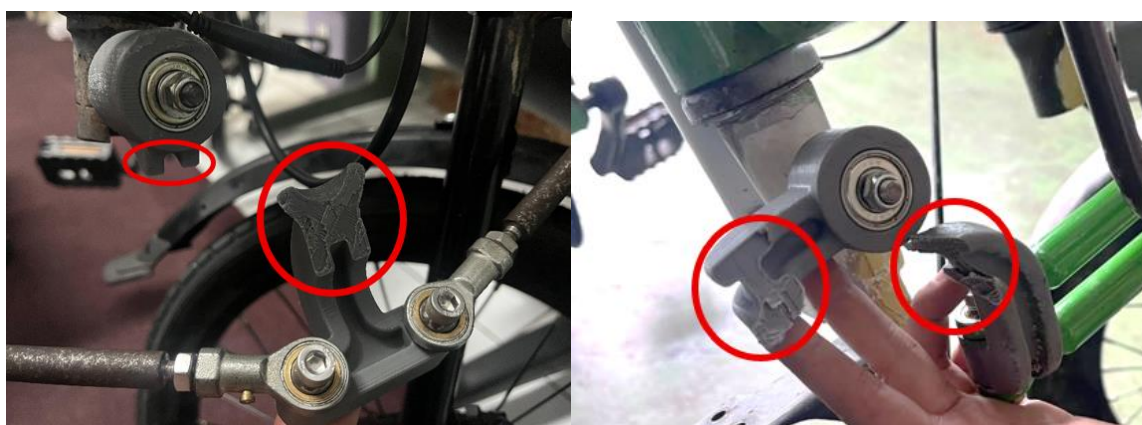
Additionally, the low shell thickness of 0.8 mm contributed to the inability of the PLA bracket to distribute the stresses effectively. The material reached its yield strength, leading to plastic deformation and ultimately causing the fracture. The design of the middle bracket was likely a contributing factor, as the lack of reinforcement in this area made it more susceptible to failure under high load conditions.

Key Factors Contributing to the Middle Bracket Failure are PLA has a lower yield strength compared to ST37 steel, making it unsuitable for high-load applications like this. The relatively thin shell of 0.8 mm did not provide sufficient resistance to the stresses experienced during the tests, contributing to the failure. The absence of reinforcements or stiffening features in the middle bracket increased its vulnerability to stress concentrations.

The right bracket also experienced a fracture, but this time, the bracket was printed with a shell thickness of 3.2 mm. This failure occurred during a right turn where the steering angle was quite extreme, leading to a small turning radius. The combination of the high lateral turning forces and small radius significantly amplified the load and stress on the right bracket. Interestingly, the linear static FEA had predicted a safety factor of 2.28 for this bracket, which theoretically indicated safe operation ( $SF > 1.5$ ). However, this static margin proved insufficient under actual dynamic conditions. The physical failure was induced by rapid dynamic shock loads and cyclic torsional stresses during cornering, which exploited the inter-layer delamination weaknesses inherent in FDM-printed PLA. This discrepancy demonstrates that while a static safety factor of 2.28 is deemed safe under static equilibrium, it does not guarantee structural integrity under real quasi-dynamic operational conditions without accounting for anisotropic material behavior and dynamic load amplification.

The PLA material was again found to be inadequate under these extreme conditions. Despite the increased shell thickness, the PLA bracket could not withstand the forces from the extreme turn, which led to the failure. The high stress was concentrated in the right bracket during the turn, where the material exceeded its yield strength, resulting in fracture.

Key Factors Contributing to the Right Bracket Failure are similar to the middle bracket, the PLA material was not suitable for the extreme forces involved in high-stress turning situations. The extreme steering angle and small turning radius created high centrifugal forces on the bracket, contributing to the fracture. Even with the thicker shell of 3.2 mm, the PLA bracket could not distribute the stresses effectively under dynamic conditions.



**Figure 14.** Middle bracket fracture (left) and right bracket fracture (right)

The results from the FBD calculations indicated that the forces acting on the bracket were well within the material's capacity to handle without failure, particularly for the ST37 steel bracket. However, the PLA bracket showed potential

for permanent deformation in the middle bracket due to the high stresses during testing, as observed in the simulation and physical testing results.

These findings are consistent with the FEA simulation results, which predicted high stress levels in the middle bracket when using PLA material, confirming the need for design adjustments, such as increased shell thickness or material changes for better durability.

#### 4. Conclusion

This study successfully designed, constructed, and evaluated a tilting steering bracket for a trolley city three-wheeled bicycle using the VDI 2221 systematic design approach and quasi-dynamic considerations. Through the evaluation of alternative functional combinations (AFK), the optimal steering configuration was selected and validated via both finite element analysis (FEA) and operational field testing. The structural evaluation confirmed that the bracket fabricated from ST37 structural steel safely withstood maximum operational payloads up to 143 kg during cornering maneuvers, yielding a safety factor exceeding 1.5 and maintaining rigid steering alignment without permanent deformation. In contrast, while FDM 3D-printed PLA demonstrated effectiveness for rapid dimensional prototyping and geometric fit validation, it exhibited insufficient load-bearing capacity and durability under dynamic cornering forces. For future research and practical manufacturing, it is recommended to evaluate commercial steering dampers to replace unavailable standard gas springs, incorporate anisotropic material models with varied print orientations for 3D-printed structural components, and conduct extended cyclic fatigue testing under full payload conditions.

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