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Structural Evaluation of a Three-Wheeler Vehicle Using Simulation Tools: A Case Study in Mexico

Evaluación estructural de un vehículo tipo mototaxi usando herramientas de simulación: caso México

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Abstract

The mototaxi, a three-wheeled vehicle equipped with a roof, is a widely utilized mode of transportation in Mexico. Typically, it is employed for short-distance journeys in exchange for payment, similar to the operation of a conventional taxi. This study conducts a structural analysis of a mototaxi-type vehicle utilized in Mexico to assess its performance and safety. It underscores the significance of this mode of transportation, widely relied upon by numerous individuals. A product design and development methodology was employed, utilizing torsional deformation simulations to validate the new geometry. The objective was to minimize torsions as much as possible, thereby enhancing the motorcycle taxi's safety and ensuring the vehicle's correct positioning. Through computer-aided design, the prevailing torsions within the casing were assessed, establishing the operating conditions to which the system is commonlysubjected. The findings from the chosen vehicular structure reveal a flexural rigidity of 6,508.15 N/mm, torsional rigidity of 27.35 KNm/°, and a range of natural frequencies between 8-21 Hz. These values indicate favorable resistance against bending forces and operational frequency. However, the torsional results exhibit deficiencies, suggesting an unsafe structure for all motorcycle taxi occupants. Consequently, technology developers and national legislators should prioritize enhancing the structural integrity of such vehicles.

Keywords: Structural, Mototaxi, Safety, ANSYS, CAE, Simulation

Resumen

El mototaxi es un vehículo de tres ruedas y con techo que se usa como medio de transporte popular en México, generalmente para recorrer caminos cortos a cambio de dinero, de la misma forma que opera un taxi. Esta investigación presenta el análisis estructural de un vehículo tipo mototaxi empleado en México, para evaluar su desempeño y seguridad, teniendo en cuenta que es un medio de transporte utilizado por muchas personas. Se empleó una metodología de diseño y desarrollo de producto, utilizando simulaciones de deformación torsionales para validar la nueva geometría, minimizando las torsiones en lo posible, tratando de mejorar la seguridad del mototaxi, así como la posición correcta del vehículo. Mediante el diseño asistido por computadora se probaron las torsiones existentes en la carcasa, determinando las condiciones de operación por las que generalmente es sometido el sistema. Los resultados obtenidos en la estructura vehicular seleccionada son para la rigidez por flexión de 6508,15 N/mm, la rigidez torsional de 27,35 KNm/° y el rango de frecuencias naturales en 8-21 Hz, valores que muestran que la estructura presenta condiciones favorables mediante esfuerzos de resistencia por flexión y la frecuencia de operación de la estructura, pero carencias en los resultados torsionales, generando así una estructura insegura para los ocupantes del mototaxi. Es necesario que los desarrolladores de tecnología como los legisladores nacionales actúen en favor de mejorar sus condiciones estructurales.

Palabras clave: estructural, mototaxi, seguridad, ANSYS, CAE, simulación

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1. Introduction

The insufficient supply and restricted public transportation coverage in developing countries have prompted the emergence of mototaxism in numerous cities worldwide, wherein motorcycles are utilized as a form of public transportation.

A mototaxi, characterized by its three-wheeled structure and roof, is a cost-effective means for individuals to fulfill their mobility requirements, akin to traditional taxis. It fills a unique niche in transportation services, catering to entire journeys and the initial and final segments of trips in densely populated, congested, or otherwise inaccessible areas. These trips are often too lengthy and challenging to traverse by foot yet fall short of commercial viability for conventional public transportation modes.

The inception of the mototaxi occurred in Paris in 1999, representing an innovative and efficient transportation solution aimed at addressing the travel requirements of passengers commuting between the city's two airports [1].

For approximately two decades, this mode of transportation has been present in Mexico City and various states of the Republic, predominantly in the form of motorcycles equipped with a canopy and cabin-incorporated motocarros [2].

The mototaxi caters to particular yet unfulfilled transportation demands and functions more as a supplementary service than a direct competitor to other public transportation modes. Its primary advantage lies in its lightweight construction, speed, and ease of parking, enabling users to traverse short distances more efficiently. According to the National Institute of Statistics and Geography, over 273,000 mototaxi trips occur daily in Mexico City and its metropolitan region, constituting 3.7% of all public transportation journeys [3].

In Juchitán de Zaragoza, Oaxaca, Mexico, the King model is frequently employed as a mototaxi owing to its versatile chassis, instrumentation, engine, power, and torque capabilities. This model achieves a maximum speed of 56 kilometers per hour and has a curb weight of 300 kilograms [4].

Mototaxis belong to the classification of small motor vehicles, alongside mopeds, scooters, motorcycles, motorized tricycles, quad bikes, and analogous vehicles [5].

The mototaxi industry grapples with numerous challenges, encompassing congestion, road infrastructure, regulatory standards, and safety considerations [6].

On a global scale, the utilization of mototaxis has adversely affected the environment, social dynamics, and road safety.

The adverse environmental impacts primarily stem from pollutant emissions resulting from inadequate vehicle maintenance and the use of low-quality fuel [7].

In the State of Mexico, mototaxis serve as sources of informal employment for both men and women, offering an average weekly income of $1236 to drivers. These drivers typically possess a secondary or high school education, with common-law marriage being the most prevalent marital status [8]. Puebla has over ten thousand estimated mototaxi drivers across over sixty municipalities [9].

Regarding road safety issues, mototaxis are responsible for numerous severe traffic accidents.

Table 1 presents some characteristics of these vehicles that highlight the safety issues associated with them.

Table 1. Characteristics of Mototaxis

Characteristic	Description
Availability	High (general community)
Capacity	Six occupants (6), plus luggage
Comfort	Low
Safety	Low (traffic accidents)
Cabin Space	Limited
Traffic Accidents	Severe due to lack of safety equipment (helmet, seat belts, airbags).
Noise	High. This can cause hearing damage due to high decibel levels.

Moreover, the chassis is commonly regarded as the vehicle's skeleton, as it accommodates the components necessary for proper operation. The chassis must possess sufficient strength to withstand impacts, torsion, vibrations, and other stresses encountered during operational activities.

Another crucial aspect concerns legislation, as all vehicles operating on public roads must adhere to specific regulations established by some institutions and laws. In numerous Mexican states, mototaxis remain largely unregulated. However, in the state of Puebla, guidelines governing mototaxis are outlined in the transportation law, particularly in articles 12 and 37 [10].

Hence, this study aims to assess the structural integrity of this mode of transportation to ascertain the level of safety provided by service providers to their users.

2. Materials and method

A product design and development methodology was employed to assess the performance and safety of the mototaxi-type vehicle, utilizing a digital model of the three-wheeled vehicle structure. The study proceeded through the following phases: benchmarking, technical characterization, development of the analysis model, and structural evaluation.

Four prominent brands in Mexico, including TSV, ATUL, KingWay, and Bajaj and their primary models were examined during the benchmarking phase. Eight key characteristics were analyzed, including maximum power, maximum torque, fuel consumption, load capacity, brakes, chassis, and stabilizer bar, as detailed in Table 2.

Table 2. Evaluation of Mototaxi Brands

Characteristic	TSV	ATUL	KingWay	Bajaj
Suspension	4	4	3	4
Load Capacity	5	3	4	3
Fuel Consum.	2	3	4	2
Brake System	3	3	3	3
Transmission	3	3	4	3
Dimensions	3	4	3	3
Chassis	4	3	2	5
Cooling System	5	4	3	4
Maintenance	5	4	4	4

Using the acquired data, each vehicle underwent an evaluation to ascertain the one possessing superior attributes. In this subsequent phase, nine characteristics were considered as delineated by the authors. Ratings were assigned on a 5-point scale, with 1 representing deficiency and 5 indicating optimal performance, as outlined in Table 2. The TSV brand, specifically the King Duramax model, attained the highest score.

The ratings were determined through consensus among the authors. Based on the averaged scores, the King Duramax was selected with a rating of 3.71. It is noteworthy that the results were closely aligned, as the four models under scrutiny exhibited very comparable characteristics and performance, thereby sharing similar attributes.

In the technical characterization, the TVS Group, an Indian company ranking third globally, is India's largest manufacturer of two-wheeled vehicles, with its products being exported to over sixty countries. Renowned for delivering high-quality vehicles that cater to customer requirements, TVS has established Motocarros TVS in Mexico. This branch, dedicated to the distribution of three-wheeled vehicles, operates under Kawasaki with the backing of Grupo Motomex.

The selected unit was the King Duramax 2020, shown in Figure 1.Based on the obtained data, each vehicle was rated to determine the one with the best qualities. For this new stage, nine characteristics defined by the authors were considered. The ratings were on a 5-point scale where 1 is deficient and 5 is optimal, as presented in Table 2. The highest score was obtained by the TSV brand, with the King Duramax model.

The ratings were assigned by consensus among the authors. According to the averages obtained, the King Duramax was chosen with a score of 3.71. It is important to mention that the results were very close because the four analyzed models have very similar characteristics and performance, thus having similar elements.

In the technical characterization, the TVS Group, an Indian company that ranks third, is the largest manufacturer of two-wheeled vehicles in India, currently exporting to more than sixty countries. It is a company known for offering quality vehicles that anticipate customer needs. In Mexico, Motocarros TVS, the branch dedicated to the commercialization of three-wheeled vehicles, is part of Kawasaki with the support of Grupo Motomex.

The chosen unit was the King Duramax 2020, as illustrated in Figure 1.

Figure 1. King Duramax 2020 [11].

Table 3 presents some of its technical features.

Table 3. Technical Characteristics of the King Duramax 2020

Property	Value
Maximum Power	10 Hp @ 4750 RPM
Maximum Torque	18 Nm @ 2750 RPM
Displacement	225 cc
Maximum Speed	63 km/h
Brake Type	Hydraulic drum
Structure Type	Semi-monocoque formed by longitudinal and transverse pressed elements
Structure Material	Metal
Curb Weight	399 kg
Ground Clearance (loaded)	169 mm
Dimensions	Length: 2647 mm Width: 1329 mm Height: 1740 mm

During the development stage of the CAD analysis model, CAD and CAE software, including CATIA V5 2020 and Ansys 2020, were utilized.

A similar configuration model was proposed using the data collected from the mototaxi benchmarking. It comprised a semi-monocoque structure constructed from longitudinal and transverse pressed elements, commonly referred to as a ladder frame or chassis-type structure, as depicted in Figure 2.

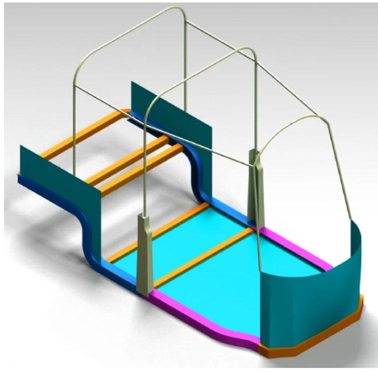

Figure 2. Ladder or Chassis Type Automotive Structure

Considering the information from the TVS manufacturer, a model comprising 30 components was developed. These components primarily encapsulate those pertinent and indispensable for analysing the vehicle's structure, including chassis elements, lower panels, and select exterior panels, as depicted in Figure 3.

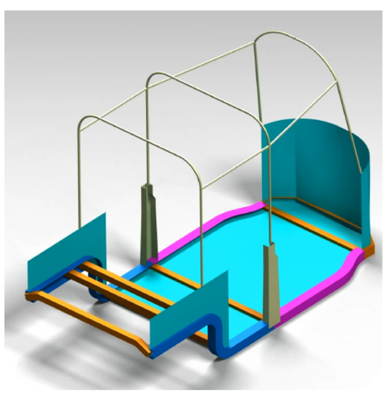

Figure 3. CAD Model of the Structure

Figure 4 depicts the structure's frontal components, featuring the removal of the front panel to expose the chassis components and panels.

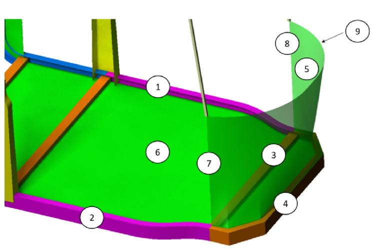

Figure 4. Front Chassis Elements

Figure 5 illustrates the intermediate elements of the vehicle, highlighting the "posts" and components responsible for supporting the passengers.

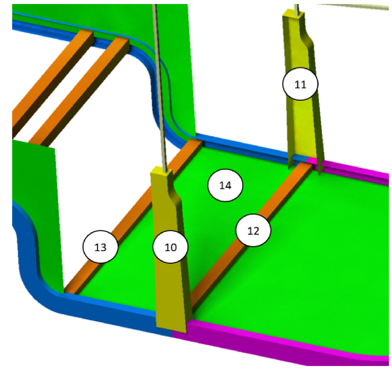

Figure 5. Intermediate Chassis Elements

Figure 6 illustrates the rear section of the structure with the components that accommodate mechanical elements like the engine system and rear suspension, along with the rear panels and the rear impact bar.

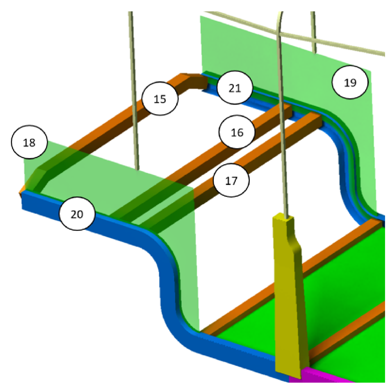

Figure 6. Rear Chassis Elements

Furthermore, additional minor pertinent elements were included in the vehicle evaluation, characterized by a roof structure possessing the following properties, as illustrated in Figure 7.

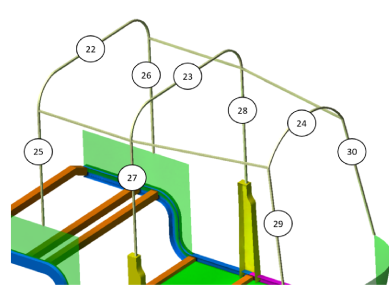

Figure 7. Estructura superior del techo

Ultimately, Figure 8 displays the final model intended for structural analysis. This model exclusively incorporates the elements utilized in the CAE evaluation of the vehicle.

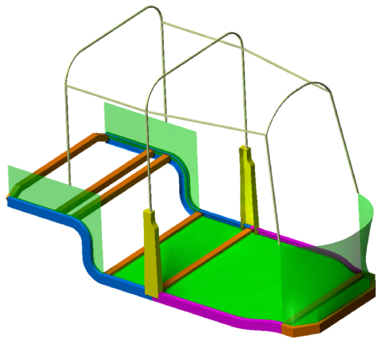

Figure 8. Global View of the Mototaxi Model for Structural Evaluation

Table 4 presents the various components utilized along with their descriptions, particularly regarding the type of profile employed for structural evaluation.

For the vehicle evaluation, several materials were initially explored for the modeled elements to ensure optimal outcomes. ASTM A36 steel and 6063-T83 aluminum alloy were chosen for their established applications in automotive structures and panels [12].

Table 4. Specification of Selected Components in the Mototaxi Structure

Section	Number	Specification	Material
Front Element	1.2	C-profile 3 in × 1,498 in × 0,258 in	ASTM A36
Front Element	3, 4, 7, 8	Square profile 2 in × 2 in × 0,25 in	ASTM A36
Front Element	5	Fiberglass panel thickness 0,109 in	6063-T83
Front Element	6	Aluminum sheet gauge 12	6063-T83
Front Element	9	Square profile 0,5 in × 0,5 in × 1,10 in	ASTM A36
Intermediate Element	10, 11, 14	Aluminum sheet gauge 12	6063-T83
Intermediate Element	12, 13	Square profile 2 in x 2 in x 0,25 in	ASTM A36
Rear Element	18, 19	Aluminum sheet gauge 12	6063-T83
Rear Element	15, 16, 17	Square profile 2 in × 2 in × 0,25 in	ASTM A36
Rear Element	20.21	C-profile 3 in × 1,498 in × 0,258 in	ASTM A36
Other Elements	22-30	Square profile 0,5 in × 0,5 in × 0,110 in	ASTM A36

Considering this, three studies were proposed using ANSYS software to assess torsional rigidity, flexural rigidity, and natural vibration modes. The pertinent global variables are outlined in Table 5.

Table 5. Technical Specification of Considered Global Variables

Study	Geometry Type	Study Type	Number of Mesh Elements
Torsion	Chassis 1D Panels Midsurface 2D	Static linear	Elements: 26616
Flexion	Chassis 1D Panels Midsurface 2D	Static linear	Elements: 26616
Natural Vibration Modes	Chassis 1D Panels Midsurface 2D	Modal	Elements: 26616

Figure 9 illustrates the applied constraints (depicted by stars labeled with the letter F) and the utilized loads (vectors identified with annotations B and C inside circles) for the torsion analysis of the structure, along with the obtained deformation values. The load values were determined by prioritizing loads that closely mimic real-world conditions, as specified in Table 6.

Table 6. Specification of Load Locations on the Primary Structure of the Mototaxi for Study

Load type	Value	Ubication
Axial	2354,4 N	Lateral
Axial	–2354,4 N	Lateral

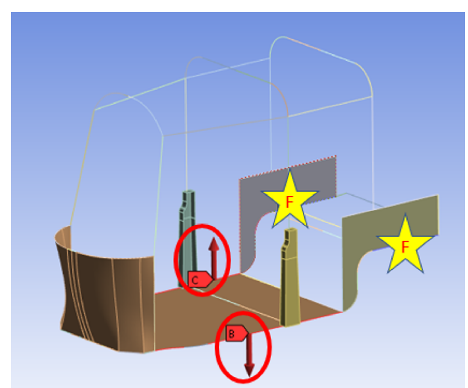

Figure 9. Global View of the Mototaxi Model Representing Applied Loads for Study

Given the possibility of mototaxi operators occasionally overloading the structure, it is imperative to ascertain its resistance to torsional forces. Consequently, investigations were conducted using a maximum load capacity of six individuals, each weighing an average of eighty kilograms, resulting in a total of 4708 N, distributed in two sections. These revised values were then applied to the lateral areas of the mototaxi structure in opposite directions to assess and validate the newly acquired results.

Figure 10 illustrates the applied constraints (depicted by stars labeled with the letter F) and the utilized loads (directional vectors annotated with B, C, and D enclosed in circles) for the flexural analysis of the structure, from which deformation values are derived.

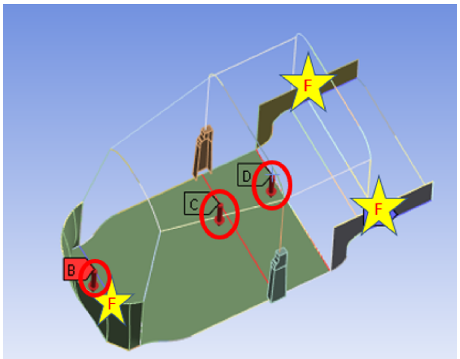

Figure 10. Constraints in the Flexural Analysis

For the flexural analysis, the maximum load capacity that the primary structure can sustain was considered, amounting to seven individuals, each averaging eighty kilograms. Consequently, with a total load of 560 kilograms, this value is distributed among the three beams depicted in the figure, resulting in a distribution of 5494 N among the three beams represented.

For the modal study, the analysis focused on examining the six natural vibration modes of the model. Figure 11 illustrates the positional constraints applied to the vehicle structure for this analysis. Table 7 specifies the type of restraints employed in the study.

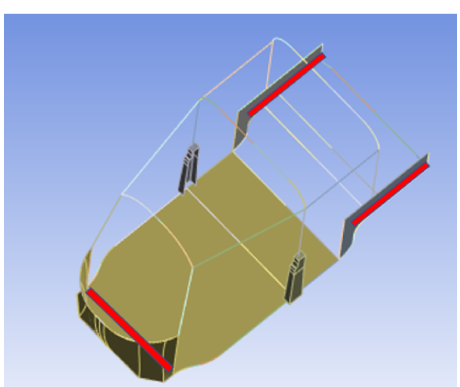

Figure 11. Positional Constraints

Table 7. Specification of Load Locations on the Primary Structure of the Mototaxi for Study

Restraint Type	Number of Restraints	Location
Fixed Support	3	Internal lower beams

3. Results and Discussion

Figure 12 illustrates the torsional deformation induced by the previously described loads.

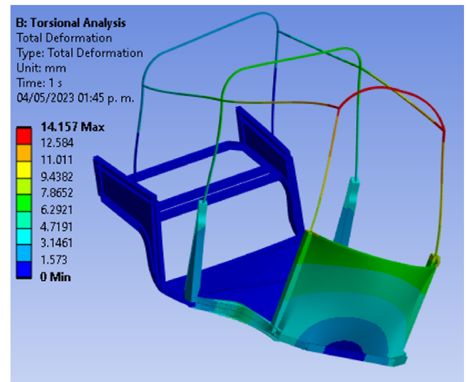

Figure 12. Global View of the Mototaxi Model Representing the Results of Torsional Loads

As depicted in Table 8, a torsional rigidity value of 27.35 KNm/º was derived from the applied torsional load and a measured structural torsion angle of 0.27251°. Furthermore, the maximum observed deformation amounts to 14.157 mm.

Table 8. Torsional Evaluation Results

Torsion results	
Maximum	(Angle)
14,157 mm	0,27251º

For flexural rigidity, Figure 13 depicts the observed deformationin the mototaxi structure.

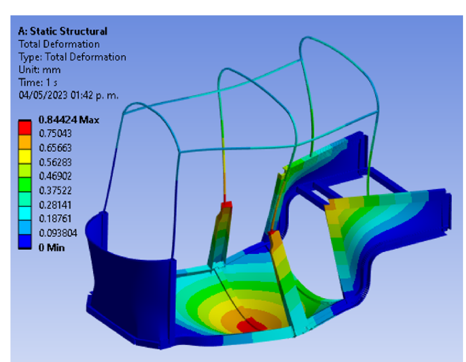

Figure 13. Global View of the Mototaxi Model Representing the Results of Flexural Loads

The maximum observed deformation is 0.84424 mm, leading to a flexural rigidity value of 6508.15 N/mm. As for the modal analysis of the mototaxi structure, Figure 14 illustrates the various vibration modes of the analyzed structure. As part of this assessment, the typical engine operating revolutions of the vehicle were identified, with an operational frequency determined to be 88 Hz.

In Table 9, the numerical values found in the vibration modes of the structure are described.

Table 9. Modal Evaluation Results

Operating Revolutions of the Mototaxi Engine	Vibration Modes Results	Numerical Values in Hertz
5250 rpm→88 Hz	1	8.01
	2	10.335
	3	15.211
	4	26.205
	5	20.592
	6	21.3

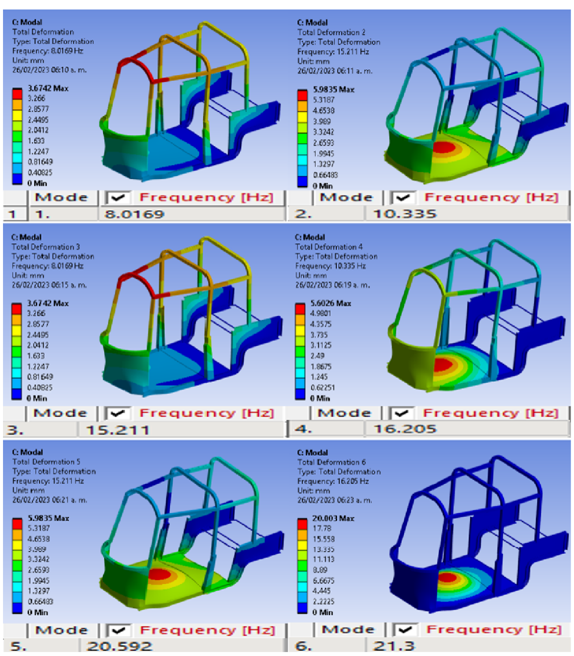

Figure 14. Global View of the Mototaxi Model Representing the Results of Applied Loads for Study

To ascertain the suitability of the acquired torsion and flexion values for the analyzed structure, the comparison by Hirz was employed as a reference. This comparison encompasses nine distinct categories, detailing specific ranges of torsional stresses for each category [13].

In the analysis of the mototaxi, the categories primarily considered were "mini car," "compact car," and "convertible," facilitating a comparable assessment. Particular emphasis was placed on the "convertible" category due to the mototaxi's configuration. Given its structural design primarily in the lower part, it bears a strong resemblance to the "convertible" category.

Based on the analysis depicted in Figure 15, it is evident that the structure exhibits greater torsional rigidity compared to the "convertible" category, which typically ranges from 10 to 17 KNm/º, while the mototaxi demonstrates a value of 27.35 KNm/º. As for flexural rigidity, a similar comparison was conducted with analogous structures from diverse studies, and Figure 16 displays six different studies [14–19] along with their respective values.

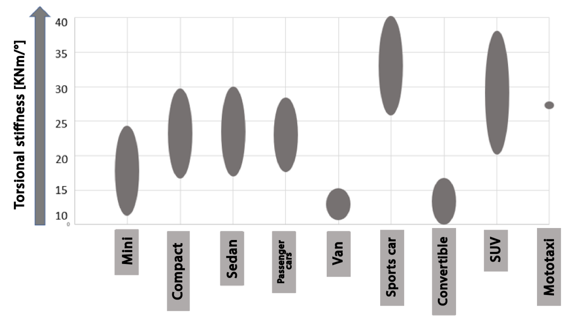

Figure 15. Comparison of Structural Torsion Resistance Results

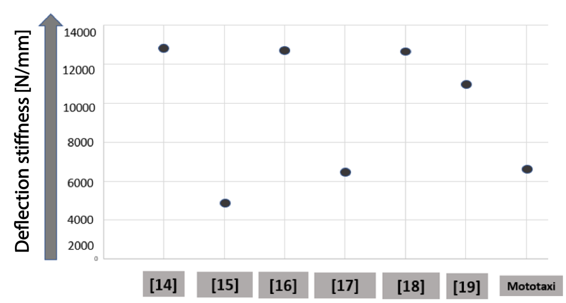

Figure 16. Comparison of Flexural Rigidity Results

When comparing flexural stresses, it is evident that the mototaxi structure exhibits a value of 6508.15 N/mm. The reviewed studies reveal comparable values, suggesting that the structure behaves similarly (with values ranging from 5 to 13 KN/mm) to other studies evaluatingflexural rigidity.

4. Conclusions

The conducted studies comprehensively assessed the performance of the vehicle structure across three primary criteria: flexural rigidity, torsional rigidity, and modal evaluation. The meticulous analysis of the calculated values and comparisons revealed that the mototaxi-type structure exhibits notable concerns regarding structural integrity. These concerns were underscored by observable deviations compared to similar structures in the vehicle's torsional studies. This discrepancy hints at potential structural behavioral issues during operation, possibly stemming from the absence of an integrated structure, including the roof.

Consequently, this deficiency impairs the structure's performance efficiency, diminishing energy absorption and dissipation capacity. Notably, the flexural studies of the structure yielded values closely aligned with those of comparable structures. In contrast, the modal evaluation revealed a lack of alignment between the natural frequencies and the operational frequency of the vehicle's components, thus indicating inadequacies under these criteria.

Similarly, A. Rodríguez [20] analyzed a tricycle structure under defined parameters and specified load cases. Unlike the aforementioned studies, which primarily focused on assessing the structure's failure and fatigue criteria, this investigation focused on evaluating the vehicle's response under static working conditions. Future work could encompass evaluations incorporating relevant failure criteria and dynamic behavior analyses, thereby addressing potential hazards associated with frontal and lateral collisions or rollovers.

While vehicles of this class were primarily developed to provide an economical mobility option for both users and operators, the structure of mototaxis poses risks to the safety of passengers. It is imperative for local and national legislation, as well as developers of this vehicle technology, to enhance its structural and dynamic conditions.

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