Indonesian Journal of Computing, Engineering, and Design

Journal homepage: http://ojs.sampoernauniversity.ac.id/index.php/IJOCED

On the Use of Steel and Aluminum Materials for Frame Structure of Electric Trike

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ABSTRACT

This work investigated the pros and cons of aluminum material used for electric trike frame compared with steel material. With a compact design and small dimension, e-trike is suitable to be used in many relatively small road accesses. However, the compact design can cause the frame to receive high and concentrated stress. The aluminum-based frame had lower strength, but lighter weight compared to the steel-based frame. In this study, the stress evaluation for both aluminum-based and steel-based frames is done using the finite element method. The minimum thickness of the aluminum-based frame was iterated to match the strength of the steel-based frame. The results showed that the aluminum-based frame has comparable performance to the steel-based frame but with lighter weight. However, the production cost of the aluminum-based frame might be a challenging issue to be solved.

ARTICLE INFO

Article History:
Received 15 Sept 2020
Revised 01 Dec 2020
Accepted 23 Feb 2021
Available online 1 Mar 2021

Keywords:
Aluminum-based frame,
Design,
E-trike,
Numerical simulation.

1. INTRODUCTION

Electric trike (e-trike) is a three-wheel electric vehicle that has been used for many purposes such as cargo delivery, tourism transportation, or garbage collection vehicle. The design of the e-trike is based on the urban city road, which has many small roads and a dense population (Arifurrahman, et al., 2018). Considering the road condition, the e-trike design is preferred because of its maneuverability and compact design. The e-trike has better load capacity than the motorcycle, which is always used by freight forwarders for good delivery. The use of electric power in the vehicle also has the potential to reduce air pollution significantly (Aziz et al., 2018). For example, based on the Indonesian Environmental Agency, 75% of air pollutants come from the transportation sector (Ridwan, 2020). Using electric drive trains, the pollution from the transportation sector can be decreased, and the air quality in Indonesia can be improved (Arifurrahman et al., 2018; Aziz & Budiman, 2017).

Structural integrity is the main focus to ensure the safety aspect in a vehicle to prevent an accident (Jusuf et al., 2017). The structure's design needs to be iterated to find the most efficient parameters, and it must be strong enough to bear the load. The frame's performance bearing the maximum load operation could be investigated by conducting static analysis (Arifurrahman et al., 2018). The maximum operational load may come from the battery, electric motor, upper structure, and driver weights. The deformation of the frame also needs to be evaluated in the static analysis. This evaluation is essential to ensure the frame vehicle does not have plastic deformation and avoid the vehicle components colliding with each other.

Another aspect that needs to be considered is the weight of the vehicle. An electric vehicle uses a battery as the primary power source (Halimah et al., 2019). The weight of the battery used for running the electric motor may increase the vehicle's power consumption (Kusuma et al., 2019). One solution to reduce the frame weight is to use materials with lower density (Cheah, 2010; Grabowski & Jaura, 2001; Joost, 2012; Kelly et al., 2015).

Several works investigated the usage of aluminum materials to replace steel materials as vehicle frames. Seyfried et al. discussed the weight reduction of several heavy-duty vehicle producers when replacing several parts of its frame from steel to aluminum, which successfully reduce its overall weight of the dump truck by 1900 kg and leads to reduced fuel consumption and tire wear (Seyfried et al., 2015). Saito et al. developed the vehicle body structure using an aluminum hybrid. The result showed that compared to a 3-door Civic car with a steel body, the design could reach 47% less weight (Saito et al., 2000). Several vehicle manufacturers also have produced aluminum-based frame. For example, Audi A8 reduces the body weight by 80% by using an aluminum-intensive space frame. Ford AIV uses stamped aluminum body structure which reduces the total weight of its vehicle by 320 kg. Renault and Lotus design its aluminum-based car, Spider, which has 30-50% lower weight than a steel-based car (Miller et al., 2000). Based on various research and model development that has been done in the automotive industry, which uses aluminum as the substitute for steel and provides a satisfactory result, study for aluminum usage in the e-trike vehicle has great potential to succeed.

Previous works of e-trike design in various research areas such as frame integrity, the component in drivetrain, electricity, etc., had already been conducted. Alpha-model was developed and patented as the light structure and high structural integrity of the e-trike (Budiman, 2020). The Alpha frame was designed as simple as possible so that the manufacturing process can be done with only bending, welding, and cutting. With the simple manufacturing process, the manufacturing cost and time can be reduced significantly. Faizal et al. investigate e-trike Alpha-model frame modal and static analyses (Arifurrahman et al., 2018; Arifurrahman, et al., 2018). A satisfactory result is found in the latest evolved alpha frame with minimum displacement at a safe frequency range. Furthermore, Sholahuddin et al. analyzed 5 kW electric motor used in the e-trike that focus on performance and weight reduction (Sholahuddin et al., 2016).

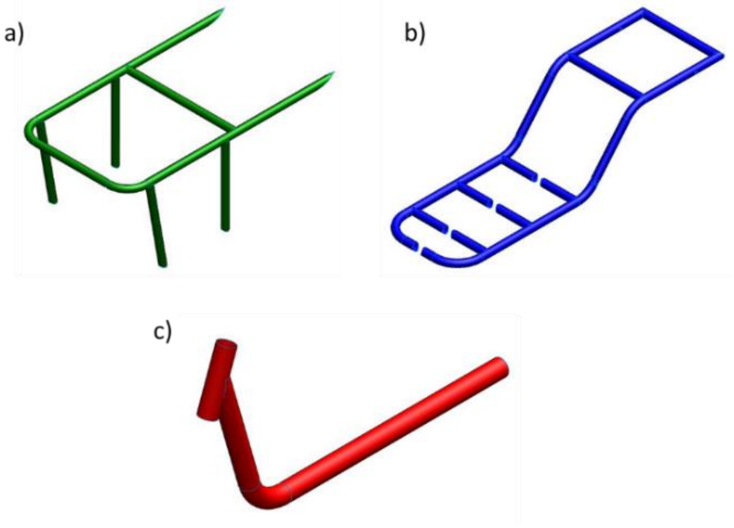


Figure 1. Alpha frame subcomponents: (a) seat frame, (b) mainframe, and (c) handling frame.

In this study, the static analysis of the Alpha frame using ASTM A36 Steel and aluminum 6016-T4 is conducted. By using aluminum, the weight of the vehicle can be decreased, and energy consumption will also decrease (McGregor, 2010). Static analysis is conducted using Finite Element Analysis (FEA) to reduce the computational cost significantly (Nurprasetio et al., 2017; Triawan et al., 2018). The main focus of the study was to find the design iteration of the aluminum-based frame that has minimal material usage and maximum stress with the steel-based frame as the design baseline. The maximum deflection of the frame should not exceed 3 mm to prevent damage to the e-trike component inside the frame. Two different dimension aluminum frame designs were then compared to find the optimum result based on the design criteria.

2. FINITE ELEMENT MODEL

2.1. Alpha Frame Geometry

Alpha frame has several versions for the design iteration. In this study, the latest version of the Alpha frame was used. The overall dimension of the Alpha frame is 2000 mm x 505 mm. The alpha frame can be divided into three subcomponents which are the handling frame, mainframe, and seat frame as shown in **Figure 1.**

A handling frame is used in the steering system of the e-trike. The handling frame is connected to the bottom side of the mainframe by using a welding joint. The handling frame extension will also bear the load of the battery placed under the seat frame to reduce the load concentration bore by the bottom side of the mainframe. The seat frame receives the load from the weight of the driver. The seat frame footing is connected to the bottom side of the mainframe and the upper side of the seat frame connected to the upper side of the mainframe. The mainframe is used for bearing the majority of the e-trike load. The mainframe receives a load from the upper structure, cargo box, battery, suspension system, and electric motor.

Table 1. Materials properties for A36 steel and aluminum 6061-T4

Property	Value		Unit
	Steel	Aluminum	
Material density	7850	2700	Kg/m^3
Poisson's ratio	0.26	0.33	N/A
Elastic modulus	200	68.9	GPa
Yield Strength	250	228	MPa
Tensile Strength	400	239	MPa
Shear Modulus	79	26	GPa

2.2. Material Model

In this study, the comparison for model materials was conducted for ASTM A36 Steel and aluminum 6061-T4 (Anon, 2020). Simulation for different materials was conducted to make a lighter frame design. **Table 1** shows the value of several properties for each material. The table shows that steel has a higher density, elastic modulus, and strength than aluminum. Based on the material properties, the aluminum-based frame has a lower weight but higher strain than the steel-based frame with the same dimension.

2.3. Loading and Boundary Conditions

The loading was carried out according to the weight of components attached to the frame such as the weight of the driver, upper structure, battery, driving motor, and box weight of 80 kg, 100 kg, 50 kg, 30 kg, and 330 kg respectively. Thus, the total loading condition was 635 kg plus the frame weight (approximately 45 kg).

Fixed support was applied at the joint to represent the handling joint and the suspension conditions. **Figure 2** shows the fixed displacement for all DOF and force placement with value. The force for each arrow indicated in **Figure 2** was distributed evenly for each arrow color.

2.4. Frame thickness

In this study, the target was to find the minimum thickness (*t*) needed for an aluminum-based frame to bear the stress induced by loading. The frame consists of different pipe diameter (*d*) for each subcomponent. The dimension of the frame for each simulation is shown in **Table 2**.

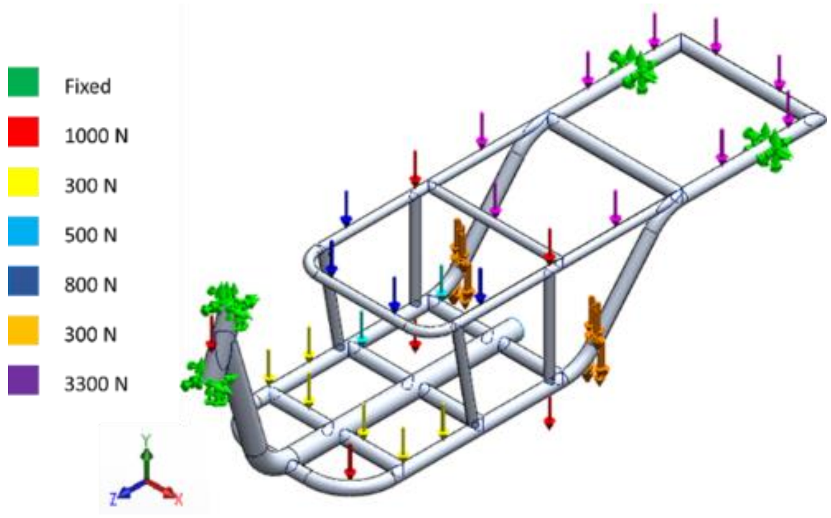


Figure 2. Support and force placement along with the frame.

Table 2. Frame dimension for each simulation.

Model	Materials	Subframe	Diameter (mm)	Thickness (mm)
1st	Steel	Seat	19.5	2.87
		Main	31.75	3.68
		Handling	50.8	3.91
2nd	Aluminum	Seat	28.2	3
		Main	41.6	4
		Handling	63.5	4.5
3rd	Aluminum	Seat	25.5	4.5
		Main	45	5
		Handling	68.8	6

The simulation was conducted for 3 cases. Case 1 is an existing frame design using steel as the material. Case 2 is using aluminum as the material and the pipe thickness is 3 mm for the seat frame, 4 mm for the mainframe, and 4.5 mm for the handling frame. The third model is using the same aluminum material with higher pipe thickness compared to the second with the value 4.5 mm for the seat frame, 5 mm for the mainframe, and 6 mm for the handling frame.

2.5. Convergence testing

In the numerical simulation, the convergence test is very important to determine if the result is valid (Hart et al., 1992; Irons & Razzaque, 1972). Convergence testing is used to find the most optimum meshing size of the model. Meshing is the discretization of the bulk model into a smaller size element. The result of the simulation becomes finer with a smaller meshing size but as the size goes down, the computation of the model is also heavier. To determine the validity of the result, the value for different meshing size is compared. When the result value of the different size mesh reached convergence value in which the variation of the value is less than 10%, the meshing size is selected for each simulation.

In this study, the convergence test was conducted by using stress value. Model 1 which used steel material was used to determine the minimum meshing size. From **Figure 3**, it could be seen when the size of the mesh reached 10 mm, the value approached the convergence line. The simulation for other models was using a meshing size of 10 mm.

3. RESULTS AND DISCUSSION

The simulation was conducted for 3 models which were explained in the previous sub-chapter. The baseline of the design was the steel-based frame due to the experimental and simulation result from previous work that has been done for the static and dynamic integrity of the existing Alpha frame (Arifurrahman et al., 2018; Arifurrahman et al., 2018). The stress distribution, deformation, strain, and weight simulation result for the aluminum frame (Case 2 and Case 3) was compared to the steel frame (Case 1) and the optimum design was chosen based on the baseline criteria and maximum displacement of 3 mm along with the frame.

3.1. First model

First model simulation was used as the baseline design and compared to the result for the 2nd model and 3rd model. First model was using steel as the material for the frame. The σ_{vm} distribution for the 1st model is shown in **Figure 4 (a)**.

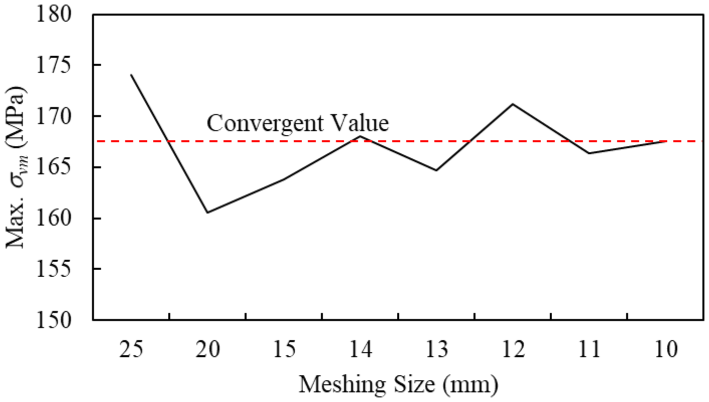


Figure 3. Convergence testing results with maximum σ_{vm} parameter.

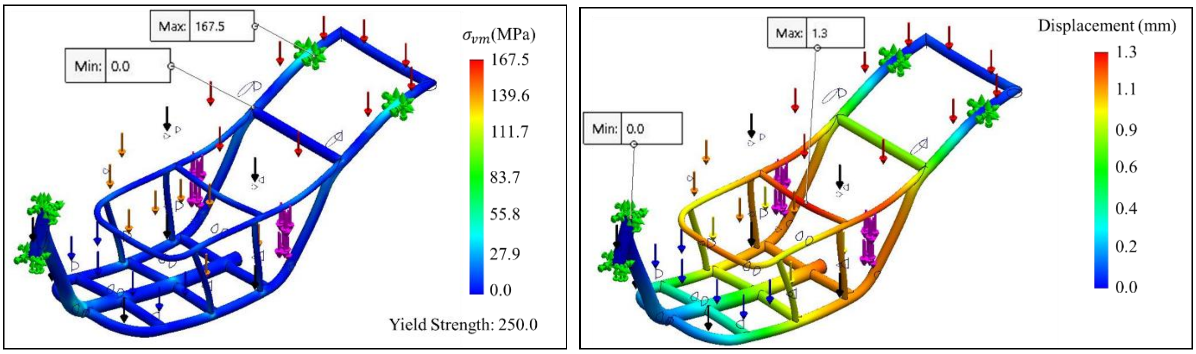
Considering both steel and aluminum are ductile materials, the von Mises criterion is implemented to determine the frame failure. It can be seen that the maximum σ_{vm} appearing in the frame is 167.5 MPa. This value is lower than the yield strength of steel. Thus, it can be concluded that 1st model frame design structure is safe and can be used to bear the load required.

Displacement due to loading conditions for the 1st model of the frame is also simulated (**Figure 4 (b)**). The maximum displacement that occurred along the frame was 1.3 mm, which was located at the seat frame. This value still far from the maximum displacement design point, which is 3mm. From the displacement perspective, the frame model design is safe.

From the safety aspect, as expected, the 1st model design is safe to be used in the e-trike operation. However, the overall weight of the frame is 41.28 kg. The weight of the frame may increase the energy consumption of the vehicle, reducing the battery performance.

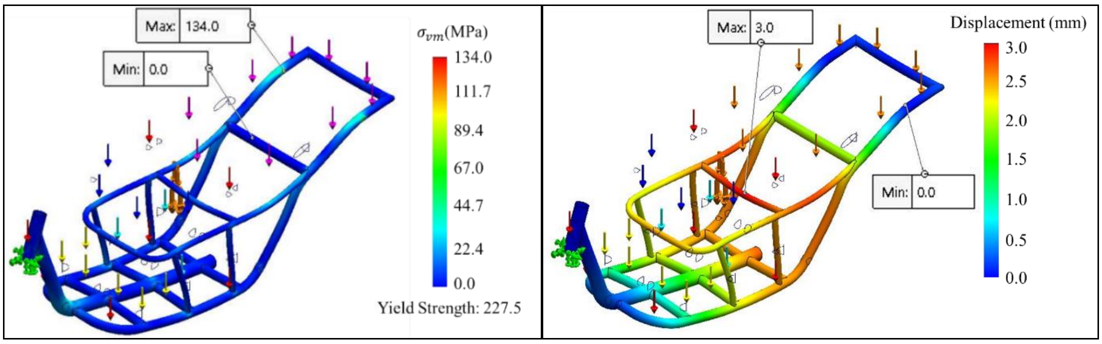
3.2. Second model

Second model was using aluminum as the material for the frame. Aluminum has lower yield strength but has a lower density. The σ_{vm} distribution for the 2nd model is shown in **Figure 5 (a)**.



(a) **(b)**

Figure 4. (a) σ_{vm} and (b) displacement distribution of 1st model.



(a) **(b)**

Figure 5. (a) σ_{vm} and (b) displacement distribution of 2nd model.

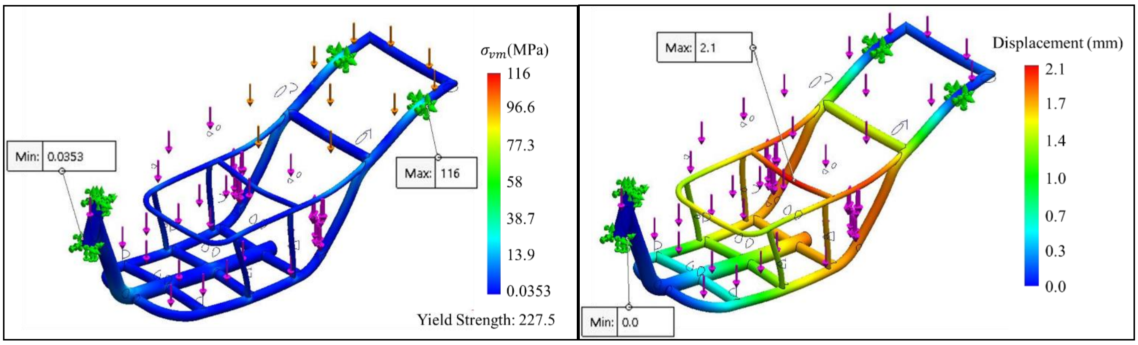
The maximum σ_{vm} that occurs in the frame is 134 MPa which is lower than the aluminum's yield strength. The 2nd model of the frame design is safe to be used for e-trike with specified loading conditions. The displacement due to loading condition was also investigated, which shows that the maximum deflection on the frame was 3.08 mm (**Figure 5 (b)**).

The displacement of the 2nd model is higher than the 1st model due to the lower modulus elasticity of the aluminum. The deflection needs to be reduced to prevent damage to the components installed on the frame, such as the battery, electric motor, etc. The weight of the 2nd model of the frame also decreased because aluminum has a lower density than steel. From the simulation, the overall weight of the 2nd model is 15.93 kg.

3.3. Third model

Third model used aluminum pipes with a larger diameter and thickness than the 2nd model. The σ_{vm} distribution for the 3rd model is shown in **Figure 6 (a)**. The maximum σ_{vm} that occurred in the frame was 116 MPa which was lower than the 2nd model. With lower σ_{vm}, the safety factor for the frame increases. The frame's structural integrity in the 3rd model is also higher than in 1st model and 2nd model.

The displacement occurring in the 3rd model was also investigated. From **Figure 6 (b),** the maximum deflection happened in the same location. Still, the value was lower than 2nd model i.e., 2.1 mm. the weight of the frame increases by increasing the pipe diameter and thickness. The overall weight of 3rd model was 21.85 kg.



(a) **(b)**

Figure 6. (a) σ_{vm} and (b) displacement distribution of 3rd model.

As a summary, each model's simulation result is shown in **Figures 7**, **8**, and **9**. The maximum σ_{vm}, safety factor, and maximum displacement is compared to the frame weight to find the optimum design for the e-trike frame.

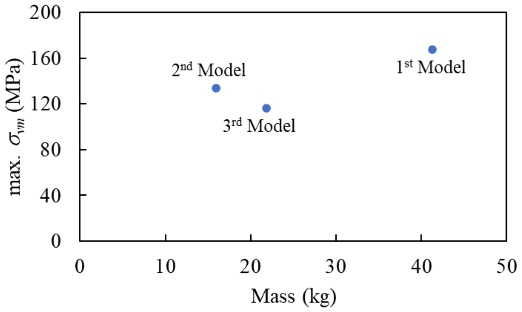


Figure 7. Numerical simulation result for maximum σ_{vm} to frame mass.

From **Figure 7,** the lowest maximum σ_{vm} is achieved by using 3rd model, followed by 2nd model. Note that 2nd model provides the lowest frame weight, and its maximum σ_{vm} is lower than 1st model. The maximum σ_{vm} is affected by the thickness of the pipe, and 3rd model has the highest pipe thickness among all models.

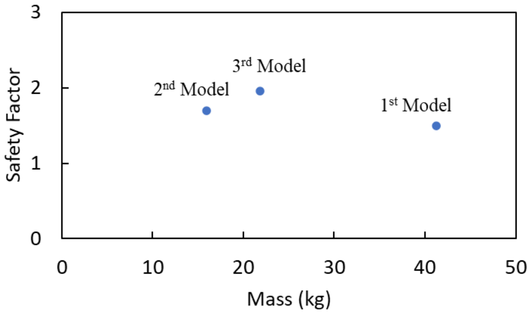


Figure 8. Numerical simulation result for safety factor to frame mass.

Figure 8 shows the safety factor for each model. The highest safety factor is achieved by 3rd model, which uses the thickest pipe and aluminum material. The value of the safety factor is affected by the maximum σ_{vm} value and material selection.

The displacement from the simulation result is shown in **Figure 9** The frame's displacement was investigated to prevent damage to the component inside the frame due to frame deflection. The highest displacement occurs in 2nd model, followed by 3rd model, and 1st model.

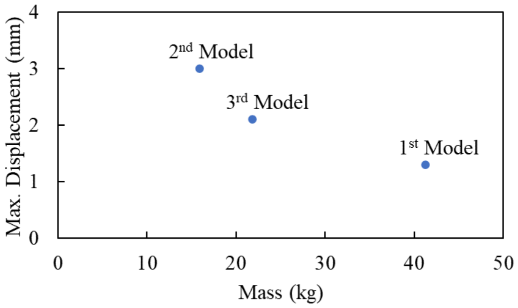


Figure 9. Numerical simulation result for displacement to frame mass.

4. CONCLUSION

Numerical simulation has been conducted for three frame models: First model with steel material and 2nd model and 3rd model with aluminum material. From the σ_{vm} distribution for the three models, all models were safe to be used for designed loading conditions. The maximum σ_{vm} and displacement values for 1st model were 167.5 MPa and 1.3 mm, respectively. First model has the lowest pipe diameter and thickness. The maximum σ_{vm} and displacement value for 2nd model were 134 MPa and 3 mm, respectively. The maximum σ_{vm} and displacement values for 3rd model were 116 MPa and 2.1 mm, respectively. Thus, 3rd model had the lowest maximum σ_{vm}, whereas 1st model had the lowest maximum deflection. The comparison was also conducted on the overall weight. The frame's overall mass values for the 1st, 2nd, and 3rd models are 41.28 kg, 15.93 kg, and 21.85 kg, respectively. Second model had the lightest weight due to aluminum's low density and lower pipe thickness compared to 3rd model. However, the maximum displacement in the 2nd model frame reached 3 mm, which reached the maximum displacement design criteria. Third model is preferred to be the chosen design due to its weight lower than the steel frame and has a safety factor higher than 1st and 2nd models. The displacement for 3rd model was also below the design criteria for the e-trike frame, which showed that the design is safe to be used.

Further research needs to be done by analyzing the economic improvement of the frame made of aluminum. Operation performance also needs to be conducted to verify the energy consumption for e-trike by using a lighter frame.

ACKNOWLEDGEMENT

This research is funded by the Education Funding Management Agency (LPDP) under Research and Innovation Program (RISPRO) for electric vehicle development with contract no. PRJ-85/LPDP/2020.

REFERENCES

Anon. (2020). SolidWorks (Version SP2.0): Dassault Systems.

Arifurrahman, F., Budiman, B. A., & Aziz, M. (2018). On the Lightweight Structural Design for Electric Road and Railway Vehicles using Fiber Reinforced Polymer Composites–A Review. *International Journal of Sustainable Transportation Technology, 1*(1), 21-29.

Arifurrahman, F., Budiman, B. A., & Santosa, S. P. (2018). *Static Analysis of an Electric Three-Wheel Vehicle.* Paper presented at the 2018 5th International Conference on Electric Vehicular Technology (ICEVT).

Arifurrahman, F., Indrawanto, I., Budiman, B. A., Sambegoro, P. L., & Santosa, S. P. (2018). *Frame modal analysis for an electric three-wheel vehicle.* Paper presented at the MATEC Web of Conferences.

Aziz, M., & Budiman, B. A. (2017). *Extended utilization of electric vehicles in electrical grid services.* Paper presented at the 2017 4th International Conference on Electric Vehicular Technology (ICEVT).

Aziz, M., Huda, M., Budiman, B. A., Sutanto, E., & Sambegoro, P. L. (2018). *Implementation of Electric Vehicle and Grid Integration.* Paper presented at the 2018 5th International Conference on Electric Vehicular Technology (ICEVT).

Budiman, B. A. (2020). Indonesia Patent No.: I. T. Bandung.

Cheah, L. W. (2010). *Cars on a diet: the material and energy impacts of passenger vehicle weight reduction in the US.* Massachusetts Institute of Technology.

Grabowski, A. G., & Jaura, A. K. (2001). Ford's PRODIGY hybrid electric vehicle powertrain weight reduction actions: SAE Technical Paper.

Halimah, P. N., Rahardian, S., & Budiman, B. A. (2019). Battery Cells for Electric Vehicles. *International Journal of Sustainable Transportation Technology, 2*(2), 54-57.

Hart, R. T., Hennebel, V. V., Thongpreda, N., Van Buskirk, W. C., & Anderson, R. C. (1992). Modeling the biomechanics of the mandible: a three-dimensional finite element study. *Journal of biomechanics, 25*(3), 261-286.

Irons, B. M., & Razzaque, A. (1972). Experience with the patch test for convergence of finite elements *The mathematical foundations of the finite element method with applications to partial differential equations* (pp. 557-587): Elsevier.

Joost, W. J. (2012). Reducing vehicle weight and improving US energy efficiency using integrated computational materials engineering. *Jom, 64*(9), 1032-1038.

Jusuf, A., Nurprasetio, I. P., & Prihutama, A. (2017). Macro data analysis of traffic accidents in Indonesia. *Journal of Engineering and Technological Sciences, 49*(1), 132-143.

Kelly, J. C., Sullivan, J. L., Burnham, A., & Elgowainy, A. (2015). Impacts of vehicle weight reduction via material substitution on life-cycle greenhouse gas emissions. *Environmental science & technology, 49*(20), 12535-12542.

Kusuma, C. F., Budiman, B. A., & Nurprasetio, I. P. (2019). *Simulation Method for Extended-Range Electric Vehicle Battery State of Charge and Energy Consumption Simulation based on Driving Cycle.* Paper presented at the 2019 6th International Conference on Electric Vehicular Technology (ICEVT).

McGregor, I. (2010). *Impact performance of aluminum structures.* Paper presented at the Structural Crashworthiness and Failure: Proceedings of the Third International Symposium on Structural Crashworthiness held at the University of Liverpool, England, 14–16 April 1993.

Miller, W., Zhuang, L., Bottema, J., Wittebrood, A. J., De Smet, P., Haszler, A., & Vieregge, A. (2000). Recent development in aluminium alloys for the automotive industry. *Materials Science and Engineering: A, 280*(1), 37-49.

Nurprasetio, I. P., Budiman, B. A., & Triawan, F. (2017). Failure investigation of plastic shredding machine's flange coupling based on mechanical analysis. *Indonesian Journal of Science and Technology, 2*(2), 124-133.

Ridwan, M. (2020). DKI Jakarta Harapkan Pemerintah Perjelas Peta Jalan Peningkatan Kualitas BBM Retrieved 10 August 2020, 2020, from https://ekonomi.bisnis.com/read/20200615/44/1252795/dki-jakarta-harapkan-pemerintah-perjelas-peta-jalan-peningkatan-kualitas-bbm-

Saito, M., Iwatsuki, S., Yasunaga, K., & Andoh, K. (2000). Development of aluminum body for the most fuel efficient vehicle. *JSAE review, 21*(4), 511-516.

Seyfried, P., Taiss, E. J. M., Calijorne, A. C., Li, F.-P., & Song, Q.-F. (2015). Light weighting opportunities and material choice for commercial vehicle frame structures from a design point of view. *Advances in Manufacturing, 3*(1), 19-26.

Sholahuddin, U., Purwadi, A., & Haroen, Y. (2016). *Design procedure for a 5 KW mini electric vehicle drivetrains.* Paper presented at the 2016 3rd Conference on Power Engineering and Renewable Energy (ICPERE).

Triawan, F., Budiman, B., Juangsa, F., Prananto, L., & Aziz, M. (2018). *Finite element analysis on the unloading elastic modulus of aluminum foams by unit-cell model.* Paper presented at the IOP Conference Series: Materials Science and Engineering.