DESIGN, ANALYSIS AND FABRICATION OF FIXED-BASE DRIVING SIMULATOR FRAME

M. A. Abdullah[1*], A. H. Mohamad[2], F. R. Ramli[3]

[1]Advanced Vehicle Technology Research Group,
Centre for Advanced Research in Energy,
Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya,
76100 Durian Tunggal, Melaka, Malaysia

[2]Faculty of Mechanical Engineering,
Universiti Teknikal Malaysia Melaka,
Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia

[3]Innovative Machine & Mechanism Research Group,
Centre for Advanced Research in Energy,
Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya,
76100 Durian Tunggal, Melaka, Malaysia

ABSTRACT

This paper describes the design, analysis and fabrication of fixed-base driving simulator (FBDS) frame. It consists of the concept design, design selection, weighted decision matrix, assembly design, design analysis, fabrication, fitting and final product ergonomic study of the FBDS frame. In the concept design, based on the driver cockpit and seat, three FBDS frame concepts are designed. These 3 design concepts are undergone design selection process which consists of weighted decision matrix. Among the design concepts, the winning design is selected based on factor of safety from design analysis, the lowest material cost and the minimum time required to finish fabrication. The selected design is then fabricated to produce actual product. The ergonomic study is then performed on the actual product of FBDS frame. The results show that the FBDS frame is statistically favoured by the ergonomic study. The detail items in the design selection and weighted decision matrix are practical and reasonable to be applied for other product design analysis before the product can be fabricated.

KEYWORDS*: Fixed-based driving simulator frame; Product design; Design selection; Weighted decision matrix; Product ergonomic study*

* Corresponding author email: mohdazman@utem.edu.my

1.0 INTRODUCTION

Driving simulators are used for several different purposes. Ranging from entertainment, to research of automotive technologies, or even study of driver behaviors, a driving simulator is a very useful tool. The goal of a driving simulator is defined as the reproduction of vehicle dynamics such as accelerations and rotations. This is an intricate task because the motion hardware displacements are subjected to limitations (Saidi et al., 2006). Therefore, vehicle signals cannot be sent directly to the motion platform and a motion cueing strategy is required. Driving simulators are often used for vehicle systems development, Human Machine Interface (HMI) studies and, as a tool for driving training in a safe controlled environment. They are virtual tools that give to the user the sensation of driving a real vehicle by associating generation of inertial cues, with visual and audio cues (Keith et al., 2005). Driving simulators are very useful research tool. Driving simulators provide a cheap and safe ways of testing new technologies to be implemented in vehicles. Besides research applications, driving simulators can also be used for entertainment purposes like integration on car games.

Driving simulators have been used to evaluate driver performance for decades. A common application is the evaluation of relative driver impairment due to fatigue, drugs, or distraction. Driving simulators have been used to provide input for a variety of roadway design issues in Europe for some time (Molino et al., 2010) and some countries have begun to use simulators more widely for this purpose. Recent traffic research projects have used simulators to investigate traffic calming in small towns (Katz, 2004, Inman et al., 2008), enhancement of visibility of curves on rural roads (Bella, 2005), driver response to a diverging diamond interchange (Saidi, 2006), and driver response to warning of an approaching red-light violator (Nehaoua et al., 2006). In addition, certain government organizations are currently funding a large project about making simulators more useful for human factors research (Nehaoua et al., 2008). However, driving simulators have been used very little for work zone research. One notable exception is a previous study (Reid et al., 1985) it is found that speed measurements collected in a virtual work zone in a driving simulator were not significantly different from the speed measurements in the actual work zone that was replicated in the simulator.

Driving simulators offer a number of benefits over in situ work zone research. Investigating the response of individual drivers in actual work zones requires data collection and data reduction efforts that are quite labor intensive compared to using automatic vehicle counters to record data about the traffic stream as a whole. Even when these intense efforts are made, data are typically only collected in a few locations and measurements are usually imprecise (e.g., estimating speed to 1 km/h increments from frame-by-frame analysis of video). In addition, drivers' behavior in actual work zones is likely influenced by the behavior of other drivers nearby. Driving simulators allow continuous measurement of driver performance in isolation or in the presence of simulated traffic.

The advantages of lab based experiment using driving simulators are (Song et al., 2003):

a) Reliability: Taking place in a controlled environment, a lab experiment is considered highly reliable since it is not influenced by external disturbances. This reliability will also be present in our experiments, as the simulator is build in a usability lab and will be free of outer disturbances.

b) Variable control: In a lab experiment the experimental control and manipulation of variables before and during the experiment is easy to control. The variable control is highly present in our testing environment, as scenarios are easy to change while the components of the simulator are still unchanged.

Replicable: Having control of the variables in a steady environment, makes a lab experiment highly replicable in terms of repeating the exact same experiment. In the experiments we are able to replicate each experiment between the test subjects which ensures the consistency of keeping the conditions the same.

c) Data collection: Running the experiment in a controlled environment ensures precise and reliable measures, and enables an easier integration and control of data collection equipment like cameras, microphones and computer logged data. By placing our driving simulator in a lab collecting data is much easier as cameras and microphones are an integrated part and are easily adjusted to record what important in the experiment.

In developing a simulator, it is important to let the development be guided by what the usage of the simulator is aimed at. In some cases, existing driving simulators or even existing driving games could possibly be used, whereas other goals of usage require building a totally customized simulator from scratch (Song et al., 2003). With the goal of the simulator in mind, researcher avoid ending up in a situation where a simulator is unsuitable or even useless in terms of its planned use. The same aspect applies to validating a simulator, where it also is important to determine what the usage of the simulator is aimed at. This matter is consistent with the results found, as we discovered a number of aspects to be considered when talking about validity. As an example, if the simulator is developed for speed research, it is possible to validate the simulator for this use, by using speed as the only or at least the most important dependent variable. Even though other aspects of the driving simulator does not comply to validate between the simulator and real driving they are in this case not of special interest. In this research, a fixed based driving simulator is developed. Three conceptual designs are evaluated based on weighted decision matrix which consists of the safety factor, cost and time required to fabricate the driving simulator frame. The practices in design for manufacturing (DFM) from previous researches (Abdullah et al., 2013a; Abdullah et al., 2013b; Abdullah et al., 2013c) are applied in the development and fabrication stages. The frame is design and analyzed by computer aided design (CAD) software and fabricated by using available materials for structure stiffness and driver's load support reliability. The driver's interface such as steering, pedals, gear knob and seat are assembled on the frame. Once the cockpit is ready, ergonomic study is performed by 30 students for evaluation.

2.0 METHODOLOGY

The concept design selection is the process where design is chosen based on the concept that generated by the solution towards the problem regarding the customer requirement of the product. This process is important to make sure that the selection is suit with the criteria that have in the product design. In the design stage, commercially available CAD software CATIA is used to draw the driving simulator frame. The design of frame consists the position for steering, gear knob, pedals and seat mountings. The dimensions of these positions are taken approximately based on actual passenger car cockpit (Figure 1). In Figure 1, *a* is the distance from the back of the seat to the steering wheel, 600 mm, *b* is the distance from the back of the seat to the gear knob, 400 mm, *c* is the distance from gear knob to the pedals, 500 mm, *d* is the distance from steering wheel to the base, 550 mm and *e* is the distance from pedals to the base, 150 mm.

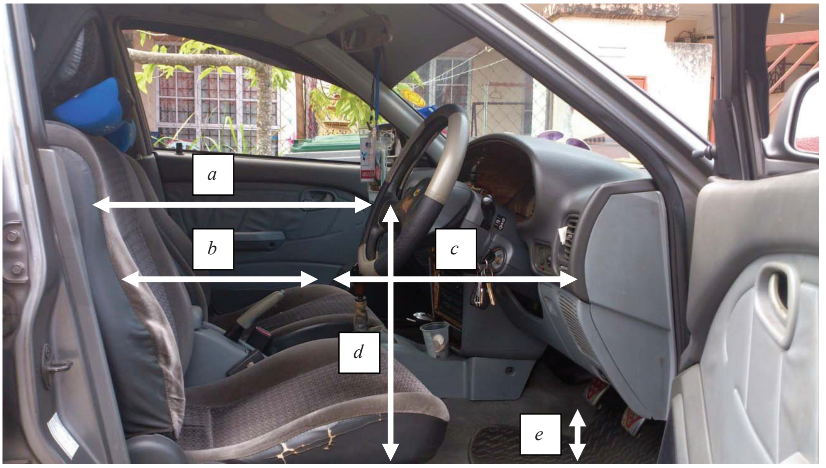

Figure 1. Passenger car Proton Wira driver cockpit

Figure 2, Figure 3 and Figure 4 show the conceptual designs of the driving simulator frames. Design I is the initial design, Design II is the improvement from Design I and Design III is the improvement from Design II. The improvements among these designs are based on the reduction in number of joints and reduction in weight. The advantages and disadvantages of the conceptual design for all three driving simulator frames are observed from the 3D CAD files and summarized in Table 1. In Table I, the decisions on the designs criteria are mainly based on designer's observation where the term 'strong' means the design has a lot of hollow frames and it can support the user, 'stable' means the design has large area of the base support and 'comfort' means the design is having perfect location for the gear knob and steering wheel.

In Design I, the disadvantages can be seen that the design is less stable due to the base and the top seat mounting are the same in width dimension. Furthermore, the amount of material used in this high because of the joining at the base take a lot of support and it is heavy. The advantage can be seen that the design is strong due to the numbers of joining occur in this part which is fasteners (bolt and nut). In Design II, the disadvantage is the seat position is joined with the front frame so that the stability is less due to weigth of the front frame which is more heavy than back frame. However, the advantage of this design is the strength of the frame. It is better because of the high amount of material used. In Design III, the disadvantage is the support at the front frame is weak due to small portion of material used and the welding at the side. The advantage of this design is stability, where it be considered more stable due to the base area is larger than the top frame.

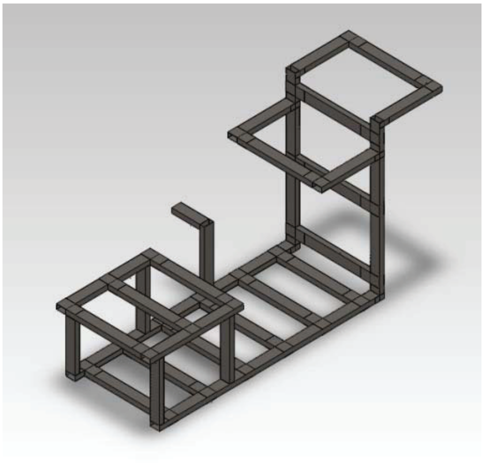

Figure 2. Driving Simulator Design I

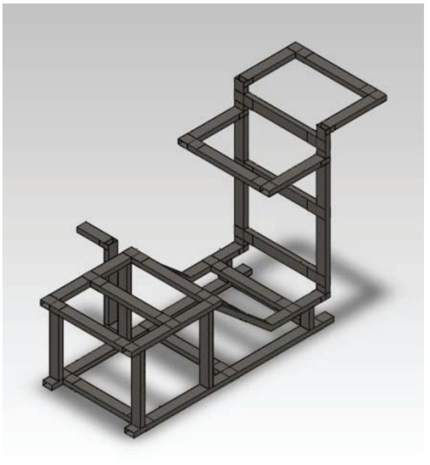

Figure 3. Driving Simulator Design II

Figure 3. Driving Simulator Design II

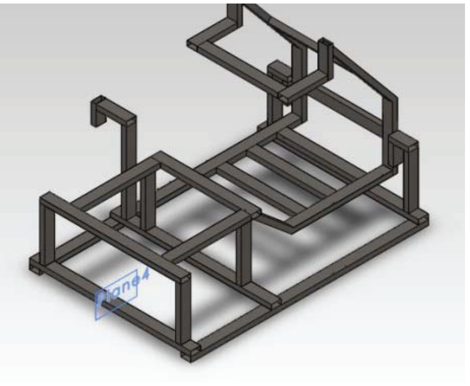

Figure 4. Driving Simulator Design III

Figure 4. Driving Simulator Design III

Table 1. Design advantages and disadvantage

Conceptual Design	Advantage	Disadvantage
Design I	Strong	Unstable
		Too many joints
		Heavy
Design II	Strong	Unstable
		Less comfort
Design III	Stable	Not strong

The conceptual designs are then undergone design analysis. Design analysis is the process of simulation study to determine whether the design is safe or not based on the factor of safety. Other consideration in the design analysis is the deflection towards load applied. There are two constraints that applied on the design which are force and fix. Force is divided into two which are 750 N for the seat and average driver weight and 100 N for the steering wheel, gear knob and pedals. Figure 5 shows the sample of force and fix constraints design analysis for frame Design III. The factor of safety for Design III is calculated by,

$$\text{Factor of safety, } FS = \frac{\text{Yield strength}}{\text{Von Mises stress}} \qquad (1)$$

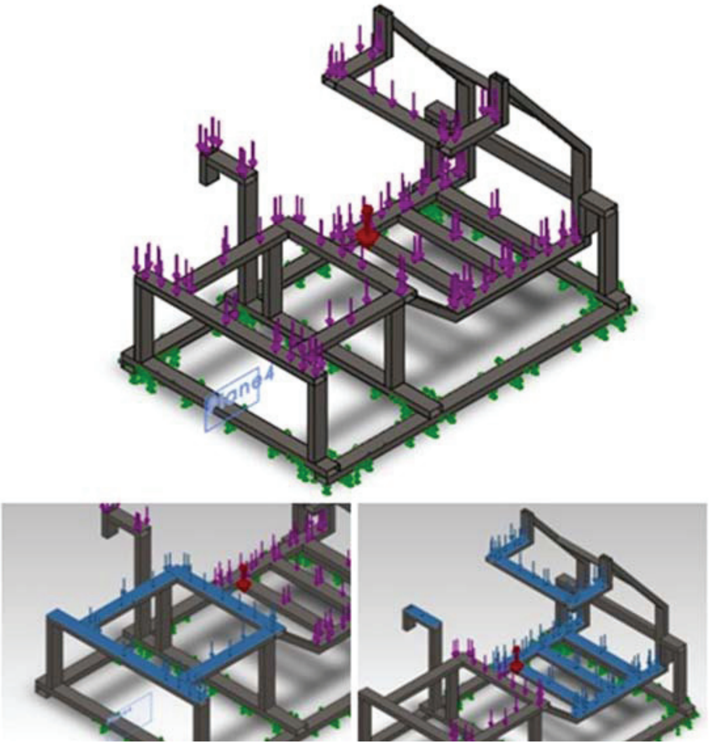

Figure 5. Force and fix constraints for Design III

After the assembly and fabrication processes completed, the driving simulator prototype is undergone ergonomic survey analysis with 30 users. The percentage score analysis range from lowest score of one to the highest score of six. Prototype ergonomic evaluation is a process where the user will test the prototype and then answer the survey based on their opinion. There are ten specifications that need to be answered by the users during the evaluation session. These are seat position, steering wheel position, gear knob position, pedal position, comfort height, finishing quality, reliability, safety, design evaluation and overall assessment as shown in Table 2.

$$\text{Percentage score for each feature} = \frac{\text{total score}}{(\text{total people x total score})} \text{ x } 100\% \qquad (2)$$

Table 2. Survey for ergonomic product of driving simulator

	Respond					
Product Analysis of Driving Simulator	**Low**		**Medium**		**High**	
Criteria	1	2	3	4	5	6
1. Seat position						
2. Steering wheel position						
3. Gear knob position						
4. Pedal position						
5. Comfort height						
6. Finishing quality						
7. Reliability						
8. Safety						
9. Design evaluation						
10. Overall assessment						
Comment/suggestion						

3.0 DESIGN SELECTION

Weighted decision matrix is the process where the evaluating of the competing criteria into score by referring to the point scales which is more logical. This is important in order to be more specific on the selecting the best criteria of the specification. However the criteria score and the calculation are based on the design process. The first criteria is the factor of safety (FS). The factor of safety is calculated by using Equation (1). The second criteria is the material cost (RM). The total cost of each design is including the material which is the hollow tube mild steel, mild steel plate, bolts and nuts. The cost of the mild steel is calculated by the design volume, design volume, m^3 x density of mild steel, kg/m^3 x price mild steel, RM/ft. The volume of the design is obtained from the CAD software and the price of the mild steel is obtained from the current price available. Table 3 shows the weighted matrix factor. The weighted index is calculated by,

FS weighted index, $WI_{FS} = FS_i \,/\, \sum_i^n FS_i \times 6$ (3)

where, FS_i is the FS for each design, and 6 is the weighted index range.

Material cost weighted index, $WI_{RM} = (1 - RM_i \,/\, \sum_i^n RM_i) \times 6$ (4)

where, RM_i is the material cost for each design in Malaysia Ringgit (MYR).

$$\text{Time constraint weighted index, } WI_{TC} = (1 - TC_i \,/\, \textstyle\sum_i^n TC_i) \times 6 \qquad (5)$$

where, TC_i is the time constraint for each design. Table 4 shows the weighted decision matrix results.

Table 3. Weighted matrix factor

Design	Design 1	Design 2	Design 3
Factor of safety (FS)	Minimum value = 2.4 from solid work analysis	Minimum value = 2.8 from solid work analysis	Minimum value = 7 from solid work analysis
Material Cost	Hollow mild steel = RM 25.25 Mild steel plate =RM 6.93 Bolt and Nut =RM10.50 Total Cost =RM 42.68	Hollow mild steel = RM 30.66 Mild steel plate =RM 6.47 Bolt and Nut =RM 9.90 Total Cost =RM 47.03	Hollow mild steel = RM 48.73 Mild steel plate =RM 4.55 Bolt, Nut and Washer = RM 2.00 Total Cost =RM 55.28
Time Constraint	Total time of all type of cutting = 3 hour 30 minute Total time of drilling 140 hole = 2 hour 20 minute Total time of all side welding = 18 hour 5 minute Total time of assembly bolt and nut = 1 hour 45 minute Total time for all process = 25 hour 40 minute	Total time of all type of cutting = 3 hour Total time of drilling 132 hole = 2 hour 12 minute Total time of all side welding = 20 hour 1 minute Total time of assembly bolt and nut = 1 hour 39 minute Total time for all process = 26 hour 52 minute	Total time of all type of cutting = 3 hour 20 minute Total time of drilling 10 hole = 10 minute Total time of all side welding = 12 hour 45 minute Total time of assembly bolt, washer and nut = 24 minute Total time for all process = 16 hour 31 minute

Table 4. Weighted Decision Matrix of driving simulator

Design Criterion	Weight Index		
	Design I	Design II	Design III
Factor of safety	1.18	1.38	3.44
Material cost	4.23	4.05	3.71
Time constraint	3.77	3.67	4.56
Total score	9.18	9.10	11.71
Ranking	3	2	1

4.0 FABRICATION

The fabrication process involves fitting, welding and finishing. Fitting process includes cutting, drilling and fastening. In the welding process, magnesium inert gas (MIG) welding procedure is selected. Figure 6 shows complete finished product of Design III driving simulator using material hollow mild steel. The next process involves grinding and painting. Grinding process is performed on the welding surface area to make it smooth. Once the surface is smooth and the grinding is finished, the painting process takes place. Then, the pedals, gear knob, steering and seat are installed on the driving simulator frame. These processes are shown by Figure 7 to 10. Figure 10(b) shows the compete driving simulator prototype.

Figure 6. Full body complete welding

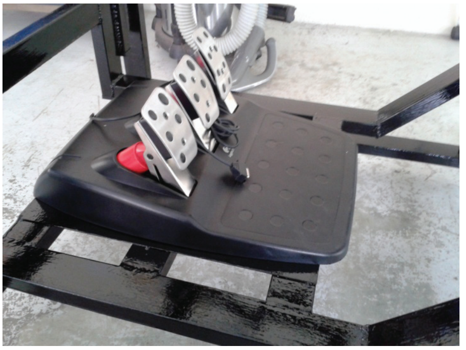

Figure 7. Installation of pedal

Figure 8. Installation of gear knob

Figure 9. Installation of steering wheel

(a) (b)
Figure 10. (a) Installation of seat and (b) Complete installation

5.0 RESULTS AND DISCUSSION

The analysis of the CAD model is performed to obtain the stress distribution and factor of safety. The load applied on the steering, gear knob and position are 100 N and on the seat is 750 N. The deformation is high on the seat and then followed by steering position which slightly bends inside. The deformation is high on the steering and then followed by the seat. The deformation is high only on the steering position compared with others (Figure 11 to 13). These happen because of in Design I and II, the steering position is quite far from the support. For the pillar support, Design I contains less support pillar compare to Design II and III. Thus the deformation is high due to small number of support pillars Factor of safety is the main key in the making of the driving simulator prototype. Comparing the factor of safety for each design, the Design III has the highest factor compared to the others. This is because of the structure joints. In Design III, the structure is simple and has wider basement. Weighted decision matrix is used to compare and select the best design for fabrication. From Table 3, the results of factor of safety are taken from the stress analysis. The total material cost is based on current hollow mid steel and mild steel plate local prices. The total time constraint or manufacturing time is the time taken to fabricate the FBDS frame from metal cutting, to drilling, welding and assembly processes. Using cost function (Eq. 3 to 5) to calculate the weighted index, the design criteria for each design are evaluated. From Table 4, Design III is ranked number one and selected for fabrication. Even though the time factor is quite high compare to others, the benefits from factor of safety and material cost give advantages to Design III. Figure 14 shows the results for ergonomic study survey by 30 users. The graphs shows that, majority of the users agree that the prototype product is reliable based on the score of 80 %. Even though the safety score is 67.78 % and the gear knob position is 68.33 %, the average score is calculated as 68.20 %. This well above 60 % and the prototype product is considered as good. The ergonomic study in this research is merely opinion from the users' perspective. It is not covering the whole detail ergonomic research. Nevertheless, with 30 users, the data is useful for further improvement on the development of FBDS frame.

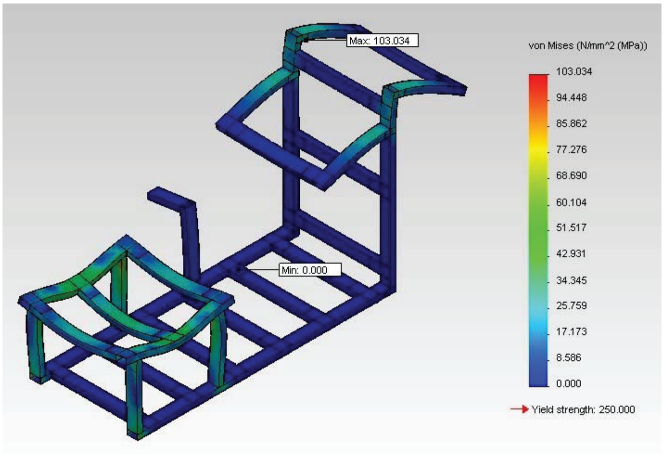

Figure 11. Stress analysis result for Design I

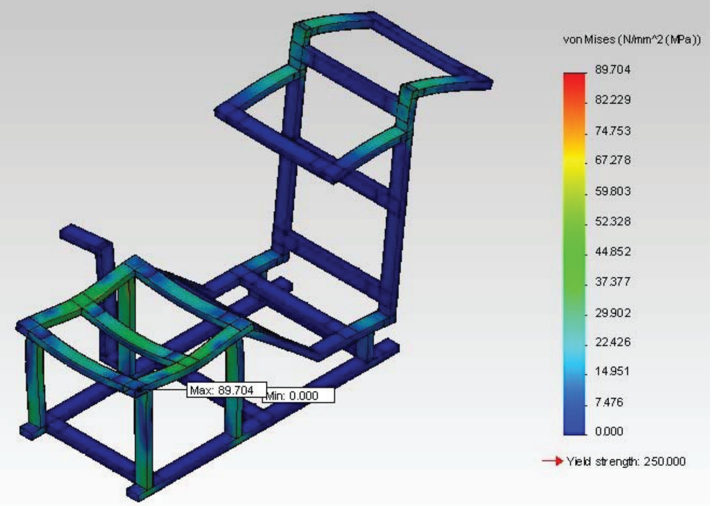

Figure 12. Stress analysis result for Design II

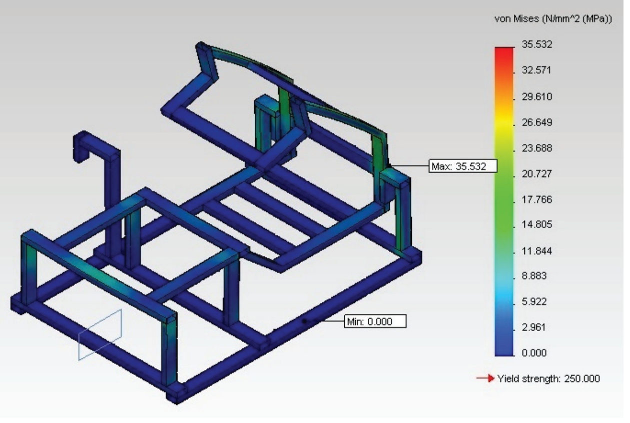

Figure 13. Stress analysis result for Design III

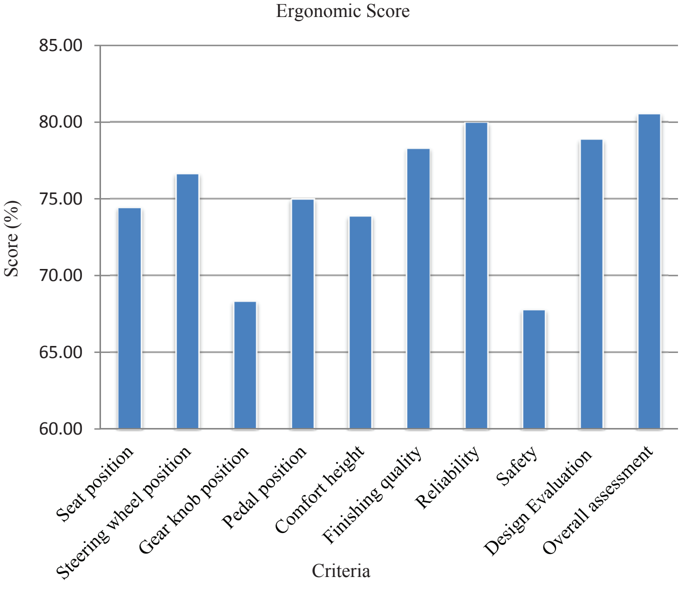

Figure 14. FBDS frame ergonomic features' scores

6.0 CONCLUSION

In this study, FBDS frame is designed, developed and fabricated. The commercial available CAD software is used in the design process. The detail design criteria is discussed and presented. The product design selection is performed based on time constraint, cost of material and factor of safety. With simple cost function, three designs have been compared using weighted decision matrix. The selected design is fabricated using available material and processes. The seat, steering, gear knob and pedals are assembled perfectly. The prototype product is also undergone ergonomic study for better product evaluation. Overall assessment of the survey shows great and promising results that the design is good and ergonomic for the users. The approaches in design selection and product assessments are proven to be applicable on other products' development.

7.0 ACKNOWLEDGEMENT

The authors gratefully acknowledged the financial support from Universiti Teknikal Malaysia Melaka (UTeM) under Short Term Grant (PJP), grant no.: PJP/2013/FKM(4C)/S01162.

8.0 REFERENCES

Abdullah, M. A., Sulaiman, N., Mat Idera, I. H., Mohd Razi, M. Z. & Ngadiman, M. N. (2013a). Design and fabrication of vehicle all-wheel-nuts remover, *International Journal of Computer Science and Electronics Engineering, 1*(3), 381-384.

Abdullah, M. A., Mansor, M. R., Mohd Tahir, M., Abdul Kudus, S. I., Hassan M. Z. & Ngadiman, M. N. (2013b). Design, analysis and fabrication of chassis frame for UTeM formula varsityTM race car. *International Journal of Mining, Metallurgy & Mechanical Engineering, 1*(1), 75-77.

Abdullah, M. A., Mansur, M. R., Tamaldin, N. & Thanaraj, K. (2013c). Development of formula varsity race car chassis In *Proceeding of International Conference on Mechanical Engineering Research, Pahang, Malaysia, 1 - 3 July 2013.*

Bella, F. (2005). Validation of a driving simulator for work zone design. *Human Performance; Simulation and Visualization,* 136-144.

Inman, V. W., Davis, G. W., El-Shawarby, I. & Rakha, H. (2008). Test track and driving simulator evaluations of warnings to prevent right-angle crashes at signalized intersections. (No. FHWA-HRT-08-070): Federal Highway Administration Office of Operations Research, Development and Technology.

Katz, B. J. (2004). *Peripheral transverse pavement markings for speed control*. (PhD. Thesis). Virginia Polytechnic Institute and State University, USA.

Keith, K., Trentacoste, M., Depue, L., Granda, T., Huckaby, E. & Ibarguen, B. (2005). Roadway human factors and behavior safety in Europe. (No. FHWA-PL-05-005): Federal Highway Administration.

Molino, J. A., Katz, B. J., Hermosillo, M. B., Dagnall, E. E. & Kennedy, J. F. (2010). Simulator evaluation of low-cost safety improvements on rural two-lane undivided roads: nighttime delination for curves and traffic calming for small towns. (No. FHWA-HRT-09-061): Federal Highway Administration.

Nehaoua, L., Arioui, H., Espie, S. & Mohellebi, H. (2006). Motion cueing algorithms for small driving simulator. In *IEEE International Conference on Robotics, and Automation*, Orlando, USA, 15-19 May 2006 (pp. 3189-3194).

Nehaoua, L., Mohellebi, H., Amouri, A., Arioui, H., Espié, S. & Kheddar, A. (2008). Design and control of a small – clearance driving simulator. *IEEE Transactions on Vehicular Technology, 57*(2), 736–746.

Reid, L. D. and Nahon, M. A. (1985). Fligth simulation motion - base drive algorithms: part 1 - developing and testing the equations. Technical Report, UTIAS No.296, University of Toronto.

Saidi, M. L., Debbeh, A., Arioui, H., Kermiche, M. S. & Abbassi, H. A. (2006). Predictive control of motion platform in driving simulator. *Asian Journal of Information Technology, 5*(2),133–138.

Song, J. B., Jung, U. J. & Ko, H. D. (2003). Washout algorithm with fuzzy-based tuning for a motion simulator. *KSME International Journal, 17*(2), 221–229.