A Redesign of the DLSU Urban Concept Vehicle Cockpit

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Abstract: Drivers of the DLSU urban concept vehicle (UCV) experience pain and discomfort due to awkward postures in the current design of vehicle cockpit. This research aims to redesign the DLSU UCV cockpit by creating a design to improve the posture of the drivers by lowering their Rapid Upper Limb Assessment (RULA) score and to eliminate discomfort in the design. The trunk contributed to a high RULA score of 4 due to the lack of lumbar support and the trunk angle flexed. Drivers also experienced discomfort on their legs due to low leg clearance. Using anthropometric analysis, appropriate clearances and reaches were determined to be incorporated into the design. Through cause analysis, the factors that contributed to the high RULA score and the discomfort of the drivers were identified. A 2^2 factorial experiment was then conducted through CATIA with the use of manikins (body dimensions of the tallest and shortest driver) to determine the significant factors affecting the RULA score. After conducting the experiment only the backrest angle was significant. One Factor RSM was conducted through CATIA and was used to determine the optimal setting for the significant factor generated in Design Experts, the backrest angle being 104.5 degrees. A physical prototype of the cockpit was produced. Drivers were subjected to testing to validate the results of the study with the use of RULA and discomfort survey It was evaluated by the drivers and the RULA Grand Score was decreased to 2 and eliminated drivers' discomfort. The redesigned vehicle is most suited for the middle 90 percent of the DLSU-ECT population with height ranging from 160 to 180 cm. Design guidelines were produced for the DLSU-ECT based from the dimensions acquired in the study for different ranges of height.

Key Words: urban concept vehicle; vehicle cockpit; RULA; anthropometry; DLSU Eco Car

1. BACKGROUND OF THE STUDY

One of the sustainable solutions to the high and ever growing levels of consumption and pollution is the movement towards alternative transportation methods. Students of De La Salle University (DLSU) joined in the effort to make new modes of transport by participating in the Shell Eco Marathon. This is a yearly event where student teams from all over the world get to design their own cars to race against other teams. For this purpose, the DLSU Eco Car Team (DLSU-ECT) created an Urban Concept Vehicle (UCV).

The first UCV to be designed and manufactured by the team was the DLSU Archer. It is an electrically powered compact car that resembles most commercial minicars except that the Archer has zero emissions, leaving a smaller carbon footprint. It maximizes fuel efficiency and speed with the innovation in the construction of its engine and body respectively.

However, the effective mechanisms of the car would be useless if it is not operated properly. The driver is the most important part of the vehicle since he is the one that turns on the ignition and makes it move. Ironically though, in the design process of the DLSU-ECT, he is placed as an afterthought. The car is optimized to its lightest and most aerodynamic size and shape, which means that the vehicle turns out to be very small. The UCV was designed according to the minimum required dimensions stipulated by the Shell Eco Marathon for vehicle height, width, and length, with increases in these dimensions only made to accommodate the engine, battery, and steering mechanisms as necessary. Whatever space remains is devoted to the driver's cockpit, and this area is not suited for the size profiles of the team's drivers. What happens is that the drivers assume awkward postures to fit in the limited space of the cockpit while operating the car.

Through focus group discussions (FGD), it was discovered that the drivers experienced discomfort as a result of the Archer's poor interior design. Through postural analysis, it was determined that the drivers posture in the DLSU Archer has a RULA Grand Score of 4 meaning drivers are exposed to medium risk of musculoskeletal injury with the risk areas being the trunk and the legs. The finding from the postural analysis serves as the problem that this study aims to resolve. The poor posture was caused by the fact that the cockpit's dimensions did not match the anthropometric measurements of the users the cockpit was intended for. The cockpit dimensions included clearances, reach distances (for functional components like pedals and the steering wheel), and seat design. The non-conformance of the Archer's dimensions with that required by the drivers' anthropometry was investigated.

This study aims to improve driver comfort in designing UCV cockpits by lowering the RULA Grand Score to at most 2 through the use of appropriate anthropometric measurements for reaches and clearances in the design of the cockpit and by enforcing proper sitting posture through appropriate dimensions based on ergonomic principles. The study also aims to produce design guidelines for the cockpit dimensions that will fit the changing height of the available drivers of the DLSU-ECT.

Noise, vibration, force exertion, visibility, ingress and egress during emergencies, and cognitive factors are excluded from the study since the reasearchers would like to focus on the physical ergonomic assessment of the vehicle cockpit

2. METHODOLOGY

The methodology of the study involves four stages: (1) Needs Identification, (2) Design Conceptualization, (3) Design Development and Iteration, and (4) Design Finalization. All stages are relevant in producing the CATIA model of the vehicle cockpit and its physical prototype for testing and validation that aims to promote proper driver posture and comfort. Fig. 1 summarizes the framework of the research methodology.

2.1 Stage 1: Needs Analysis

The first stage involves the identification of the problem and its causes. It relates how the results from the focus group discussion (FGD) to the causes explored in the postural analysis, and seat design and anthropometric analysis.

2.1.1 Focus Group Discussion

In order to identify the problem areas of the current design of the DLSU Archer, Focus Group Discussions were conducted with the two main DLSU-ECT drivers. The FGD asked drivers about their experience while operating the UCV as well as their concerns regarding the awkward posture they had and the resulting aches thereafter. The FGD explored situations where the drivers experienced any discomfort, the kind of pain experienced and the location of body parts. Severity and frequency of occurrence were also considered. The line of questioning of the FGD followed the questions based on a discomfort survey by Hedge, Morimoto & McCrobie (1999).

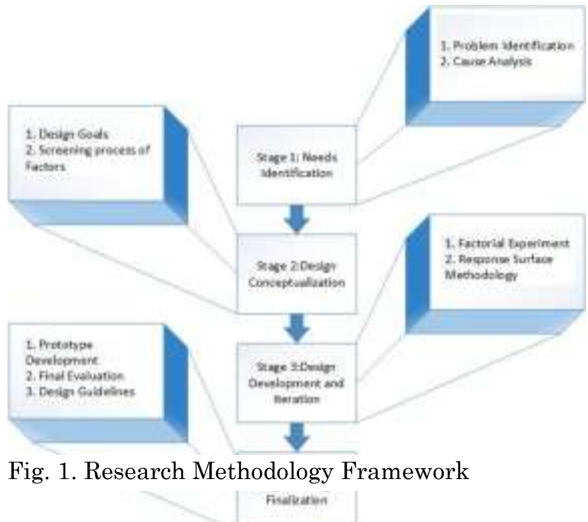

Fig. 1. Research Methodology Framework

2.1.2 Rapid Upper Limb Assessment (RULA)

RULA was carried out to assess the static driving position of the drivers in the vehicle. Five drivers selected as subjects for the DLSU Archer. Each driver assumed their driving position for 15-20 minutes inside the vehicle. They were photographed to be able to measure the angles assumed by their position using Microsoft Visio as shown in Fig. 2. Once the angles have been identified, the RULA sheet by McAtamney and Corlett (1993) was used to determine the posture scores of the drivers in their position and identification of the areas where risks to

MSD are most likely to occur.

Fig. 2. Driver's posture in DLSU Archer

Table 1. RULA Scores in DLSU Archer

Body Part	Driver 1	Driver 2	Driver 3	Driver 4	Driver 5	Ave. RULA Score
Upper Arm	1	2	1	1	1	1.2
Lower Arm	1	1	1	2	1	1.2
Wrist	1	1	1	1	1	1
Neck	1	1	1	1	1	1
Trunk	4	4	4	4	4	4
Legs	1	1	1	1	1	1
Grand Score	4	4	4	4	4	4

Each driver's posture was analysed in the vehicle, with RULA results shown in Table 1. It has been determined that the average RULA score is 4, which means that further investigation is needed to improve on the driver's posture. It can be observed that the trunk score contributed to the high RULA Grand Score.

2.1.3 Cause Analysis

A cause analysis was conducted to understand the reason for the high RULA score and other sources of discomfort. It consists of anthropometric analysis and seat design analysis. The dimensions of the vehicle cockpit and its components dictate the underlying reasons why the driver is forced to assume an awkward position. Since the car is designed for the DLSU-ECT, their population were used as participants. The non-conforming car attributes dimensions of the DLSU Archer in relation to the anthropometric measurements of the team are presented in Table 2.

The second part is through seat design analysis to check if the seat dimensions and angles of the seat supported the DLSU-ECT driver's measurements and comfortable posture. The non-conforming car seat attributes can be seen in Table 3. The backrest angle was considered since it was not appropriate for the drivers given the seat to ceiling height. The angle was to upright for the available space which led the drivers to slouch in their seats in order to not hit the ceiling.

Findings from the cause analysis have been gathered together with the results of the FGD and RULA to formulate the problem of the study.

2.2 Stage 2: Design Conceptualization

The layout of the vehicle cockpit with regards to the placement of its components will stay as depicted in the DLSU Archer. What will change in this new design would be the size of the cockpit and the angles of the seat, making sure that the clearances and reaches are suited to the driver's anthropometric measurements so that he does not have to assume an awkward posture.

Design goals have been established to successfully conceptualize the design of the cockpit. The goals of the design is to increase driver comfort by designing the cockpit with reach and clearance dimensions appropriate to his anthropometric measurements, decrease the driver's risk of incurring musculoskeletal disorders by making the seat angles and reach distances support proper posture in line with the comfortable angle ranges stated by Grandjean (1980) and to optimize the trade-offs between the necessary clearances and reaches with the requirements of the Shell Eco Marathon rules (minimum required dimensions of the cockpit) and the goals of the team.

Table 2. Non-conforming DLSU Archer Dimensions to DLSU-ECT Drivers' Anthropometric Data

Car Attribute	Actual Dimension (cm)	Body Part	Percentile used	Anthropometric Data (cm)
Seat to ceiling distance	91	Sitting height + head clearance allowance	95^{th}	102.57

Steering wheel to backrest	51	Thumb tip reach	5th	59.61
Ground to steering wheel	46.5	Knee height (Knee clearance)	95th	51.67
Pedal reach	89	Length of upper and lower leg	5th	86.42

Table 3. Non-Conforming UCV Seat Dimensions to DLSU-ECT Drivers' Anthropometric Data

Seat Attribute	Actual Dimensions	Body Part	Percentile used	Anthropometric Data/ Literature
Upper backrest width	37.8 cm	Shoulder breadth	95th	45.99
Backrest angle	100'	Trunk angle	--	100'-120'

2.3 Stage 3: Design Development and Iteration

In the cause analysis, the specific car dimensions that contributed to the high RULA score and discomfort of drivers are identified. Controllable factors that contributed to the RULA score have been determined. The pedal reach and backrest angle are set as the controllable factors in the experiment. Other seat dimensions, reaches and clearances have been set to constant based on the anthropometric analysis to accommodate most of the users of the population. Factorial experiment was applied in order to systematically test and evaluate the levels of the different settings of the factors and be able to optimize these factors to attain the best result (Montgomery, 2005). Experiments were performed using CATIA as seen in Fig. 3 wherein two manikins were used for the experiment representing the tallest and shortest drivers of DLSU-ECT and that the car components were laid out following the set dimensions.

Fig. 3 Manikin with car components factorial run

A factorial experiment was first conducted to assess if the resulting factors significantly affect the response, RULA Trunk score. Once the significant factors have been determined, these factors were used for Response Surface Methodology (RSM) for optimization. Moreover, in RSM, a categorical factor, the type of person, is added since the best settings for both the tall and short drivers is needed to be determined as a means of trading off for both type of height.

2.4 Stage 4: Design Finalization

2.4.1 Final CATIA Model

The final dimensions for clearances, reaches, seat and angles based on anthropometric measurements, DOE, and literature were translated into a CATIA model. A confirmation run using the CATIA model and the manikin was conducted through CATIA to make sure that the appropriate dimensions fulfilled the design goal, which is to have a RULA Grand Score of 2 below.

2.4.2 Prototyping and Testing

The CATIA model was translated into the final output which is a physical prototype. The overall work envelope was made using wood. To test the prototype, the drivers sat on the driver seat for 15-20 minutes (race duration) to determine both the posture score and comfort evaluation. The RULA Grand Score was based on the RULA worksheet and the comfort evaluation was based on a modified discomfort survey by Hedge & McCrobie (1999).

The RULA Grand Score served as the validation for the virtual and physical model of the design. The average RULA Grand Score of the confirmation run in CATIA and the testing of the prototype were compared to determine if the settings generated the desired results. The comfort evaluation, on the other hand, served as the guide if the new design was able to increase postural comfort.

If discomfort was experienced in the design, adjustments were made in the car dimension relating to the body part which experienced discomfort. Adjustments on the prototype were based on Damon & McFarland (1966) computed range for the middle 90% of the population. After adjusting, the driver was situated in the prototype again and the RULA analysis and comfort evaluation were done until the driver became comfortable in the driving position. Lastly, recommendations were made to ensure that areas of the new design were addressed for future designs.

3. RESULTS AND DISCUSSION

3.1 Factorial experiment

A 2^2 factorial experiment was conducted for the backrest angle and pedal reach, if they significantly affect the, RULA trunk score. Only significant factors was be used for optimization using Response Surface Methodology (RSM). Using ANOVA, it has been determined that only the backrest angle was significant ($p<0.05$). Hence this factor was considered for RSM.

3.2 Response Surface Methodology

Since there is only one variable that was significant in affecting the RULA trunk score, a One Factor Design of RSM has been chosen for optimization. Fig. 4 shows the interaction graph for both the tall and small drivers as it can be seen the angle of the backrest in which the RULA score is at a minimum.

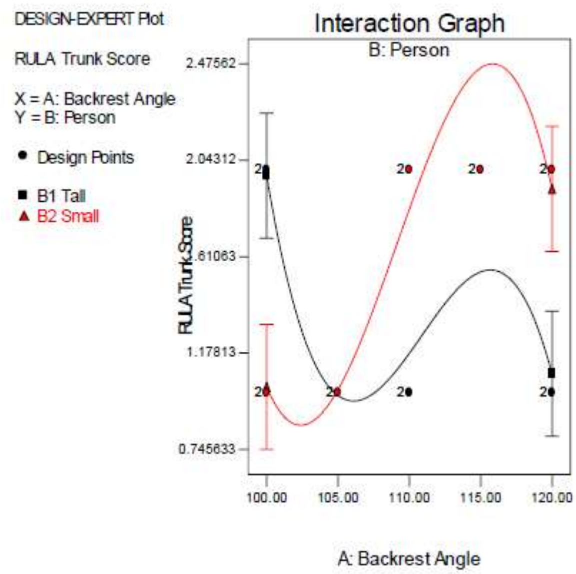

Fig. 4. Interaction Graph of the RULA Trunk Score and Type of Person

It can be observed that a point near 104'-105' is the optimal backrest angle for both the tall drivers and the small driver having a low RULA trunk Score. Using the Design Expert software's criteria function, it can be seen that two angles have been determined as shown in Table 4. The angle that would be used would be 104.5' due to its convenience as it is easier to implement for the physical prototype.

Table 4. List of Solutions at the Intersection Point from RSM

Number	Backrest Angle (degrees)	Person	RULA Trunk Score
1	104.50	Short (154.1 cm)	0.96082
2	104.80	Tall (181.4 cm)	0.997161

3.3 Prototype Development

3.3.1 CATIA Model and Physical Prototype

The CATIA model's dimensions were based on the anthropometric measurements of the DLSU-ECT drivers for clearances and reaches, optimal setting for the backrest angle obtained from the expdriment and other dimensions acquired from literature. The model included the overall work envelope based on the dimensions stated in the Shell

Eco Marathon rules. The list is shown in Table 5. Fig. 5 and Fig. 6 illustrate the dimensions. The result of the confirmation run in CATIA showed a RULA Grand Score of 1, which means that the driver's posture in the model results to an acceptable posture.

Table 5. Dimensions of redesigned vehicle cockpit

Particulars		Measurement	Basis
1.	Driver's compartment width	70 cm	Shell Eco Marathon rules
2.	Backrest width	45.99 cm	Shoulder breadth, 95th percentile
3.	Backrest height	57.04 cm	Shoulder height, 5th percentile
4.	Seat breadth	33.92 cm	Hip breadth, 95th percentile
5.	Seat height	10 cm	Literature from Mariotti & Jawad (2000)
6.	Lumbar support protrusion	5 cm	Literature from Bhise (2012)
7.	Seat pan angle	5 degrees	Literature from Bhise (2012), ranges from 5-15 degrees from the horizontal
8.	Seat-to-ceiling distance	102.57 cm	Sitting height, 95th percentile + 10 cm clearance based from Shell Eco Marathon rules
9.	Pedal reach	86.42 cm	Length of upper and lower leg, 5th percentile
10.	Steering wheel reach	53.63 cm	Thumbtip reach, 5th percentile in middle range of adjustments by Damon et al. (1966)
11.	Vertical distance from floor to steering wheel	51.67 cm	Knee height, 95th percentile
12.	Backrest angle	104.5 degrees	Result from RSM as optimal setting

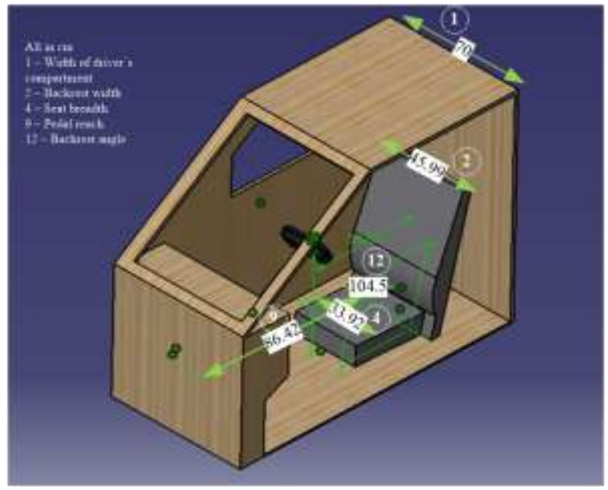

Fig. 5. CATIA model with dimensions, isometric view

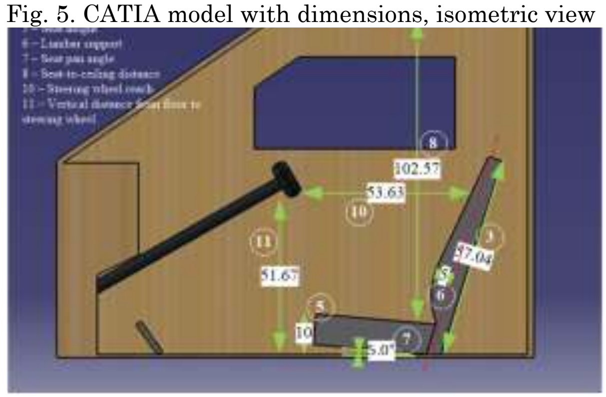

Fig. 6. CATIA model with dimensions, left view

For the physical prototype (Fig. 7), the work envelope, seat, dashboard, and pedals were made using wood. A lumbar support was added to the seat and the steering wheel was made from Styrofoam.

Fig. 7. Physical prototype of redesigned UCV

3.3.2 Prototype Testing and Design Evaluation

The physical prototype was initially tested by letting four drivers of the team sit in the prototype for 15 minutes. The results of the test are summarized in Table 6.

Table 6. Initial prototype testing results

Driver	RULA Grand Score	Comfort Evaluation
1	2	Comfortable
2	2	Discomfort in forearm
3	2	Discomfort in upper arm
4	2	Comfortable

The design was able to solve discomfort in risk areas of upper and lower back. Based on the feedback given by the drivers while they were in the prototype and their answers from the discomfort survey, the drivers' backs were very comfortable because they felt the difference given by the lumbar support. Backs were reclined comfortably their lower and upper backs on the backrest and their shoulders were not anymore slumped nor their trunks flexed because there was ample seat to ceiling clearance for their height. The trunk angles significantly lowered to less than 10 degrees and since lumbar support was provided, the trunk RULA score only had a value of 2.

The pedal reach was near enough for all of them to operate the vehicle without having to move their hips from the H-point of the seat. Leg pain was also solved since the floor to steering wheel vertical clearance was fit for all of the drivers. Their legs and knees did not come into contact with the steering wheel and the steering shaft. Horizontal leg clearance was also given so that leg movement was not restrained.

However, a problem area was the upper arm and forearm. Although the steering wheel reach was already adjusted closer to the driver based on the middle setting of the range of adjustability, the drivers still experienced discomfort. Although the steering wheel reach is still within functional requirements meaning the drivers can very well reach it and operate the steering wheel, sustaining this arm posture for at least 20 minutes can cause fatigue and ache in the upper arms and forearms. Therefore, the steering wheel reach was adjusted closer to the drivers to minimize the angle formed by their forearms and upper arms, and to bring the upper arms closer to their torso.

Due to the discomfort experienced in the upper arms and forearms, the steering wheel reach had to be adjusted to 50.63 cm as being as a value within the range of 47.64-59.61 cm computed for the middle 90 percent. Another testing was done using the adjusted value and it resulted to an average RULA Grand Score of 2 and discomfort was eliminated.

Because the steering wheel was adjusted nearer (50.63 cm) to the drivers compared to the previous steering wheel reach of 53.63 cm, the drivers could reach the steering wheel more and their upper arm forearm angles decreased, giving them additional comfort as their upper arms are nearer to their torso. This means that the drivers did not experience discomfort on their arms anymore and they can sustain that posture when driving.

Both CATIA confirmation runs and physical prototype testing achieved a desirable RULA Grand score of at most 2, which means that the redesigned vehicle affirms that the drivers will be able to do their driving task without the risk of musculoskeletal injuries and back pain.

Table 7. Final prototype testing results

Driver	RULA Grand Score	Comfort Evaluation
1	2	Comfortable
2	2	Comfortable

Fig. 8. Driver in final prototype for testing

4. CONCLUSIONS

The DLSU-ECT drivers experienced discomfort while driving the DLSU Archer. It has been determined that the significant body part that contributed to the awkward posture of the drivers assessed through RULA is the trunk. The car dimensions involved in contributing to the high RULA score is the low seat-to-ceiling distance as well as the pedal reach. Moreover, the drivers experienced discomfort in areas such as the upper and lower back and legs, which were evaluated through the use of the discomfort survey. For the back, there was no lumbar support and that backrest width was too short. Lack of knee clearance caused discomfort for the legs of the drivers due to the low vertical distance from floor to steering wheel.

The proposed design of the UCV was able to incorporate appropriate seat dimensions, clearances and reaches using anthropometric analysis and literature to successfully design the cockpit in addressing the driver's posture and comfort. DOE was then able to improve the design of the cockpit by optimizing the backrest angle to lower the RULA score. The design, which is most suited for the middle 90 percent of the team (160-180 cm in height), was able to improve the drivers' RULA Grand Score from 4 to 2 and eliminate discomfort. Design guidelines were produced for the DLSU-ECT containing recommended car dimensions for the appropriate driver height.

For future studies, it can be recommended that an assessment of the effects of vibration to the driver's posture as it affects the posture of the drivers while driving. Including visibility and assessing the dynamic tasks of drivers in designing the vehicle cockpit is suggested. Moreover, a real-life simulation for designing vehicle cockpits, wherein the drivers are able to drive the vehicle with the set dimensions, are also recommended.

5. ACKNOWLEDGMENTS

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