Assessment of Student Formula driver's safety through optimization of impact attenuator sizing

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ABSTRACT

This research focuses on determination of the optimum size of the impact attenuator of the Student Formula race car. The Alminium based honeycomb impact attenuator has been selected due to its desirable weight to energy absorption capacity. The attenuator is located in the front of the vehicle internal frame in which the driver is seated as its main purpose is to protect the driver from a front impact collision. All parameters used in this study are relevant to KMUTT Student Formula race car, ie. vehicle frame, attenuator energy absorption characteristics, weights and heights of drivers, seat belt positions, and the maximum speed recorded during a lap. The analysis consists of two parts, (1) computation of final vehicle velocity after the attenuator deformation and (2) the driver's Head Injury Criteria (HIC) obtained from simulations in the ADAMS multibody dynamics software. The honeycomb material is available in sheets of 50mm thickness. Hence the optimization of attenuator volume is performed by determining the appropriate surface area and the number of layers. It is found that the attenuator consisting of 4 layers of 150 x 200 mm honeycomb, which satisfies the minimum TSAE regulations, provides safety for the driver in a 25 km/hr crash but not in a 60km/hr crash – the actual maximum speed experienced during the competition. An attenuator with 7 layers of 335 x 350 mm surface area would be sufficient in such a case.

INTRODUCTION

The student formula competition is an engineering based race car competition organized by the national automotive engineering body, such as the Thailand Society of Automotive Engineering (SAE). There are many editions of the competition in several countries such as USA, Japan and Thailand. The organizers aim to promote the use of engineering knowledge in the design processes, manufacturing and race execution. Figure 1 shows a drawing and an actual photograph of the Student Formula race car. All participants are higher education students, with a majority in the field of mechanical and automotive engineering. As the students of King Mongkut's University of Technology Thonburi (KMUTT) are aiming to enter the competition in Japan and Thailand, hence the contents presented in this paper will align with the requirements of the regulations of JSAE and TSAE student formula competitions.

Driver safety is always the top priority in any type of race and the student formula makes no exception. Moreover, the driver is also a student with limited driving experiences when

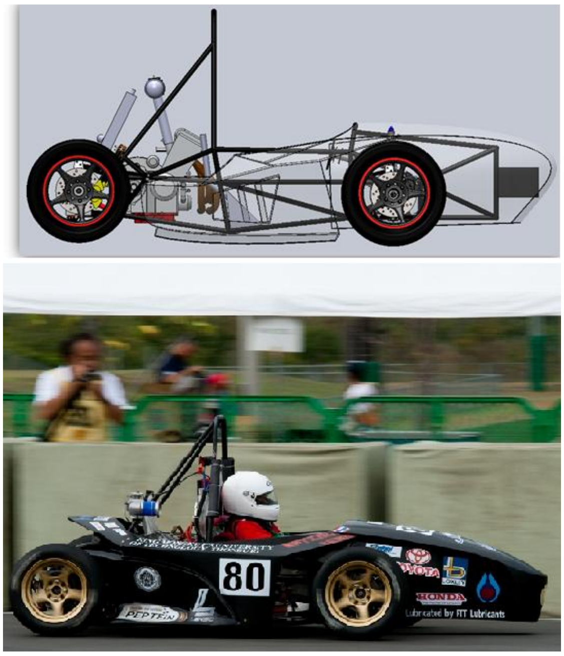

Figure 1. *A detail drawing showing the structural frame, engine, seat, tyres and other parts of the Student Formula race car designed by the KMUTT team and a photograph of the actual race car during a lap at the 2009 JSAE Student Formula competition*

compared to professionals. This fact leads to great concerns when the driver is faced with a decision in a split second in the case of losing the control of the car. Hence the car safety features must be even more rigorously embedded into the designs and manufacturing of the vehicle.

In the 'dynamic' part of the competition (actual races), the driver is expected to maneuver the race car around a track which contains all types of corners such as chicanes, hairpin and even a slalom. The race is held on a track that is usually set up on a flat hard concrete open space instead of a specially built race track. These features show that the competition track may be more difficult to drive than a dedicated race track as the flat surface does not provide banked curves and plastic cones are used to line up the sides do not provide visual aids that the red-white painted curbs do. For the safety features, there are tyre walls and soft sponge walls lining the perimeter of the tracks to provide a barrier between the cars and the spectators. These are sufficient for the spectators' safety as race car top speeds rarely exceed 60 km/hr.

OBJECTIVES

This research focuses on the design of the front impact attenuator only. Although the car may be subject to crashes on the sides and in the back, the safety features for these situations are beyond the scope of this work. The front impact attenuator is located inside the nose cone of the race car and is attached to the front part of the car structural frame. The requirements as stated by the 2011 Formula SAE Rules [1] are that when mounted on the front of a vehicle with a total mass of 300 kg and running into a solid non-yielding impact barrier with a velocity of 7.0 m/s, the average vehicle deceleration must not exceed 20 g's, with a peak deceleration lower than 40 g's. The attenuator dimension must also follow the rules which state that it must be at least 200 mm long with a minimum of 100 x 200 mm cross section area (at 200 mm forward of the bulk head).

Since the rules do not stipulate the designs and choice of materials of the impact attenuator, the teams are given the freedom to make their own decisions freely. From the author's own experience at the competitions, examples of possible impact attenuator materials and designs which satisfy the competition stewards close inspection range from cardboard boxes rolled into a cylinder, stacks of soft drink aluminium cans and solid steel bars. Each design has its advantages and disadvantages in terms of strength, weight, structural integrity and aesthetics. It is up to the engineers who design the car to prioritize what features are the most important for their car.

Aluminium Honeycomb is the material chosen by the KMUTT team. Its structural deformation and energy absorption characteristics have

Figure 2. *The Universal Testing Machine that was used to determine the characteristics of the aluminium honeycomb samples*

Figure 3. *The aluminium honeycomb specimens are constructed using layers of sandwich constructions of various cross section areas. Each layer is 50mm thick. The structure is tested to destruction under axial loads applied by the Universal Testing Machine.*

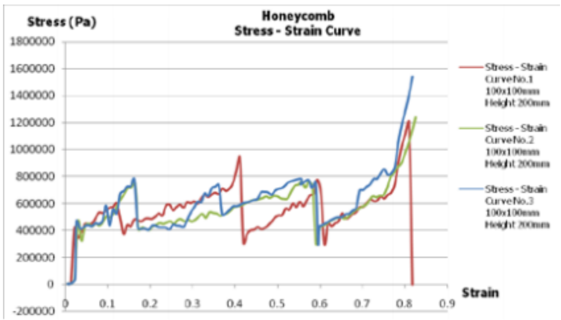

Figure 4. *The test results have been post-processed to show the stress-strain characteristics of the aluminium honeycomb structure. This data is then further processed to determine the energy absorption per volume.*

been experimentally determined [2]. Samples of aluminium honeycomb sandwich structure with different dimensions are tested on a Universal Testing Machine as shown in figure 2. Figure 3 shows that the testing machine is programmed to crush the specimen with a velocity of 7 m/s until it has been flattened. The loads experienced by the testing machines are recorded and processed into stress-strain curves as shown in figure 4. Finally, the areas under these curves are calculated and used for the determination of the energy absorption per volume of the honeycomb structure. The calculation shows that this value is 471,893.502 J/m^3 .

In summary, the objectives of this work are

1. Determination of the minimum size of the aluminium honeycomb impact attenuator that satisfies the safety requirements for a Student Formula competition
2. To gain knowledge of the influence of parameters of the impact attenuator that may affect the driver safety during a crash
3. To use the research results in the new design of the race car for the competition in the following year

METHODOLOGY

Assuming the worst case crash scenario that could happen during the Student Formula competition, the vehicle collides head-on with a rigid barrier at a velocity of 60 km/hr and all the impact impulses act on the impact attenuator. Moreover, the tallest and heaviest driver available to the team (176 cm and 62 kg) is seated inside the vehicle giving the maximum forward momentum which must be retarded during the crash.

The crash will be modeled as follows. As the vehicle collides with the rigid barrier, the impact attenuator will start to deform thus slowing down the vehicle. Once the impact attenuator has been completely flattened, the final velocity will be used as an input to computer simulations to determine the level of driver injury. The calculations are divided into two main parts

(1) Determination of the vehicle velocity after the deformation of the impact attenuator

The rate of deceleration is computed using a simple energy relationship [3]. The aluminium honeycomb energy absorption capacity is 471,893.502 J/m^3. Hence, the vehicle velocity after the complete deformation of the attenuator may be given by

$$\frac{1}{2}m(v_2)^2 = \frac{1}{2}m(v_1)^2 - (K \times V) \qquad \text{Eqn.1}$$

where
m denotes the total mass of the driver and vehicle
v_1 denotes the initial velocity of the vehicle
v_2 denotes the final velocity of the vehicle after the deformation of the attenuator
K denotes the impact attenuator absorption capacity
V denotes the deformed volume

(2) Determination of driver injury level through computer simulations

Again, assuming the worst case impact scenario when the right vehicle frame collides with the non-moving rigid barrier, there is no energy absorption and the vehicle would, in theory, bounce off with the same magnitude of velocity. This final velocity will be used as the initial condition to be input into the computer simulation that models the crash injury on a dummy seated in the race car as depicted in figure 5. ADAMS LifeMOD is chosen to simulate the crash and determine the injury level.

Other calculation parameters that must be defined before the computation can begin include the body movement restraints due to the 6-point safety harness which is a mandatory race car kit. Figure 6 shows a photograph of such a safety harness. The restraints are programmed into the simulation which results in the driver body restricted movement during the crash. Another boundary condition that must be carefully specified is the

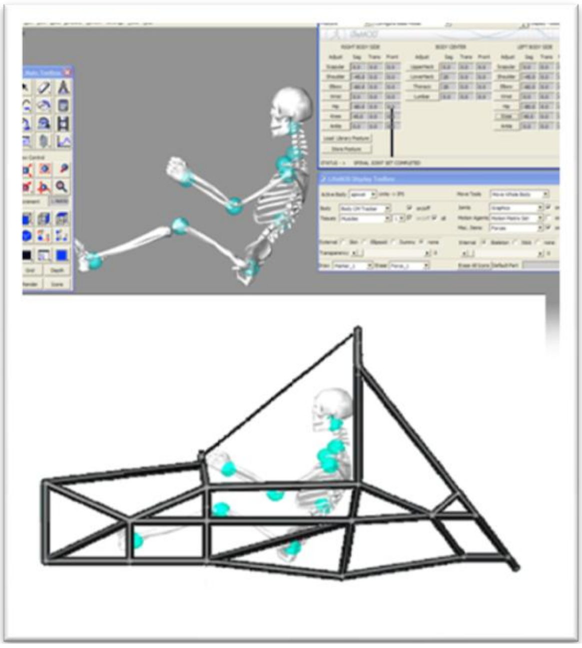

Figure 5. *The skeleton shows the position of the driver when seated in the race car cockpit. The vehicle structural frame depicted in the figure resembles the actual dimensions of the KMUTT race car 2010 model.*

Figure 6. *A 6-point safety harness is mandatory equipment on a Student Formula race car. Its body restraining characteristics are modeled in the computer simulation.*

seat and foot rest positions. These govern the driver's body and feet movement limitations.

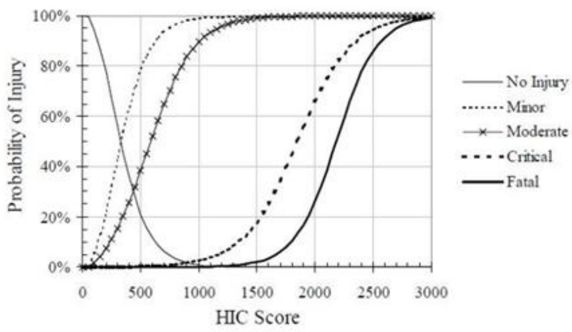

Figure 7. *Probability and severity of head injury for a range of HIC score*

Previously, the KMUTT team selected the aluminium honeycomb impact attenuator with 4 layers of 150 x 200 mm cross section area where each layer is 50 mm thick. This dimension will be used as a baseline in the computation. Two sizes of the cross section areas will be considered here, 150 x 200 mm and 335 x 350 mm and the number of layers ranges from 4 to7 (thickness from 200 to 350 mm)

As the driver is securely restrained and the car structure is assumed to be non-deformable, the injury that he can sustain during a crash under these circumstances is the neck whiplashes. The simulation will determine the severity of such injury sustained by the driver by considering the value of Head Injury Criteria (HIC) [4, 5].

$$HIC = \left\{\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)\ dt\right]^{2.5} (t_2 - t_1)\right\}_{max}$$

Eqn.(2)

where

$a(t)$ denotes the acceleration of the driver's head computed at its centre of mass

t_1 and t_2 denote the starting and final times during the simulation period

The acceleration of the driver's head centre of mass during the deceleration after the collision has occurred will contribute to the severity of the injury. The following data shown in figure 7 is taken from reference [4] and it shows the probability and severity of head injury over a range of HIC values.

In the case of our Student Formula racecar design, it is important to realise that the drivers are not professionals and should be given as much safety assurance as possible. Hence, it is realistic to use the HIC score of 1500 as the allowable limit for the driver safete. At this score, there is a 20% chance of the driver sustaining a critical head injury and a small chance of just under 5% of sustaining a fatal injury. The critical head injury is classified as an injury that is not life-threatening but may cause concussion and unconsciousness.

Finally, the simulations are performed using the ADAMS LifeModel software where the test parameters are (1) car velocity during impact, (2) cross section areas of the aluminium honeycomb impact attenuator and (3) thickness or number of layers of the aluminium honeycomb impact attenuator. Values of HIC experienced by the drivers in full frontal crashes with these conditions are calculated and presented in table 1 and figure 8.

Car velocity during impact (km/hr)	Number of layers (each layer is 50 mm thick)							
	4		5		6		7	
	Impact attenuator cross section area (in mm)							
	150x200	335x350	150x200	335x350	150x200	335x350	150x200	335x350
25	764.57	-	752.70	-	714.00	-	472.25	-
35	903.60	840.11	896.10	656.40	870.00	179.10	854.00	-
45	984.60	970.55	976.70	912.00	975.00	864.00	962.00	851.00
55	2146.90	1465.70	2054.00	1278.30	2003.40	1024.70	1995.00	997.00
60	3984.99	2190.60	3013.46	1988.00	2528.60	1567.80	2284.89	1465.27
65	6663.68	2732.64	6460.00	2601.50	4181.36	2569.00	3339.66	2530.16

Table 1. *Values of Head Injury Criteria (HIC) computed at different crash velocities and with different configurations of aluminium honeycomb impact attenuators. Shaded boxes indicate cases where the driver have a minimum of 20% chance of sustaining critical head injuries.*

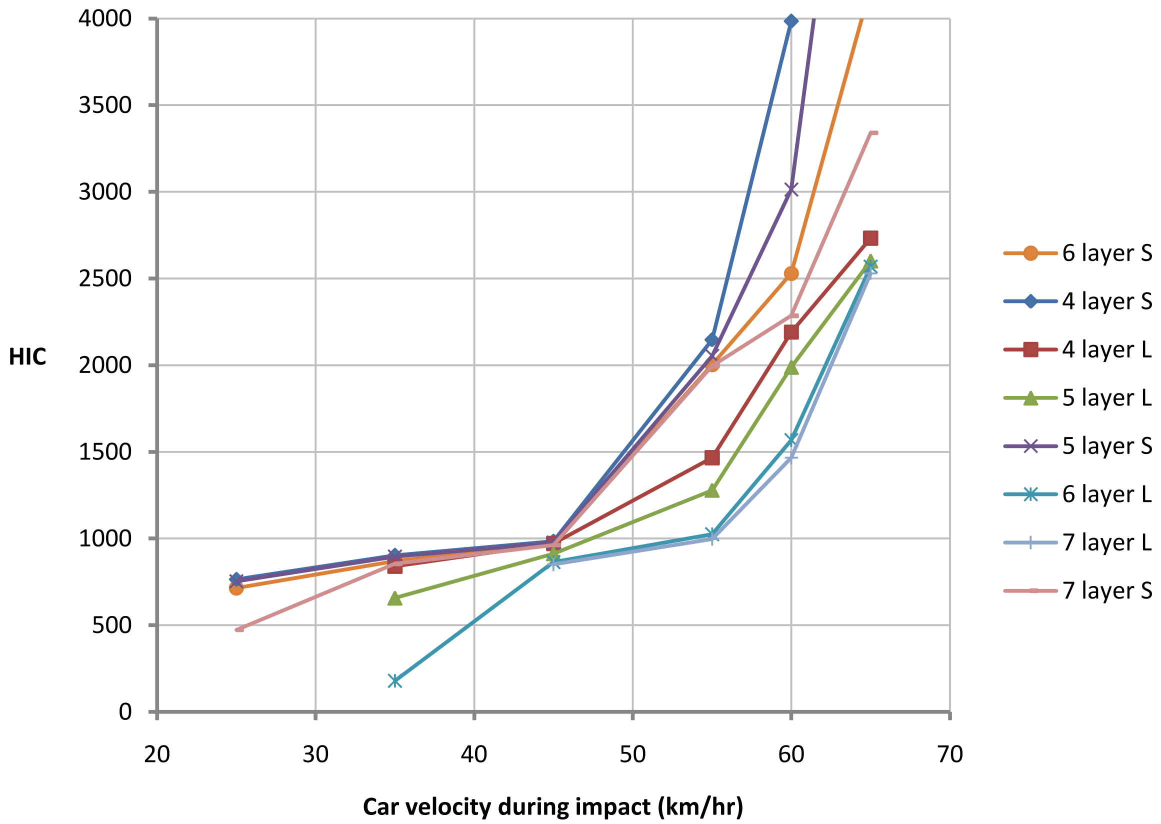

Figure 8. *Values of HIC are plotted against the car velocity during impact with different configurations of aluminium honeycome impact attenuator. Note that the legends 'L' and 'S' denote large (335x350mm) and small (150x200mm) cross section areas, respectively*

The simulation results show that only the 7-layer 335x350mm aluminium honeycomb impact attenuator has the capability to keep the driver 'safe' (HIC lower than 1500) when the car velocity is 60 km/hr. Other configurations, though more compact and lighter, will not be able to provide enough safety assurance to the driver at that same speed. Note that 60 km/hr is the maximum velocity the driver is likely to experience during the Student Formula competition, although this may not be the maximum speed the car is capable of. The results also show that all impact attenuators fail to protect the driver by keeping the HIC lower than 1500 when the car impact velocity is at 65 kh/hr or higher.

CONCLUSION

This research has demonstrated the determination of the optimal size impact attenuator for the Student Formula race car. It is found that an aluminium honeycomb attenuator with seven 50mm thick layers of 335x350 mm cross section area would provide sufficient safety to the driver in a 60 km/hr crash. This is the actual maximum speed experienced during the competition. Findings presented in this work will be used in the future design considerations of the impact attenuator for the Student Formula race car.

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