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ANALYSIS THE EFFECT OF SEAT FOAM ON PASSENGER HEAD INJURIES IN BUS FRONT CRASH ACCIDENTS

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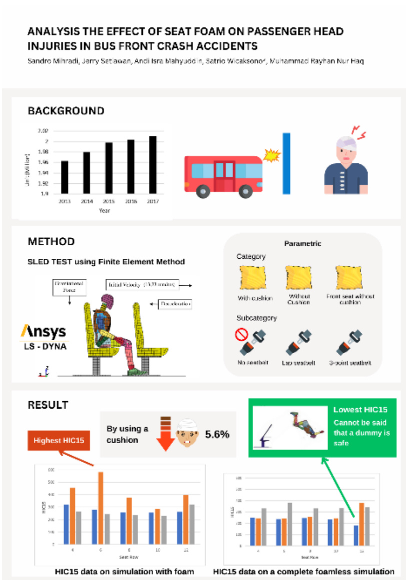
Graphical abstract



Abstract

The number of motor vehicle accidents keeps increasing from year to year. Based on Badan Pusat Statistik Indonesia in 2022, there are twenty-eight thousand people who died due to accidents. The number of accidents keeps increasing around 6.26% every year, which is most likely due to the escalation in the number of vehicles. The number of inter-city buses is growing around 2.23% every year. According to National Highway Traffic Safety Administration (NHTSA), most common type of accident that often occur on buses is frontal collisions. This accident can cause serious injuries or death because of impact on the passanger's head. The severity of head injury can be calculated using Head Injury Criterion (HIC) which has several categories of injury consequences. The research is focused on sled test simulation by finite element method which uses acceleration data from Mihradi. The simulations are divided into three categories: chair with cushion, chair without cushion, and without front chair's cushion. Each category has three subcategory of seatbelt system, namely lap seatbelt, lap and shoulder seatbelt, and without seatbelt. There are several conclusions from simulation's result. First, the use of cushion can reduce HIC_{15} around 5.6% in comparison to no cushion case. Second, shoulder seatbelt is the safest type of seatbelt that can be used in bus. Third, the use of cushion changes the whole model dimension and change the dummy's movement in front collision, which resulted in different value of HIC_{15} in comparison to case without cushion. Thus, cushion must be modelled in order to get accurate HIC_{15} values.

Keywords: Bus, HIC, sled test, frontal collision, simulation

1.0 INTRODUCTION

Buses are one of the mass transportation designed to transport people in large numbers. In Indonesia, buses are still the favorite land transportation for people to travel outside the city. Relatively cheap prices and good affordability are the advantages of buses that are not shared by other land transportation, evidenced by the increase in the number of buses. Based on the Badan Pusat Statistik (BPS), the average growth in the number of buses in 2018–2022 in Indonesia has increased by 2.23% with a total of 243,450 buses in 2022 [1]. The growth trend in the number of buses in Indonesia is presented in Figure 1.

However, the large transportation capability allows the number of victims in an accident to be more than other land transportation means. Based on data from Kepolisian Republik Indonesia, the number of motor vehicles accidents throughout 2022 reached 139,258 cases [1]. In 2022, the death toll due to motor vehicle accidents reached 28,131 people and seriously injured as many as 13,365 people [2]. In the United States, this type of bus collision from the front ranks second after rollover accidents [3]. According to the U.S. National Safety Department, the probability of dying from a motor vehicle accident is one in 114 people in the United States [4]. Of the total accidents, 71% of people who have car accidents and 50% of people in motorcycle accidents have head injuries [5]. Head injuries from this accident resulted in 25,000 deaths and about one million people hospitalized. Head injuries in humans can be measured based on Head Injury Criteria (HIC) values according to FMVSS standards issued by the National Highway Traffic Safety Administration (NHTSA).

There are three aspects affecting passenger safety against frontal crashes: superstructure strength, seatbelts, and seats. There have been many studies related to testing the strength of the bus superstructure in Indonesia, as was done by Vadila who conducted a forward collision test on the bus according to the FMVSS 208 standard using the full-scale barrier test method [6]. A forward collision test on the bus focuses on examining the behaviour of vehicle components such as seats, seat belts and passengers, namely the sled test. On sled test, dynamic loads are applied to some vehicle components such as seats, instrument panels, control systems, seat belts, and other components along with dummy as a substitute for human models to analyse occupant reactions to frontal or side impacts. The dynamic load given is generally in the form of a vehicle slowing down.

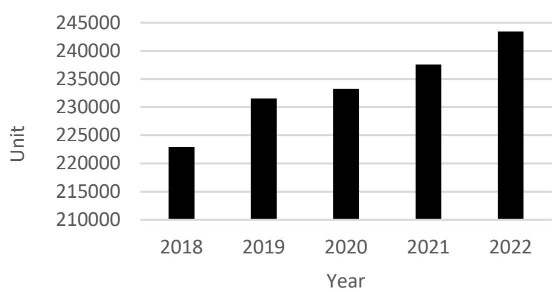


Figure 1 Development of the total number of buses in Indonesia (2013-2017) [1]

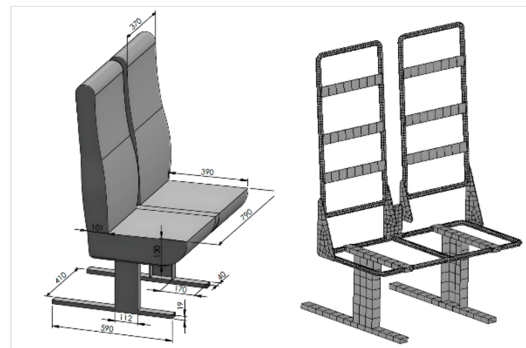
In this research, the author will do sled test with the deceleration data that has been obtained from Mihradi's research [6] using foam, without foam, and without foam in the front seats at certain seating locations for HIC values. Sled test consists of three parts: without a seat belt, with a two-point seat belt (lap seatbelt), and three-point safety belts (combined lap and shoulder seatbelt). The seat model used is a large bus type bus seat (big bus) with a capacity of 58 passengers.

2.0 METHODOLOGY

The simulation is carried sled test with the help of LS-PrePost and ANSYS Mechanical APDL software. This test was carried out to get the value of the occupant's head injury at several seat positions. Bus seat modeling of PT. Trijaya Union was performed on solidworks software and processed on LS-PrePost. modeling is done on four main components: the seat structure, foam, floor, and dummy.

Chairs produced by PT. Trijaya Union is used on large bus types (big bus) capacity of 58 passengers with a 2-3 seat layout. Modeling is done on a seat with a capacity of two people. Seat dimensions is measured, simplified, and modeled in Solidworks software. The seat consists of two main components, namely steel structure and foam. The results of bus seat modeling are shown in Figure 2a.

The seat structure generally consists of three components: a hollow quadrilateral cross-section, a hollow cylinder, and a triangular-shaped reinforcement. The modeled chair structure is a chair for two people. Meshing is carried out on the three types of components using the Auto Mesher menu in LS Prepost with the type of two-dimensional element (shell). The size of the structural element with a quadrilateral cross section is 42 mm, the size of the element for hollow cylinders is 10 mm, and 20 mm for triangular reinforcement. The combined structure of the seats can be seen in Figure 2b. This complete seat modelling follows engineering drawings from Mihradi et al [7] . The seat structure uses steel material with type STKM 13B. Table 1 shows the mechanical properties of STKM 13B.



a) b)

Figure 2 3D Model. **(a)** Overall bus seat. **(b)** Finite element model of seat structure

Table 1 Mechanical properties of STKM 13B [10]

Material Properties	Value
Density	7.83 x 10^{-6} kg.mm^3
Modulus Young	200 GPa
Poison Ratio	0.3
Ultimate Tensile Strength	667 MPa
Yield Strength	450 MPa

Foam is one of the main components in this study because the dummy head will be in contact with the foam part of the chair. To reduce simulation time, foam is only attached to one side only (as shown in Figure 3). Three-dimensional (solid) elements are given to foam with a size of 20 mm using the Solid Mesher submenu. Complete seat modeling consists of two rows of seats with a pitch of 770 mm between the front sides of the foam with each other.

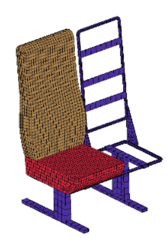


Figure 3 Finite element model of foam

The parameters required to define a foam material are density, yield stress, stress to strain curve, and KCON. The KCON parameter is the stiffness coefficient for the contact between the foam surface and other materials. These values are obtained from foam testing according to ASTM D 3574 standards on bus seats produced by local manufacturer in Indonesia. Table 2 showing the values of some foam material properties. The bus floor is required as a structural base for the seats and dummy to ensure they remain securely in place during deceleration. The dimensions of the bus floor are adjusted to accommodate the seat size, with the selected dimensions being 2000 mm in length and 1000 mm in width. The meshing process is carried out with the Auto Mesher submenu with an element size of 250 mm. In the seat model without foam, a thin plate is used as the seating base, as shown in Figure 4. Both the base plate and the floor are modeled as rigid materials using the 020_RIGID card. The material type of other seat components are presented in Table 3.

Table 2 Material properties of foam

Material Properties	Value
Density	6×10^{-8} kg.mm^3
Modulus Young	0.55 MPa

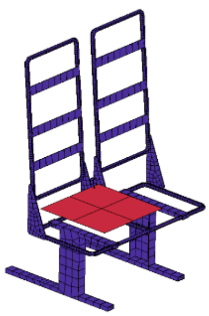


Figure 4 Finite element model of floor and seat

The dummy model used in this research is the Hybrid III 50th Percentile Male Rigid artificial Livermore Software Technology Corporation (LSTC), which has been adjusted to the standard size for adult men in Indonesia with a standing height of 169.2 cm and seated height of 83.56 cm [9]. According to The Lancet, Southeast Asians have an average Body Mass Index (BMI) of 22. Based on this value, the average body mass of Southeast Asians is estimated to be 62.98 kg [10]. In configurations where the dummy is not in contact with foam, the recommended static and dynamic friction coefficients between the dummy and other components in the crashworthiness simulation are set to 0.2 and 0.15, respectively [11]. Specifically, for contacts involving the dummy and foam components, the SLDTHK parameter is set to a value of 1.5 mm in the AUTOMATIC_SURFACE_TO_SURFACE type. SLDTHK represents an optional solid element thickness, creating a specific distance between the foam and the dummy, ensuring that the foam interacts correctly with the dummy without unintended penetration. The modeling of all components along with the dummy are shown in Figure 5.

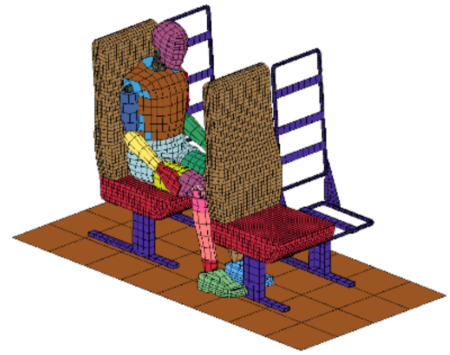
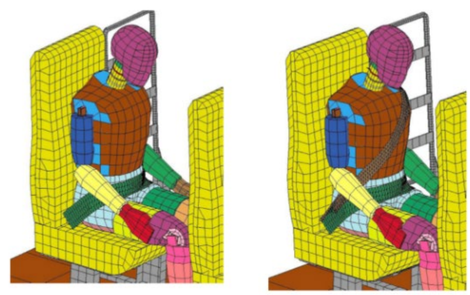


Figure 5 Finite element model of all components with dummy

Table 3 Material type of each component

Component	Material Type
Seat structure	024 PIECEWISE_LINEAR_PLASTICITY
Foam	057-MAT_LOW_DENSITY_FOAM
Seat belt	B-01-SEATBELT dan 034-MAT_FABRIC
Floor and seating	020-RIGID

The sled test is divided into three parts: without a seatbelt, with a two-point seatbelt (lap seatbelt) as shown in Figure 6 a, and with a three-point seatbelt (a combination of lap seatbelt and shoulder seatbelt) as shown in Figure 6 b..



a) b)

Figure 6 Finite element model of **(a)** two-point seatbelt (lap seatbelt) **(b)** three-point seatbelt (a combination of lap seatbelt and shoulder seatbelt)

The sled test simulation scheme is shown in Figure 7. The model is subjected to a downward gravitational force of 0.0098 mm/ms². In accordance with FMVSS 208 regulations, an initial velocity of 48 km/h (13.33 m/s) is applied. The velocity direction is set so that the bus moves forward.

Deceleration data is provided in the sled test to simulate the real-life conditions a vehicle would experience during a crash. The deceleration data used in this simulation is obtained from Mihradi's research [6]. In Mihradi's study, a full bus model was tested using a full frontal barrier crash, where nodal accelerometers were placed in rows 4, 6, 8, 10, and 12 to measure deceleration. The deceleration data from these rows is utilized in this sled test simulation to ensure accuracy and relevance to real-world crash scenarios.

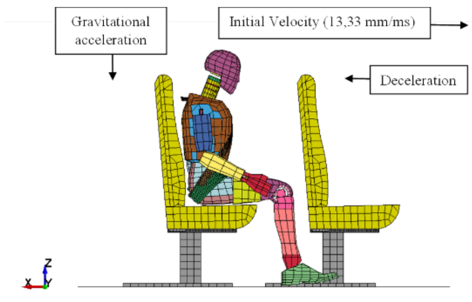


Figure 7 Sled test simulation scheme

3.0 RESULTS AND DISCUSSION

The analysis was carried out on a simulated sled test. The simulation is divided into three seat configurations: with foam (Figure 8a), without foam (Figure 8c), and without foam on the front seat (Figure 8 b) and in the case without a seatbelt, with a two-point seatbelt (lap seatbelt), and with a three-point seatbelt (a combination of lap seatbelt and shoulder seatbelt). The pre-processing and postprocessing processes are carried out using LS-PrePost software, while the solving process is carried out on ANSYS Mechanical APD software

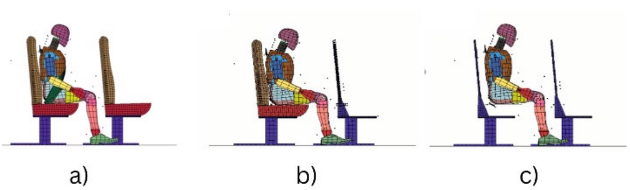


Figure 8 Configuration **a)** with foam. **b)** without foam on the front seat. **c)** without foam

3.1 Convergence Test

This study focuses on seat's foam effect on head injury scores. Therefore, convergence testing is performed on foam components. The test was conducted on a 10-row simulation with a 3-point seat belt. Simulations were conducted on three element sizes, namely 30 mm (3942 elements), 25 mm (7176 elements), and 20 mm (12650 elements).

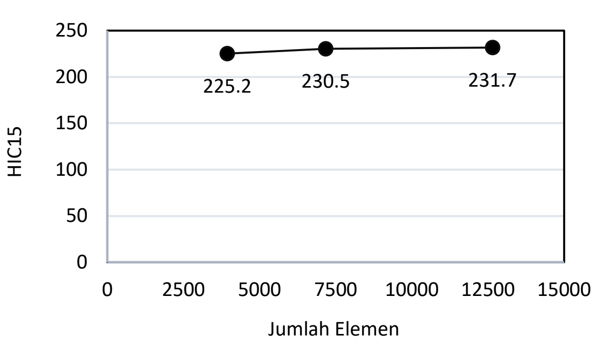


Figure 9 Convergence test results

The purpose of this convergence test is simply to ensure that the simulation results are stable and do not change significantly with smaller elements in the model. Figure 9 shows the effect of the number of elements on the HIC_{15} value. There is a relative error of 0.5% between the element size 20 mm and 25 mm, and 2.3% difference between element size 25 mm and 30 mm. Therefore, the 20 mm element size used for the foam can be considered to have achieved convergence.

3.2 Validation

In this study, the simulation of the seat without foam on the front seat and equipped with a lap seatbelt yielded an average HIC15 value of 326, with no head contact observed between the dummy and the front seat.

This finding is closely aligned with the results from El-Jahwari's study, where an average HIC_{15} value of 335 was recorded, and the dummy's head experienced minor contact with the front seat [12]. El-Jahwari's study was conducted experimentally using a sled test with a car, testing a dummy seated in the rear seat. Despite this difference, the sled test setup in El-Jahwari's study is nearly identical to the one used in this simulation, both aiming to replicate the same crash scenario under similar conditions. Despite this, the difference in average HIC_{15} values between the two studies is only about 4%, indicating that the results are consistent and validating the accuracy and reliability of the simulation conducted in this research.

To ensure the validity of the simulation, it is crucial that specific criteria are met according to the LS-DYNA usage guide. When static and dynamic friction coefficient value parameters are defined based on the type of contact between components, the sliding energy is expected to have a positive value [13]. Additionally, the energy value of the hourglass must be less than 10% of the peak value of internal energy [13]. These requirements are essential for validating the contact energy and hourglass energy within the simulation. As shown in Figure 10, the simulated energy curve of row 4 with the 3-point seat belt meets all these validation requirements. This result is representative of other simulation outcomes, indicating that all simulations conducted in this study are valid.

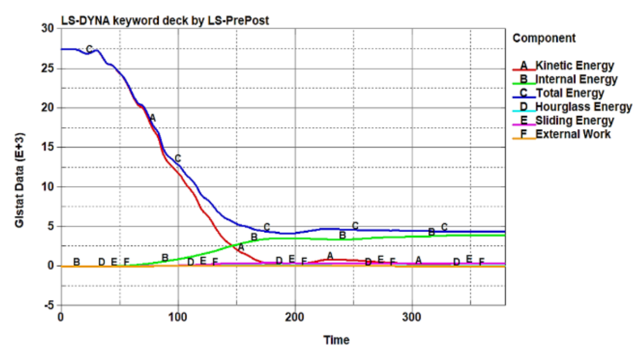


Figure 10 Energy curve of row 4 with the 3-point seat belt

3.3 Head Injury Criterion (HIC)

The HIC value is calculated based on acceleration data at the center of the dummy head over time. This calculation has been done automatically by LS-DYNA by finding the highest value at an interval of 0 ms to 380 ms. Based on FMVSS standard number 208 entitled Occupant Crash Protection, the permissible HIC15 value is 700 or equivalent to 30% risk of serious head injury (skull fracture and concussion)[14]. HIC_{15} results are divided into three parts: simulation with foam, simulation without foam on the front seat, and simulation without foam entirely (dummy placed on rigid seats). Table 4 presents the HIC15 data for the configuration with foam. The results for the configuration without foam are shown in Table 5, while Table 6 displays the data for the case without foam on the front seat. Each table includes results for five seating positions: rows 4, 6, 8, 10, and 12.

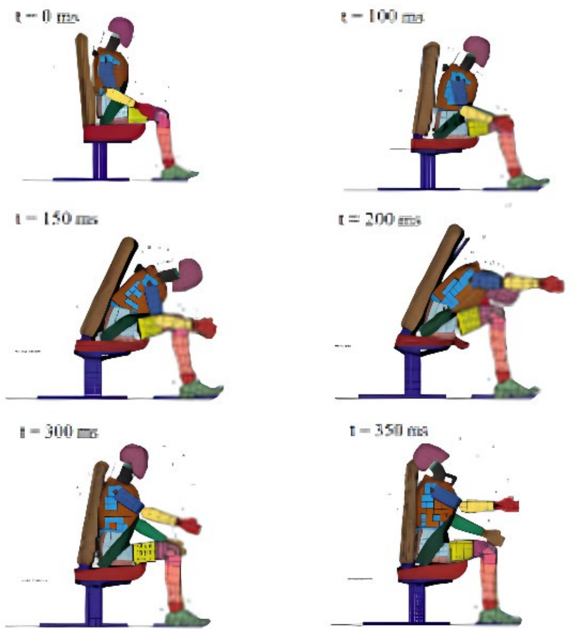


Figure 11 Simulation of sled test in row 4 with 3-point seat belt

Table 4 HIC_{15} data on simulation with foam

Row	No Seat Belt	2-Point Seat Belt	3-Point Seat Belt
4	319.6	455.4	265.5
6	280.9	581.3	245.7
8	259.3	377.8	238.5
10	255.1	285.5	231.7
12	261.3	394.6	323.0

Table 5 HIC_{15} data on front foamless simulation

Row	No Seat Belt	2-Point Seat Belt	3-Point Seat Belt
4	235.9	328.9	248.1
6	238.9	355.5	247.9
8	232.7	375.2	248.6
10	209.6	301.2	252.5
12	207.8	373.3	292.7

Table 6 HIC_{15} data on a complete foamless simulation

Row	No Seat Belt	2-Point Seat Belt	3-Point Seat Belt
4	249.6	245.2	331.0
6	236.1	242.9	381.7
8	246.1	255.5	331.4
10	233.4	244.2	335.2
12	179.8	378.2	342.3

From the simulation results, the highest HIC value was found in the simulation with foam in row 6 with a 2-point seat belt. The HIC_{15} value obtained is 581.3 with a maximum head acceleration value of 100 mm / ms2. this HIC_{15} value is recorded when the head changes direction as shown in Figure 12. This HIC_{15} value can cause loss of consciousness for up to an hour and a 45% chance of intermediate injury according to the Prasad-Mertz curve[15], [16], [17], [18].

The lowest HIC15 value in this simulation was observed in the configuration without foam, specifically for the unbelted dummy seated in row 12. The recorded HIC15 value was 179.8, measured while the dummy was airborne, as shown in Figure 13. In this case, the dummy's head did not make contact with the front seat structure.

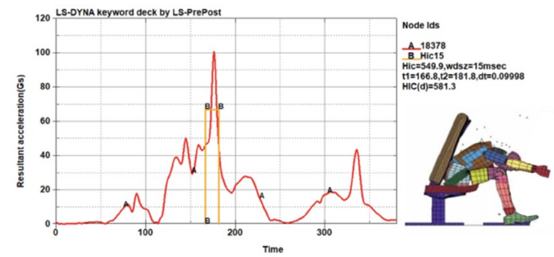


Figure 12 Head acceleration curve row 6 2-point seat belts with foam

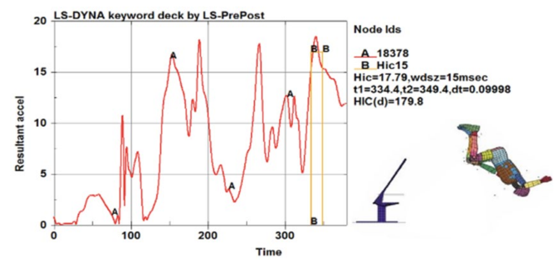


Figure 13 Head acceleration curve of row 12 head without seat belt without foam

3.4 Comparison

From the simulation results without using seat belts, the HIC_{15} value on seat structures that use foam has a greater value compared to seats that do not use foam at the front and those that do not use foam. In seats that use foam, the HIC_{15} value is taken when the dummy head hits the front foam, while in seats that do not use front foam, the HIC_{15} is taken when the dummy head hits the seat structure. This is due to the value of head acceleration when hitting the seat structure being lower than when hitting foam, besides that the time span for HIC retrieval when hitting the seat structure is shorter than when hitting foam. The time span in cases with foam is close to 15 ms, while in cases without foam, the retrieval range is below 10 ms. The time span is influenced by the addition of foam so that the distance between the dummy and the seat becomes closer. The difference in the average HIC_{15} value of all rows between seats that do not use foam and seats that do not use front foam is not too far, but when viewed in row 10 there is a difference in HIC_{15} values of 24 points or about 10%. This is because using foam causes a lower speed decrease, which results in lower acceleration values.

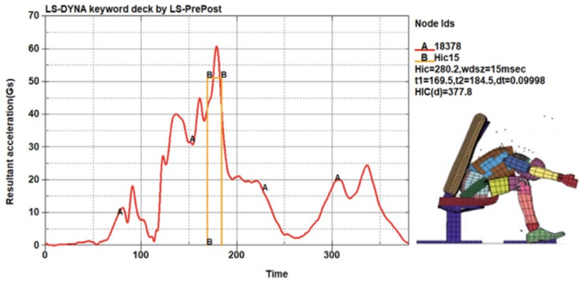


Figure 14 Head acceleration curve row 8 2-point seat belt with foam

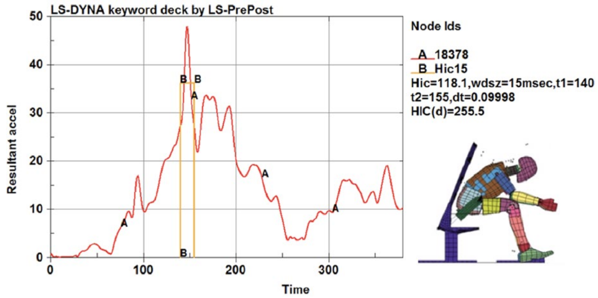


Figure 15 Head acceleration curve row 8 2-point seat belt without foam

From the simulation results using a 2-point seat belt, the HIC_{15} value in cases with foam has the highest value compared to cases without foam on the front seat and seat without foam at all. In the simulated case with foam, the HIC_{15} is taken when the head changes the direction of motion, while in the case without foam, the HIC_{15} is taken when the head moves downward as presented in Figure 14 and Figure 15. This causes the acceleration value in the case with foam to be 20% higher compared to the case without foam. When compared to the case without front foam, there is a huge difference in HIC_{15} values in line 6. This is because in the simulation with foam, the dummy head hit the upper leg which is characterized by an increase in the internal energy of the knee by 400%. Internal energy curves in the knees and head are presented in Figure 16 and Figure 17.

In the simulation using a 3-point seat belt, the HIC_{15} value in the case without foam has a higher HIC_{15} value when compared to the simulation using foam. When reviewed specifically in row 12, the HIC_{15} value in both foam-using and non-foaming cases is the same taken when the head hits the back of the chair. From the results of the head acceleration curve shown in Figure 18 and Figure 19, the maximum absorption value in the foam case is lower than the acceleration value in the case without foam. These results suggest that the use of foam can decrease the HIC value by about 5.6%.

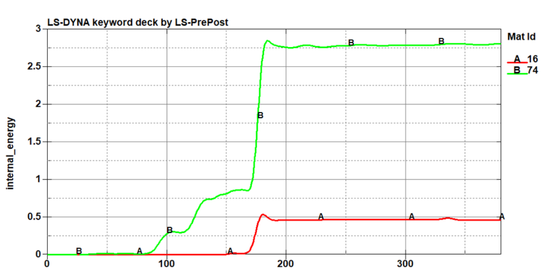


Figure 16 Internal energy curve of head (16) and right foot (74) dummy row 6 2-points seat belt with foam

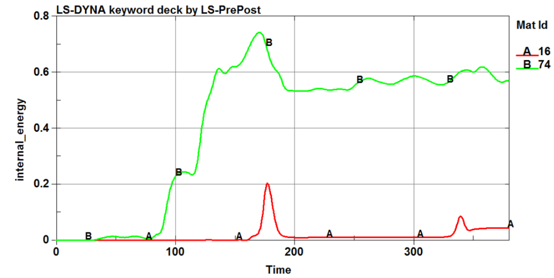


Figure 17 Internal energy curve of head (16) and right foot (74) dummy row 6 2-point seat belt without front foam

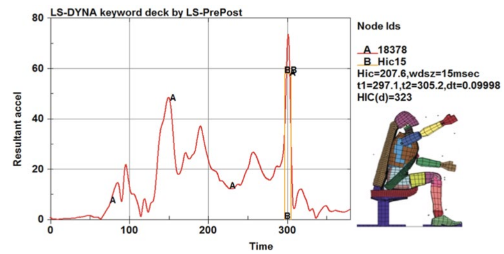


Figure 18 Head acceleration curve row 12 3-point seat belt with foam

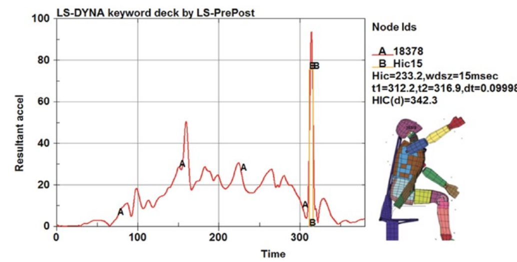


Figure 19 Head acceleration curve row 12 3-point seat belt without foam

4.0 CONCLUSION

After analysis and discussion of the simulation results, it was found that using a cushion can reduce HIC15 by around 5.6% compared to no cushion case. This is because using foam on the chair can change the overall dimensions and change the dummy's movement. Thus, the cushion must be modeled in order to get accurate HIC_{15} values. The highest HIC_{15} value of 581.3 was obtained in the case of seats with foam with dummies that use 3-point seat belts and are in row 6. While the lowest HIC_{15} value of 179.8 was obtained in the case of seats without foam with dummies that did not use seat belts and were in row 12. But from these results, it cannot be said that a dummy is safe because there is a phenomenon in the form of a dummy being thrown. Excluding the configuration without seat belts, the HIC15 results indicate that the use of three-point seat belts yields the lowest values. Therefore, the implementation of three-point seat belts in buses may be recommended.

There are several suggestions that can be used in future research, including testing the strength of the chair first according to UNECE regulations, such as UN R17 on the strength of the chair structure. The method used in this study should be carried out on seats that have been tested to see the effect on passenger head injuries. Seats that do not comply with regulations should not be permitted for use and therefore do not require further analysis. Future studies could include an analysis of injuries to other body parts, such as the neck and knees.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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