Research Article

Injury Risks of Rear Occupant in Typical Four-door Type of Pick-up Truck under Vehicle Collision

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Abstract
This research explores the injury risks of occupants in four-door type of pick-up truck using experimental based collision with Hybrid III dummy for occupant injury indicators. The full-sized crash laboratory was developed to conduct full frontal impact based on standard regulation. To verify performance of full-sized crash laboratory and vehicle deceleration, low and high speed tests were conducted at the same vehicle. The Hybrid III dummy with head and chest sensors was used at the rear outboard seat during high speed test. Consequently, the deflection and thoracic viscous criteria, which represent the chest injuries, are up to 93 mm and 3.96 m/s, respectively, high beyond the standard requirement. Moreover, the most important finding of this research is that the four-door pickup truck is subjected to the 2nd impact up to 116.51 G at dummy head with higher resultant acceleration than the 1st impact (65.62 G) due to the limited space behind the rear headrest and thinner backrest of rear seat. This research also investigates the post-crash results to illustrate the suggestive idea for improving crashworthiness of future design resulting in mitigation of occupant injuries.

Keywords: Vehicle crash test, Head Injury Criteria (HIC), Viscous Criteria (VC), Anthropomorphic Testing Device (ATD), Thorax Compression Criterion (ThCC), Pick-up truck

1 Introduction

In Thailand, the product champion of light-duty pickup truck has been promoted through exemption from exercise tax since 1992 [1]. The variant of pickup truck includes two-door type with enclosed cab and four-door type based on the same chassis in Thailand. With multi-purpose vehicle for carrying passenger and goods, the four-door type of pickup truck are commonly used in Thailand. However, the different geometry within occupant chamber between the four-door type of pickup truck and sedan type of vehicle are the space behind the rear headrest. Therefore, the rear windshield glass of pickup truck is close to headrest due to the space limitation. Furthermore, the rear seat is uncomfortable due to the limited adjustment of backrest inclination and seat position for leg room. Usually, the rear seats in both pick-up truck and sedan type of vehicle cannot be adjusted, and the position of seat belt is also fixed without the pretensioners, although the surrounding area of the front seats are different than that of the rear seats. Therefore, the safety equipment for protecting the rear seat occupant is less in comparison with the front seat occupants. For this reason, the rear seat occupant can be subjected to high risk of injury. Martin *et al.* revealed that the chest and abdomen injuries in the rear occupants were higher in the front occupants [2]. Zuchowski also studied research works related to the safety of front and rear seat passengers based on road accident data [3]. It was founded that there was higher risk of death for rear seat passengers than that for drivers in cars from accident data between 2001 and 2006 in France. If the rear occupants do not wear seat belts, risk of death is higher than that without fastening the seat belt.

Based on the accident data in 2019 from Office of Transport and Traffic Policy and Planning, the pickup truck was the top vehicle involved in traffic accident on the 100,759.20 km of urban and highway roads under the responsibility from Ministry of Transportation (MOT) in Thailand [4]. This information revealed that 91% of traffic accidents were two-vehicle collisions especially for light-duty pickup trucks and passenger cars with 32.46% and 29.31% of total 30,885 accidental vehicles, respectively. Due to limited in-depth investigation, the cause of death and injury area for rear occupants of pick-up truck cannot be obtained in Thailand.

Low speed impact in vehicle collision can cause either occupant injuries or vehicle damage. Based on momentum theory, more rigid chassis and vehicle frame for the purpose of less vehicle damage can cause higher impact force. For rear impact collision from more rigid vehicle, a neck injury that is the most common identified as “Whiplash” can be occurred in urban traffic accident. Ono et. al. studied the head-neck-torso kinematics responses under impact speed of 4, 6 and 8 km/h from twelve volunteers on a sled that can simulate the actual car impact acceleration on the vehicle seat without headrest. The female neck injury were higher than that of male due to the different alignment of cervical spine at those speed impacts [5]. Similar research works identifies that low speed of rear collision causes neck injuries of occupants [6], [7]. For frontal impact collision at low speed, spin flexion was found at base of neck and it was the greater for the youngest volunteers [8].

A pick-up truck normally has engine with substantial mass located at the front vehicle. During the frontal impact at high speed, the inertia from engine can cause the certain displacement at engine mounts in the forward direction until it reaches impact barriers. Then the engine is pushed back against the firewall related to the longitudinal chassis of frontal vehicle structures [9]. Therefore, the gap between the engine and the firewall for passenger compartment is dependent on the deformation of longitudinal chassis and the geometry of engine.

To clarify the injury risks of rear occupant in a four-door pickup truck under full frontal collision, the kinematic motion and injuries of rear occupant dummy with fastening seat belt are investigated under high impact speed due to limited adjustment of rear seat in the present research. Furthermore, the movement of dummy are recorded by high-speed cameras to be used for verification and analyze of the result obtained from sensers inside dummy.

2 Crash Test Standards for Vehicle and Injury Criteria

To prevent fatality and injury from road accidents, the decade of action for road safety were globally developed in 2011 [10]. These concepts are based on framework of national activities in five pillars such as Pillar 1: road safety management, Pillar 2: safer road and mobility, Pillar 3: safer vehicles, Pillar 4: Safer road users and Pillar 5: Post-crash response. Crash test standards for vehicle are developed to improve vehicle safety through harmonization of relevant vehicle standards. Based on vehicle regulation from United Nations Economic Commission for Europe (UNECE), there are vehicle test standards for both active and passive safety. For passive safety, UNECE R33 was developed for approval of vehicle regarding to the behavior of the structure of the impacted vehicle in a head-on collision. The requirement of this regulation is based on the geometry of vehicle structure after collision at speed of 48.3 km/h. The specification of residual space for passenger and driver compartments at the front seats after collision are the key indicators along the longitudinal, horizontal and vertical directions. Furthermore, no rigid component parts that cause the risk of serious injury shall be in the residual space. To keep the occupants in vehicle compartment, the vehicle door should not be opened under the influence of impact.

To identify the risk of injury in vehicle under the crash test, biomechanically-based crash test dummy or Anthropomorphic Testing Device (ATD) named Hybrid III was developed in 1973 [11]. The dynamic responses of head, neck, thorax and knee components with integrated transducers from Hybrid III are measured to calculate injury criteria in each human body part. The concept of Head Injury Criteria (HIC) is based on correlation of the measured kinematics from the head of Hybrid III as shown in Equation (1) [12]. HIC implies that contact between the head and any vehicle component is not allowed to cause high resultant acceleration over the maximum time duration.

In UNECE regulation R94, the approval of vehicles with regard to the protection of the occupants in the event of a frontal collision requires head performance criteria (HPC) in which HIC from Hybrid III is used. In the requirement of UNECE regulation R94, HIC should not exceed 1000. And the resultant acceleration at the head dummy should not be higher than 80 times of earth gravity (G = 9.81 m/s^2) for more than 3 milliseconds (ms) [13].

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

Where $a(t)$ is resultant acceleration with respect to time and $(t_2 - t_1)$ is the maximum duration time of 36 ms. However, impact duration for pedestrian protection test in UNECE regulation R127 takes only 15 ms because the head of pedestrian shortly impacts the bonnet of vehicle without any restraints [14]. The threshold of HIC performance limit for pedestrian protection is also 1000 which is similar to the requirement of UNECE regulation R94.

Apart from HPC requirement, the thorax compression criteria which is defined as chest deflection at hybrid III dummy should not exceed 42 mm as mentioned in UNECE regulation No. 94. Furthermore, the thoracic displacement rate as representative of viscous criteria from the experimental results of dummy chest should not exceed one meter per second. The viscous criteria can be calculated from the product of the compression and the rate of deflection of the sternum as shown in Equation (2).

$$Viscous\ Criteria = 1.3Max\left[(V_{(t)}C_{(t)})\right] \tag{2}$$

$$V_{(t)} = \frac{8(D_{(t+1)} - D_{(t-1)}) - (D_{(t+2)} - D_{(t-2)})}{12\partial t} \tag{3}$$

$$C_{(t)} = \frac{D_{(t)}}{0.229} \tag{4}$$

Where D_t is the deflection in meter unit at impact time (t) and ∂t is time interval in seconds during the deflection measurement. Each parameter of Viscous Criteria can be obtained from Equations (3) and (4) in order to determine the maximum value of $V(t)$ $C(t)$. In UNECE regulation No. 94, the viscous criterion for the thorax shall not exceed 1.0 m/s. Furthermore, Thorax Compression Criterion (ThCC) which is determined by the absolute value of the thorax deformation shall not exceed 42 mm. However, there are additional Thorax Acceptability Criterion (ThAC) for approval of seats in large passenger vehicle as mentioned in UNECE R80 [15]. In this requirement, ThAC should be less than 30 g for periods of more than 3 ms.

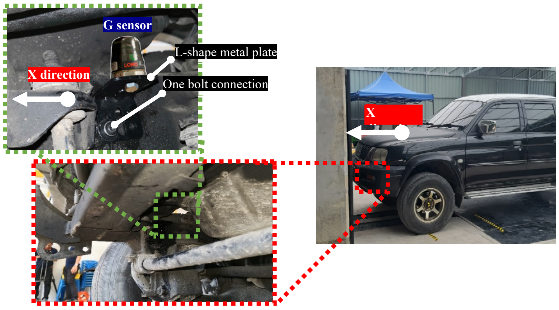

Figure 1: Position of deceleration sensor for low speed test.

3 Experimental Preparation and Methodology

The target vehicle from a popular brand was used because it can represent unique occupant chamber of pick-up truck with four-door type with vertical plane of rear windshield glass. This vehicle was also retrofitted with gasoline engine as shown in Table 1. Due to limited number of target vehicle, the low speed impact was firstly conducted at vehicle speed of 16 km/h (10 mph). After low impact test, this vehicle was then used for conducting high speed impact at 54 km/h. Furthermore, the three-axis accelerometer was installed using L shape metal plate with bolt connection at frontal right side of vehicle chassis in order to measure vehicle deceleration during the low speed test as shown in Figure 1. For high speed test, it was installed between the front seats in vehicle compartment.

The three-axis accelerometer and angular sensors were installed in head and chest of 50% Hybrid III dummy to identify the head and chest injuries respectively. To measure head and chest injuries, three-axis accelerometers from KYOWA model ASE-A-1KM32Z7L were used with maximum amplitude of 1000 G and 1% of non-linearilty. Such sensors

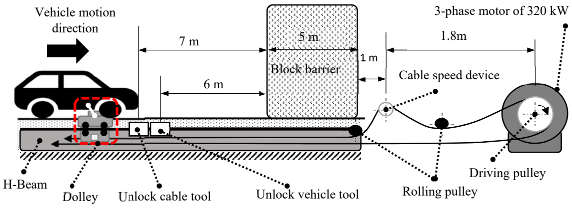

Figure 2: Layout configuration of full-sized crash laboratory.

were installed at the standard positions with geometry requirement inside Hybrid III. Based on the requirement of UNECE regulation R94 and Asean NCAP protocol, the accuracy of three-axis accelerometer shall be more than ± 1.5 per cent of the channel amplitude with 250 g for minimum amplitude of head acceleration [16]. And the error of displacement shall be less than 1 per cent of channel amplitude with 100 mm for minimum amplitude of chest deflection. In this research, Hybrid III 50% was set in the 2nd row at left outboard position behind front passenger seat only for high speed test. The dummy installation was set with the same procedure as mentioned in UNECE R94.

To prepare the full-frontal collision at low and high speeds, the full-sized crash laboratory should include four basic units such as block barrier, towing unit, dolley and run-up track. Furthermore, unlock cable and vehicle tools should be included together with cable speed measurement device as shown in Figure 2. In this research, the dolley was designed to lock and unlock vehicle and cable as shown in Figure 3. The block barrier was also designed to absorb impact energy from target vehicle. Based on UNECE regulation R33 for head-on collision, the block barrier should be made of reinforce concrete with minimum width and height of 3 m in front and 1.5 m respectively [17].

The thickness of block barrier must be such that to have its weight at least 70 tons. The towing unit should have sufficient power and torque for propelling vehicle to reach the target impact speed. The vehicle acceleration should be controlled to satisfy the length of run-up track and the friction utilization of transmission unit. During acceleration, the dummy position should be maintained from the initiation to final impact speed. Therefore, three-phase motor of 320 kW was used in this full-sized crash laboratory with constant acceleration of 1.962 m/s^2 or 0.2G (G = 9.81 m/s^2) in the controlling system for low and high impact speed of 16 and 54 km/hr respectively.

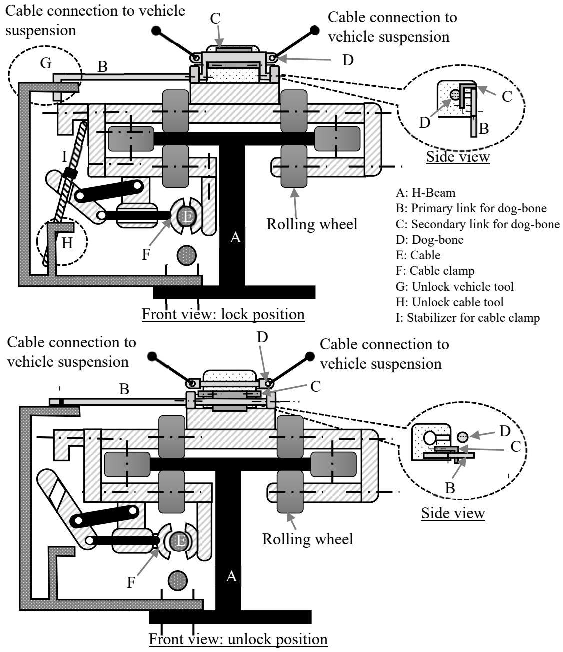

Figure 3: Layout configuration of dolley for lock and unlock positions.

To reach such vehicle speeds, the driving pulley in the towing unit of crash laboratory plays the essential role to obtain the towing force through cable. Maximal towing force (T_1) can be exerted from friction coefficient in the cable and pulley system (μ), the pre-tension load (T_2) in the cable and wrap angle (β) as shown in Equation (5). The requirement of towing force (T_1) can be calculated from Newton's law of motion under the vehicle mass of 1988 kg with 0.2G acceleration. The friction coefficient in cable and pulley system (μ) is set at 0.1 [18]. Therefore, the pre-tension (T_2) and wrap angle (β) were set at 2600 N and 4.19 radian respectively in both low and high speed tests.

$$T_1 \leq T_{2^{e^{\mu\beta}}} \quad (5)$$

The towing force in the cable should be used through the dolley to pull and release the target vehicle. The dolley should be designed to unlock the cable after releasing the target vehicle as shown in Figure 3. Finally, the run-up track should have certain range and structural area for speeding vehicle and accommodating the dolley respectively. Therefore, the specification of full-sized crash laboratory for investigating vehicle

Table 1: Target vehicle specification

No	Items	OEM Standard Vehicle*	Target Modified Vehicle
1	Vehicle type	Four-door pickup truck	Four-door pickup truck
2	Vehicle model year	2003 (4WD, MT)	2003 (2WD, AT)
3	Total weight	1,795 kg (Kerb mass)	1,988 kg (with pre-load mass)
4	Front axle weight	N/A	968 kg
5	Rear axle weight	N/A	1,020 kg
6	Engine type	Diesel Engine	Retrofit with gasoline engine
7	Vehicle Length, mm	4,955 mm	4,955 mm
8	Vehicle Width, mm	1,775 mm	1,775 mm
9	Vehicle Height, mm	1,800 mm	1800 mm
10	Wheel base, mm	2,960 mm	2,960 mm
11	Impact speed	Off-set frontal Impact at 64 km/h	Full frontal impact at 16 km/h***
			Full Frontal impact at 56 km/h***
12	No. Dummy Type	Two Hybrid III dummies	One Hybrid III dummy***
13	Sitting position	Passenger & Driver	2nd row behind passenger seat***
14	Assessment	3.80 out of 16**	Head and chest injuries***

C.G. = Center of gravity, 4WD = Four-Wheel drive, 2WD = Two-Wheel drive, AT = Automatic Transmission, MT = Manual Transmission
*Vehicle specification based on public information
**Score from offset frontal Impact protocol from the Australasian New Car Assessment Program (ANCAP)
*** Target conditions in this research work

structure and kinematic motion of rear occupant under low and high speed tests is described in Table 2.

Table 2: Specification of full-sized crash laboratory

Units	Specification
Block Barrier	
Material	Metal reinforced concrete
Weight	97,000 kg
Width	4 m
Length	5 m
Height	2 m
Towing Unit	
Three-phase motor	320 kW max power
Controlling system	Speed and acceleration
Transmission Unit	
Driving pulley	Steel pulley with diameter of 350 mm with wrapping angle of 4.19 Radian
Driven pulley	Steel pulley with diameter of 350 mm
Cable	Seamless cable with diameters of 11 mm with pre-tension load of 2600 N
Run-up track	
Length	140 m
Width	6 m
Structure area	H-beam (175 mm × 175 mm) with thermal compensation

To identify the vehicle speed, tachometer or revolution counter measures the rotation of a toothed ring integrated on small pulley diameter of 101.86 mm which is directly rotated with correlation to the cable speed. Since the target vehicle is locked to the dolley which is pulled by the cable, the vehicle speed can be measured by the cable speed device that uses the tachometer with toothed ring on small pulley. The specification of tachometer with toothed ring on small pulley is Model SNDH-T4L-G01 with maximum frequency 1 Hz to 15 kHz. The location of the cable speed measurement device is shown in Figure 2. The accuracy of such device was calibrated with the motor speed in the controlling system.

4 Results and Discussion

At low and high speed tests, the speed of vehicle and driving pulley was illustrated at Figures 4 and 5. It revealed that the pre-tension of cable from theoretical calculation was not sufficiently high for the vehicle mass of 1988 kg and 1795 kg at low and high speed tests respectively. The additional reasons are related to the inertia and friction drag force of cable mass on the track together with the actual friction coefficient in cable and pulley system. Furthermore, the cable slip from low speed test is higher than that from high speed test due to the influence of vehicle mass. However, the target of low speed can be achieved at 15.61 km/h which was within ± 1 km/h based on Asean NCAP requirement of speed variation. But the high speed was achieved at 42.19 km/h. If the pre-tension of

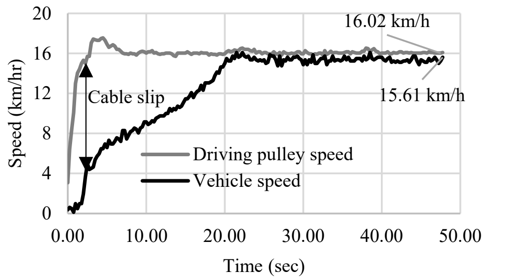

Figure 4: Vehicle and driving pulley data under low speed test.

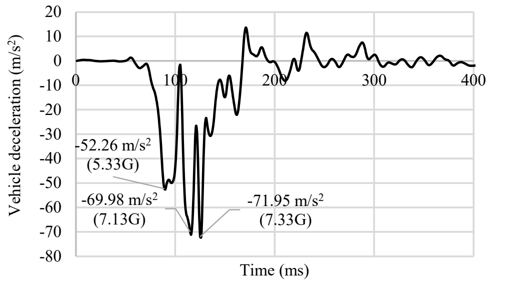

Figure 6: Vehicle deceleration at the front chassis in x direction under low speed test.

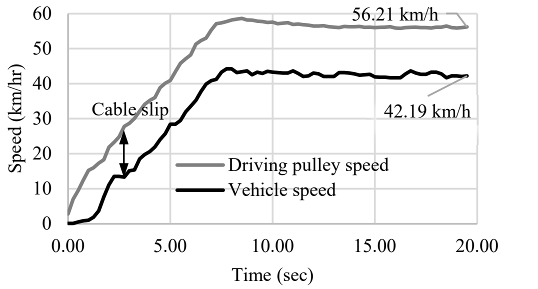

Figure 5: Vehicle and driving pulley data under high speed test.

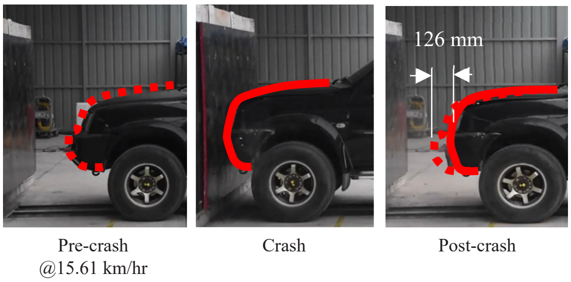

Figure 7: Vehicle structure deformation under low speed test.

cable was set at higher than 2600 N, the target for high speed of 56 km/h can be achieved. However, influence of vehicle mass and pre-tension of cable in the crash laboratory is the future study to achieve the target vehicle speed.

At low speed test without dummy installation, there were three intermittent peaks of vehicle deceleration at 52.26 (5.33G), 69.98 (7.13G) and 71.95 (7.33G) m/s^2 due to vibration effect of sensor installation as shown in Figure 6. Such sensor installation with L-shape metal plate using one bolt connection were the main cause of additional vibration. To assess the consequence of such deceleration, vehicle collision at low speed can cause only damage of bumper and radiator of vehicle resulting in vehicle deformation by 126 mm as shown in Figure 7. Furthermore, there was no deformation at the front section of longitudinal chassis in the tested vehicle. However, vehicle deceleration at corridors between 3G and 8G of frontal impacts are found to have major injury patterns in pediatric neck of 10 year's old child commonly occurred at the interspinous ligament in the C7–T1 segment [19]. Therefore, there is high risk for children sitting in the pickup truck without standard child seat in case of road accident at low speed collision. Furthermore, pickup trucks equipped with bull bar, also known as crash bar, might increase vehicle deceleration at low speed and more likely to cause pedestrian injuries [20].

At high speed test with dummy installation, the resultant head acceleration of dummy was recorded as shown in Figure 8. It illustrated that there were two continuous intermitted peaks of 643.70 and 1142.95 m/s^2 (65.62G and 116.51G) at the time of 87.8 and 146 ms respectively after the vehicle firstly touched the block barrier. The 1st peak of head impact is normally found in typical head-on vehicle collision. However, the 2nd peak of head acceleration was higher because the rebound phase from the restraint system caused the dummy head to hit the seat backrest as shown in Figure 9. Furthermore, the amount of 2nd peak was obtained from the limited space behind rear headrest resulting in less thickness of seat backrest for the typical four-door type of pickup truck. Similarly the 2nd peak of head collision to B pillar can be found in the front seat during the frontal offset collision [21]. However, the first peak of dummy head occurred after the maximum vehicle deceleration of 734.33 m/s^2 (74.85G) at 21.6 ms as shown in Figure 10. This is

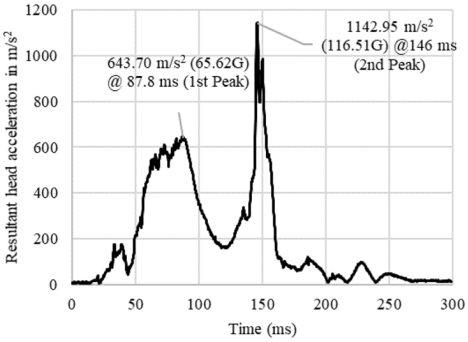

Figure 8: Resultant head acceleration in dummy under high impact test.

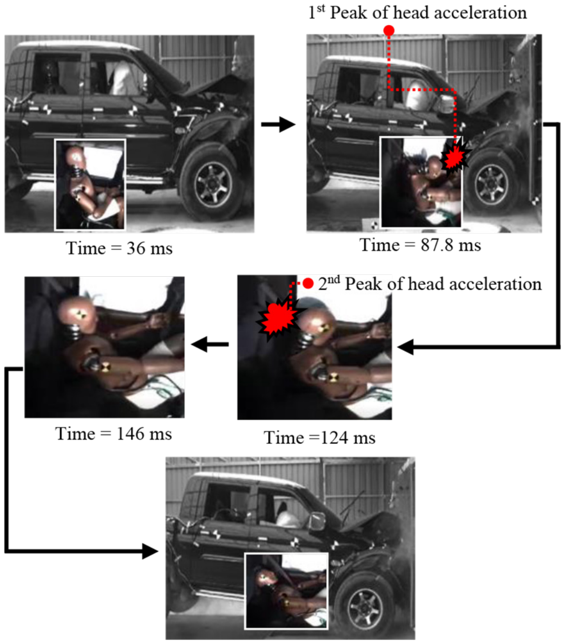

Figure 9: Collison time of dummy motion from the beginning stage of vehicle collision.

due to the dummy head motion from original position to the restraint position at 87.8 ms. To identify risk of rear occupants in the pick-up truck, maximum value of HIC was found at 917.104 from the time of 59.6 to 95.6 ms during the 1st peak of head impact using Equation (1). And HIC was 716.99 from the time of 142.4 to 157.4 ms during 2nd peak of head impact. In spite of higher head acceleration in 2nd peak, this HIC was less than HIC from the first peak due to the influence of periods of impact time [22].

During the high speed collision, the time of

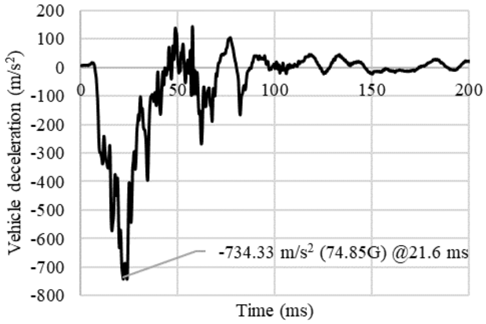

Figure 10: Vehicle deceleration at the floor between front seats in x direction under high speed test.

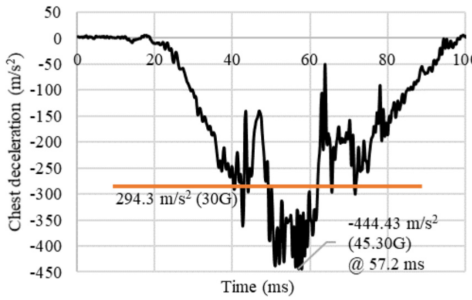

Figure 11: Chest deceleration in x direction under high speed test.

maximum chest deceleration of 444.43 m/s^2 (45.3 G) was also found at the time of 57.2 ms due to the influence of restraint system from the seat belt as shown in Figure 11. This restraint system actuated at the time of approximately 20 ms before maximum vehicle deceleration at 21.6 ms. To investigate the chest deflection and the thoracic viscous criteria, data from chest deceleration were firstly integrated with time using kinematic theory of motion for the chest velocity and deflection as shown in Figures 12 and 13 respectively. However, utilization of such calculated data can be accepted with limited value because the geometry constraint inside the actual chest dummy cannot be deformed up to the calculated 0.436 m at time of 87.8 ms during the 1st peak of head dummy as shown in Figure 13. Therefore, it is necessary to use displacement sensor install in dummy chest for more realistic and accurate information. However, the calculated data from chest velocity and deflection at the time of maximum chest deceleration were used to calculate the viscous criteria. Consequently, the chest velocity, deflection and thoracic viscous criteria at

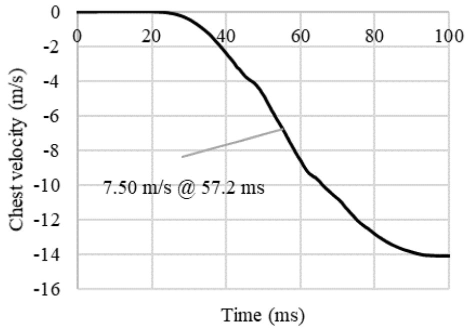

Figure 12: Chest velocity with collision time from numerical integration of chest deceleration.

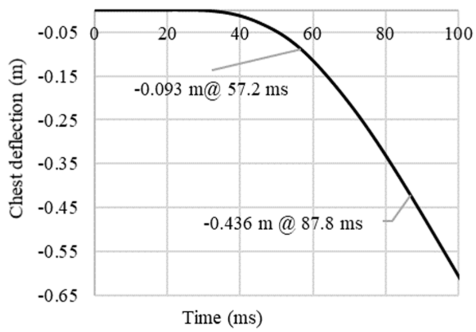

Figure 13: Chest deflection with collision time from numerical integration of chest velocity.

time of 57.2 ms are 7.50 m/s, 0.093 m (93 mm) and 3.96 m/s. These calculated data are beyond the limited requirement from UNECE regulation No. 94 for chest deflection and thoracic viscous criteria at 42 mm and 1 m/s respectively. Furthermore, the chest deceleration data was higher than the requirement of UNECE regulation R80 at 30G (294.3 m/s^2) for periods of more than 3 ms as shown in Figure 11.

To investigate vehicle structure under high speed test, the overall length of vehicle was deformed by 229 mm as shown in Figure 14. The total crash energy from vehicle mass mainly absorbed by the front section of vehicle body and longitudinal chassis from the beginning of collision time to approximately 50 ms as shown in Figure 10. This impact caused buckling effect in vehicle chassis resulting in the reduction of crashworthiness for protection of occupant injury. Thus, the maximum vehicle deceleration of 74.85 G in this pickup type chassis are directly related to 1st head acceleration of 65.62 G and chest deceleration

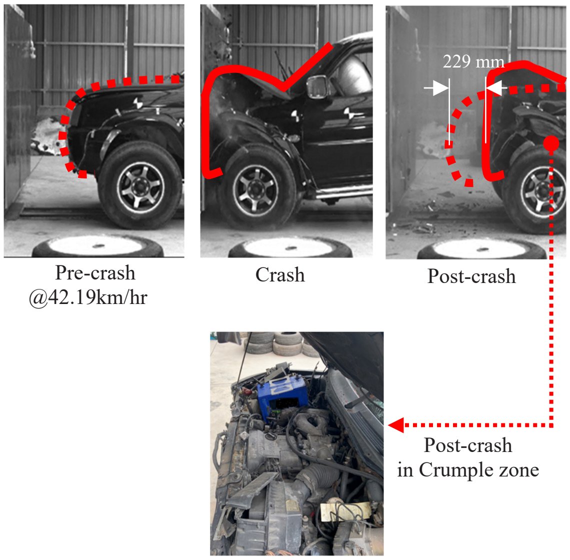

Figure 14: Vehicle structure deformation under high speed test.

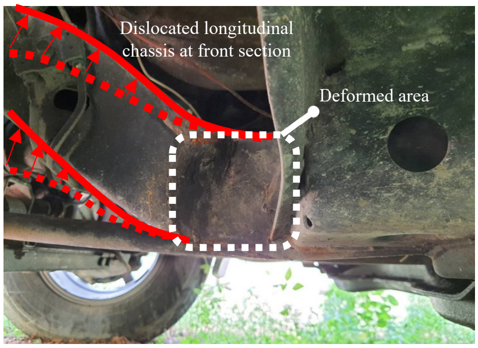

Figure 15: Damaged chassis at the front section of vehicle under high speed test.

of 45.30 G. Deformed area in longitudinal chassis is illustrated in Figure 15. To improve crashworthiness, design of vehicle chassis through collapse behaviour for absorbing impact energy especially in the pickup truck should be taken into account [23]. With collapse behaviour in vehicle chassis, the deceleration of vehicle and the occupant head and chest could be decreased, respectively.

During the high speed test, the pre- and post-crash for the longitudinal gap in engine compartment was measured as shown in Figure 16. It revealed that there was no available gap in front of the engine to absorb the impact energy through the vehicle body and chassis.

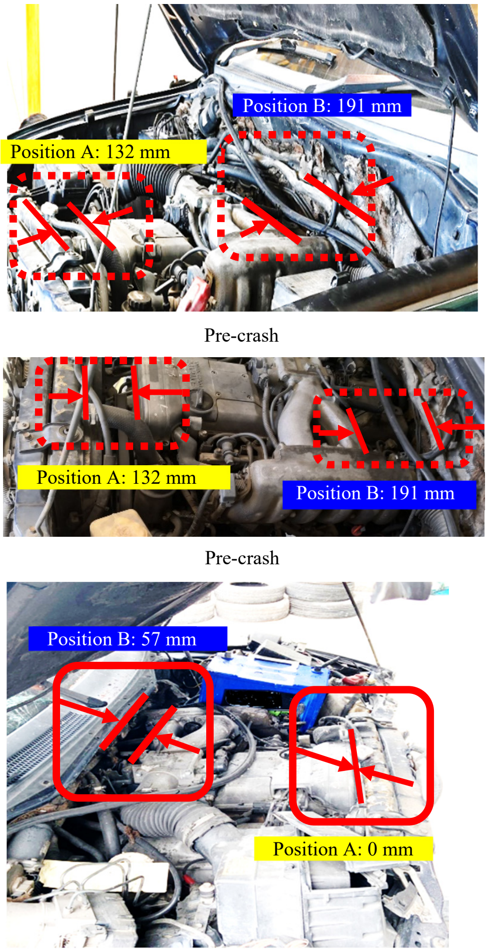

Figure 16: Gap measurement in engine compartment under high speed test (Position A: Gap before engine block, Position B: Gap behind engine block).

However, dislocation of engine caused the closet of gap from 191 mm to 57 mm under the impact speed of 42.19 km/h. Thus, there was no intrusion of engine against the occupant compartment. If vehicle collision is higher due to overspeed driver behaviour, there are higher risks to cause occupant injuries from the engine block intrusion and high vehicle deceleration.

Thus, design and repair of vehicle structures should be considered to avoid the intrusion of solid blocks like engine and transmission unit [24]. If conventional used vehicle is retrofitted with electric driving motor and battery packaging in the front section of vehicle, post-crash examinations under various accident scenarios should be necessary to enhance the vehicle safety standards under new generation of automotive industries [25].

5 Conclusions

This research conducted full-sized collision test to clarify the injury risks of rear occupant in a four-door pickup truck under low and high speed conditions.

The results during low speed test show that there are no major damage of vehicle chassis. There is only the frontal deformation at the bumper section. The vehicle deceleration at low speed impact is also low than 10 G. However, this value might cause neck injury for child occupant without standard child seat. The results of high speed test show that the deflection and thoracic viscous criteria, which represent the chest injuries, are up to 93 mm and 3.96 m/s, respectively, high beyond the standard requirement.

The most important finding of this study is that the four-door type of pickup truck is subjected to the 2nd impact up to 116.51 G at dummy head with higher resultant acceleration than the 1st impact (65.62 G) due to the limited space behind the rear headrest and thinner backrest of rear seat. This scenario inevitably should be used to improve the crashworthiness of future design, which enormously result in the injury mitigation. In the same manner, the study of Jothee *et al.* pointed out the airbag deflects causing fatal penetrating neck injury [26]. Based on their finding, the OEM-supplier cannot neglect the hidden problem but should improve the future design.

Lastly, the author would suggest some ideas for future improvement or design. To improve the crashworthiness for vehicle, design of longitudinal chassis with collapse behaviour is necessary for improving crashworthiness and absorbing the impact energy. Furthermore, the closet of gap between engine block and firewall is dependent on vehicle chassis. Therefore, vehicle chassis performance for retrofitting vehicle with new engine or electric motor should be considered and evaluated in term of vehicle deceleration and deformation under high speed collision.

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