ANALYSIS OF WAYFARER SIDE, FRONT AND REAR IMPACT WITH A LIGHTWEIGHT PICKUP TRUCK AT CENTER AND FRONT CORNERS

A Thesis by

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The following faculty members have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science with a major in Mechanical Engineering.

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DEDICATION

To my parents, my sister, my brother, my cousins, my best friends and

to my advisor Dr. Hamid M. Lankarani

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ABSTRACT

Wayfarer injuries and fatalities in the United States has taken an uprise in the past few decades. According to the data estimated by National Highway Traffic Safety Association (NHTSA), there are severe pedestrian injuries and fatalities. These injuries in many instances are caused by smaller trucks which are now dominant upon other passenger vehicles. Procedures have been proposed and implemented by the European Experimental Vehicle Committee (EEVC) for increasing pedestrian protection. In this study, computational impact analyses of 50th percentile pedestrian with a wayfarer – Lightweight Pickup truck are carried in a multi-body MADYMO workbench to examine the kinematics and potential injuries of the wayfarer in a vehicle collision. A Multi-body lightweight pickup truck model is developed and utilized with the 50th percentile male pedestrian model. The analysis of injuries is evaluated at three locations in the front end. The simulations are run at the side, front, and rear pedestrian standing configurations. Different factors including height of wayfarer, speed, and hood stiffness of the vehicle might influence the kinematics and severity of injury in a collision. The crash simulations are carried out at five different speeds to mirror the scenarios of traffic accidents occurring to adult wayfarers. The kinematic responses of the wayfarer, head injury locations, and injuries sustained at the head, chest, pelvis, and lower extremities are analyzed. The injuries to the wayfarer's head are shown to be dominant compared to other body parts. A Design of Experiments (DOE) is performed to examine the importance of truck design parameters and also to reduce head injury. Generally, at medium and higher speeds, injuries are more severe as body forces reach maximum level during post kinematics. This study also provides a method to update vehicle design to reduce the injuries and fatalities to wayfarers and can also be utilized for future collision protection regulations.

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LIST OF ABBREVIATIONS

EEVC	European Experimental Vehicle Committee
TTI	Thorax Trauma Index
FARS	Fatality Analysis Reporting System
AIS	Abbreviated Injury Scale
GSI	Gadd Severity Index
HIC	Head Injury Criteria
NIC	Neck Injury Criteria
FMVSS	Federal Motor Vehicle Safety Standards
FEA	Finite Element Analysis
PMHS	Post Mortem Human Surrogates
NHTSA	National Highway Traffic Safety Association
NCAC	National Crash Analysis Center
NCAP	New Car Assessment Program
LTV	Light Trucks and Vans
ATD	Anthropomorphic Testing Device

CHAPTER 1

INTRODUCTION

1.1 Background

Walking is the easiest, most affordable, and most ecologically friendly mode of human transportation. Walking, particularly in urban and suburban areas, provides vital links between residential, retail, and commercial land areas, as well as access to public transportation. Unfortunately, whether walking with the dog, commuting to work or school, or exercising, walking has become more dangerous in recent years [1]. The total of LTVs in the U.S. on the road system has increased by 200 percent in the last 20 years. As compared to passenger vehicles, LTVs are more offensive [2]. As a result, there are more questions about pedestrian safety when LTVs are used. Whenever pedestrians are involved in a crash, they are unprotected unlike the vehicle impacts as vehicles are equipped with seatbelts, airbags, etc. [3]. Thousands of wayfarers are killed or injured per year in road traffic accidents across the world, leading to economic costs and long-term effects. Each year, approximately 5,500 pedestrians are killed, and 69,000 other people are injured in motor vehicle collisions in the United States. This reports for 13% of all traffic deaths and 5% of all accidents in the United States (NASS, GES, FARS). Many other countries around the world, such as the United Kingdom, Japan, and Australia have a greater proportion of pedestrian accidents [4].

According to the Deaths Analysis Reporting System of the United States Department of Transportation, 4,800 pedestrians were killed in road accidents in 2002, a drop of 13% from the

5,550 pedestrians killed in 1992. In 2002, 71,000 people were involved in a traffic accident. Among the wayfarers, one-fourth of all children between the ages of 5 and 9 years were killed in traffic accidents in 2002, and 6% of all youth under the age of 16 years were hospitalized in traffic crashes [5].

It is important to provide an appropriate approach for the new vehicle front design that is pedestrian-friendly to reduce the risk of pedestrian injuries in an unexpected accident. Pedestrian fatalities have declined significantly over the last twenty years, but they still count for 11% of all motor vehicle fatalities.

With a high prevalence of automobile pedestrian collisions, pedestrians are mainly affected by the vehicle front. The majority of these collisions occur at speeds up to 40 kmph [6]. The necessary data comes from crash tests conducted by the European Experimental Vehicle Committee (EEVC) and government research laboratories. The sub-unit testing methods can be used to detect truck front impact energy and local stiffness, which seem to be two of the most common factors of pedestrian injury [7].

While the number of light truck vehicles (LTVs) on US roads continues to rise, a new point of concern about wayfarer safety has identified, as seen in Figure 1.2 and Figure 1.3. LTVs can pose a greater risk of injury or death for vulnerable road users such as pedestrians than passenger cars, due to their significantly different scale, shape, and stiffness values [5].

LTV sales increased from 20% to nearly 50% of all the light passenger automobiles sold between 1980 and 1999, shown in Figure 1.2 (Automotive News, 1980-1999). With such a significant shift in the US passenger vehicles, it's important to look at the safety implications for Pedestrians and motorists.

From 2009 to 2018, the percentage of pedestrian casualties in the United States rose by 53%, increasing from 4,109 in 2009 to 6,283 in 2018 as shown in Figure 1.1. As opposed to 2009, this leads to more than 2,100 additional traffic fatalities in 2018. While the number of pedestrian deaths has grown, the total number of traffic fatalities has only increased by 2%. According to NHTSA's statistical estimation of traffic fatalities for the first half of 2019, there will be a 3.4 percent decrease in total traffic deaths compared to the beginning of 2018. Pedestrian deaths as a proportion of overall motor vehicle accident deaths rose from 12 percent in 2009 to 17 percent in 2018, corresponding to a rise in the number of pedestrian deaths [1].

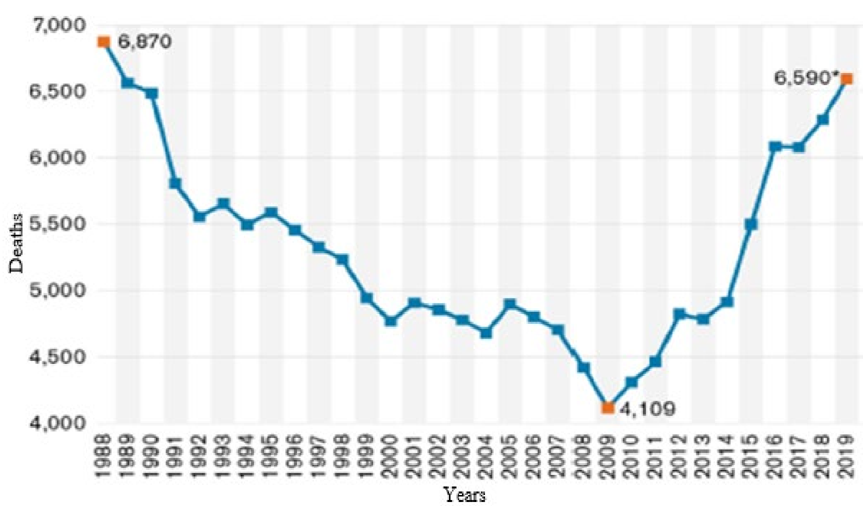


Figure 1.1. Pedestrian Deaths in US since 1988 [1]

In LTV – Car accidents, several studies have already shown that LTVs are not compatible with vehicles (Summers et al., 2001; Gabler and hollowell, 1998, 2000; Joksch, 2000;

IIHS, 1998) [2]. According to reports, 81 percent of critically injured passengers in LTV-car accidents appeared to be in the car [8].

Mizuno and Kajzer utilized Japanese traffic accident data to compare the similarities of cars and LTVs in collisions with pedestrians, finding that LTVs faced a substantially higher death risk than passenger cars. Jarrett and Saul provided data from a clinical study conducted in the United States that indicated LTVs may pose a greater risk to pedestrian safety than vehicles [9].

According to new studies, the type of vehicle influences the risk of human injury. In the June issue of Prevention Efforts, the study "Pedestrian Crashes: Higher Injury Severity and Mortality Rate for Light Truck Vehicles Compared to Passenger Vehicles" was released. The researchers looked at 540 traffic deaths in six cities (Seattle, Chicago, San Antonio, Fort Lauderdale, and Dallas) from 1994-1998.

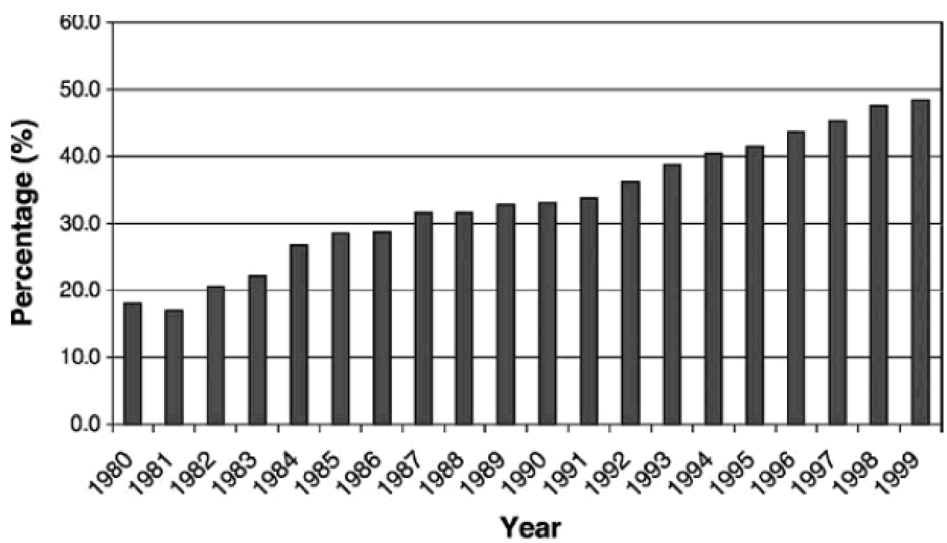


Figure 1.2. US sales of light trucks and vans [8]

As compared to pedestrians hit by motor cars, pedestrians struck by light trucks had a threefold higher risk of serious injury and a 3.4 rate higher risk of death. Investigators from the University of Virginia's Center for Applied Biomechanics and the Harborview Injury Prevention & Research Center (HIPRC) collaborated on the study.

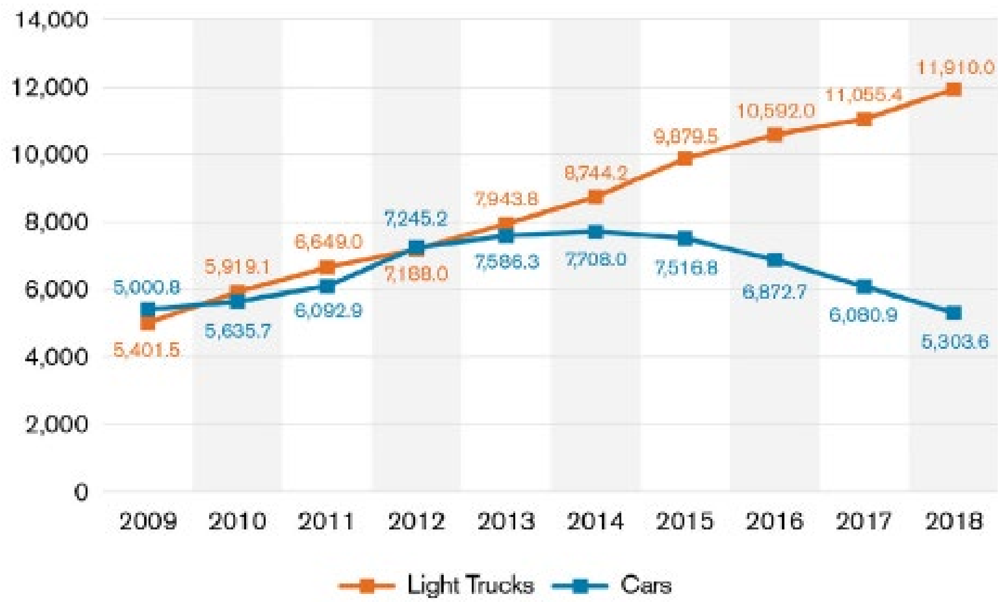


Figure 1.3. Retail Sales (in Thousands) of Passenger Cars and Light Trucks: 2009-2018 [1]

The proof that LTV collisions result in a substantially higher risk of serious injury and loss for pedestrians confirms the value of technological testing to measure vehicle safety not only for occupants but also for pedestrians [10].

According to one report, urban areas account for 85 percent of pedestrian accidents, whereas rural areas account for 15%. Even then, rural areas account for 25% of fatal pedestrian accidents, indicating the relatively more serious nature of pedestrian collisions outside of metropolitan areas. Even though the majority of pedestrian collisions occur in cities, 60% of all pedestrian collisions in cities do not occur at intersections. In comparison, 75% of child pedestrian accidents occur outside of an intersection. The number of crashes that happen at intersections varies depending on the type of collision. Age is also a significant factor, with 75% of child traffic accidents occurring at intersections, compared to the percentage of elderly pedestrian crashes occurring at crossings [8].

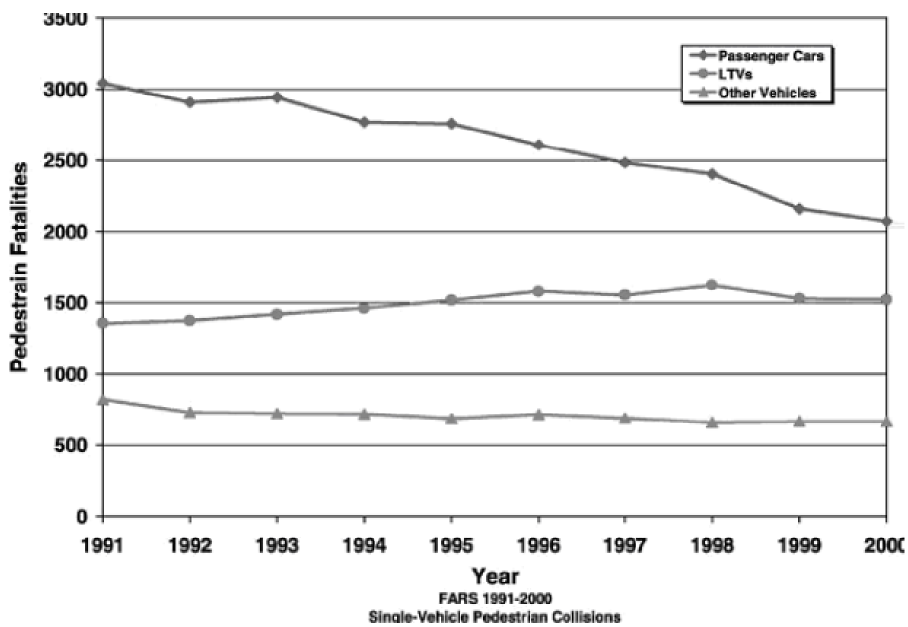


Figure 1.4. Pedestrian fatality trend by vehicle type for single vehicle–pedestrian Collisions [8]

In 2000, 4739 pedestrians died as a result of their injuries, down 18% from 1991. From 1991 – 2000, the exponential rise in pedestrian deaths is seen in the graph above. Figure 1.4 indicates that the reduction in deaths occurs mostly in the passenger car category when distinguished by vehicle class and limited to single-vehicle accidents. While the rate of pedestrian fatalities caused by car collisions decreased by 32% between 1991- 2000, the number of pedestrian deaths caused by LTV collisions raised by 10% [8].

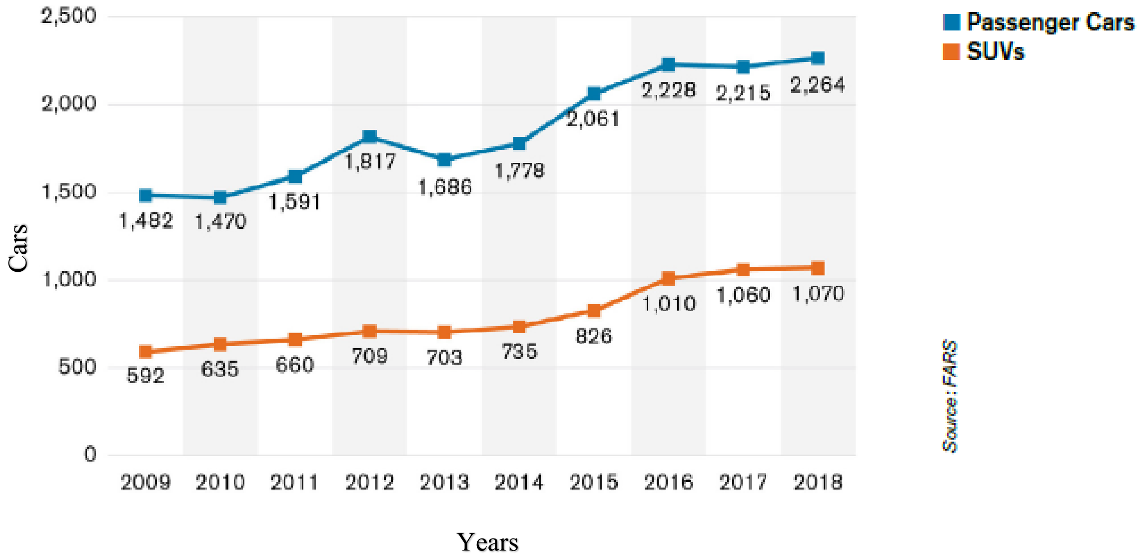


Figure 1.5. Number of Pedestrians Killed in Single-Vehicle Crashes Involving Passenger Cars [1]

Based on initial figures from the first 6 months of 2019, as well as historical data on the total numbers and proportions of pedestrian accidents in the first and second halves of the year, the GHSA estimates that there will be an estimated 6,590 pedestrian fatalities in 2019, a 5% rise from 2018, or approximately 300 additional deaths as shown in Figure 1.5 [1].

About 74% of cases of Pedestrian collisions occur when there is zero traffic management, 7% whenever there is a stop regulatory, and 17% when there is a traffic signal. This breakdown, however, varies greatly depending on the type of accident. When a vehicle turns at a junction, 63% of pedestrian collisions occur where there is a signal, compared to 17% overall (as shown in Table 1.1). When it comes to speed limits, the majority of pedestrian accidents happen in areas where the speed limits are less and medium [11].

Speeding is a significant contributor to all forms of collisions. Speeding was a major contributor about 31% of all fatal accidents in 2003. When a pedestrian is involved, speeding has serious implications. From Figure 1.6, At 40 mi/h, a person walking has an 85% risk of being killed; at 30 mi/h, the chance drops to 45%; and at 20 mi/h, the death rate drops to just 5%. A pedestrian is more likely to be struck at higher speeds.

TABLE 1.1

PERCENTAGE OF PEDESTRIAN CRASH TYPES [11]

Pedestrian crash types	% of crashes
Crossing at intersection	32%
Crossing mid-block	26%
Not in road (e.g., parking lot, near curb)	9%
Walking along road/crossing expressway	8%
Backing vehicle	7%
Working or playing in road	3%
Other	16%
Total	**100%**

Motorcyclists are less likely to watch a pedestrian at a greater velocity, and much less likely to actually brake in time to prevent striking one [11]. The 25 to 44 age group accounts for the majority of pedestrian casualties. When deaths per 100,000 people are estimated, however, the older age group stands out more than the others. Nonetheless, in terms of traffic deaths and injuries, children, and young adults of ages 2 to 22 are heavily represented in comparison to their ratio in the U.S. population. In every age group, there are more male deaths than females. Males surpass females in pedestrian crashes at the age of two years, and even in the younger population, pedestrians under the age of five years, the population pedestrian mortality rate for men is 1.7

times that of women. Pedestrian accidents are often caused by alcohol. According to the report, 42 to 61 percent of severely wounded pedestrians had blood alcohol concentrations of 0.10 or higher. It appears that pedestrians who have consumed alcohol pose a higher risk to pedestrian safety [12].

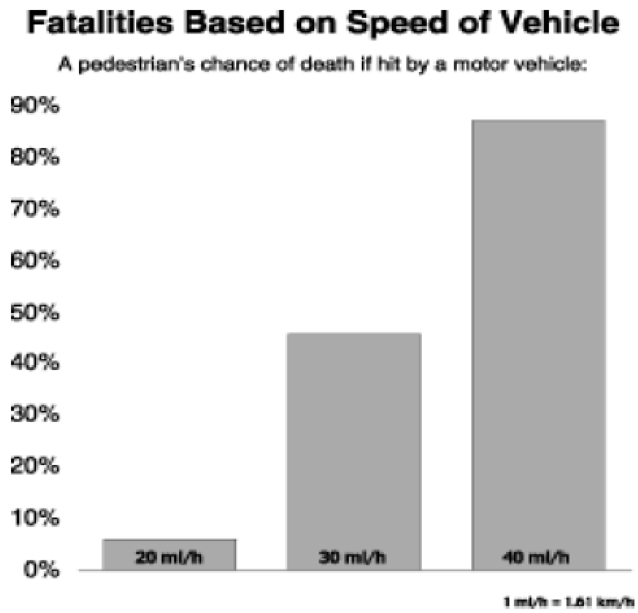


Figure 1.6. U.K. Department of Transportation, Killing Speed and Saving Lives, London, 1987 [11]

In urban areas, empirical evidence has shown that pedestrians and cyclists are vulnerable to collisions with motor vehicles. In the United States, wayfarers account for 11% of all highway deaths in 2001, and in Europe, they report for 20% of deaths [13, 14]. When looking at the data from the Fatality Analysis Reporting System (FARS) on pedestrian deaths, it is clear that Light truck vehicles and vans are the leading cause of death [15]. Because of the reduced price of small vans in recent years, minivan sales in China have exploded. As per the China Association of Automobile Manufacturers' (2009) statistical survey, the total sales of inter-passenger vehicles (primarily minivans) exceeded 1.9 million, a rise of 83.39 percent over the period the year before.

As the number of minivans expands, the research of pedestrian safety in minivans becomes increasingly necessary. Many studies on dynamic reactions and damages in sedan-pedestrian collisions have been conducted [16].

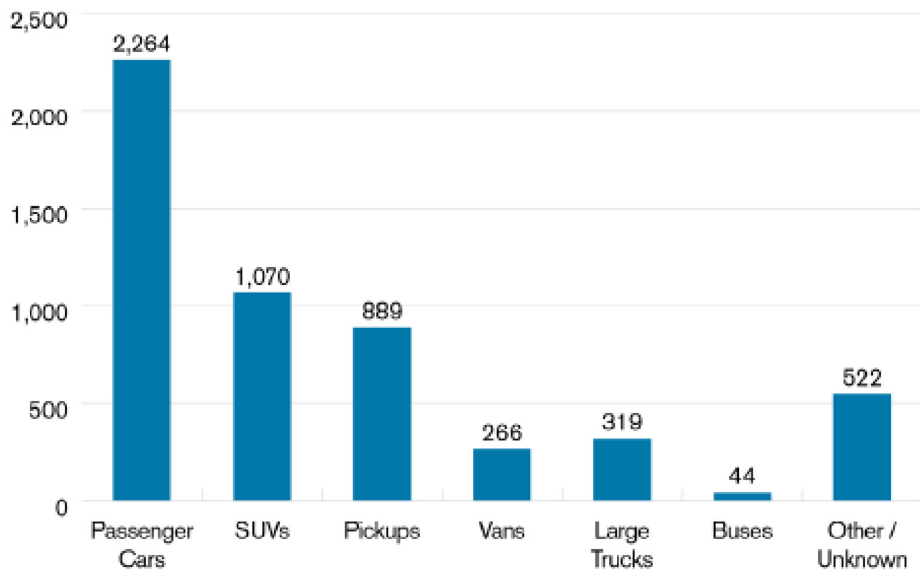


Figure 1.7. Pedestrian risk by vehicle type (FARS and GES, 1995–2018) [1]

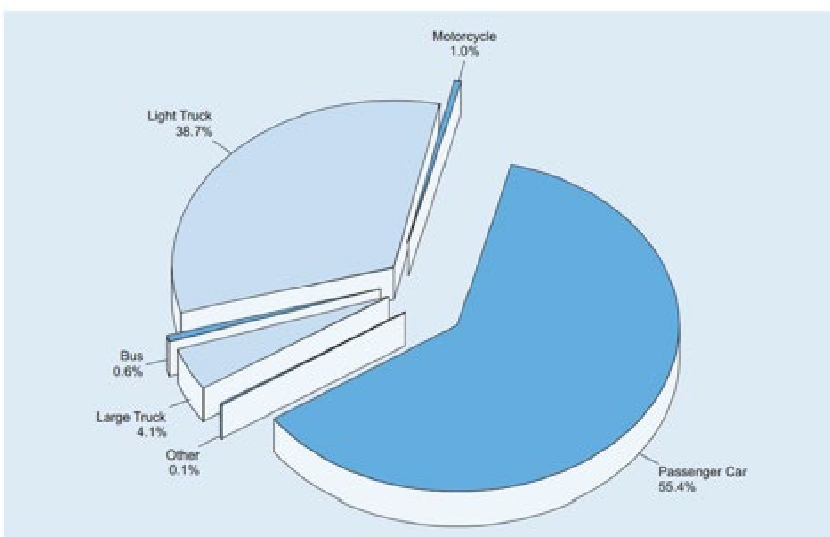


Figure 1.8. Pedestrian fatal crashes (FARS and GES, 1975-2014) [8]

As shown in Figure 1.7 and Figure 1.8, all types of LTVs pose a greater danger to pedestrians than vehicles. The scariest vehicle is a large van, with a PRM of 133, while the safest is a passenger car, with a PRM of 45. When a big van collided with pedestrians, 13.3 percent of pedestrians resulted in the death of the crash. On the other hand, only 4.5 percent of pedestrian collisions featuring a car resulted in a pedestrian fatality. The Pedestrian fatalities occurred in 11.5 percent of major SUV-pedestrian collisions. A pedestrian hit by a van is almost three times more probable to die than a pedestrian hit by a vehicle, according to our findings. Pedestrians impacted by big SUVs have double the risk of dying as pedestrians are hit by cars [8, 12].

Passenger cars in general pose a greater danger to pedestrians than light trucks. When a big van collided with pedestrians, 13.3% of pedestrians died as a result of the crash. Only 4.5 percent of pedestrian collisions involving a vehicle, on the other hand, resulted in pedestrian death. A pedestrian fatality occurred in 11.5 percent of pedestrian incidents involving large SUVs. A pedestrian hit by a van is almost 3 times more probable to die than a pedestrian struck by a vehicle, according to our observations. Pedestrians hit by big SUVs have double the chances of death than pedestrians hit by cars [8, 16].

From 2009 to 2018, retail sales of passenger cars and light trucks in the United States were in the thousands, reflecting a dramatic rise in light truck sales (which includes SUVs) and a general decrease in passenger car sales. Later on, light truck sales as a percentage of overall light-vehicle sales continue to rise steadily [1].

In terms of biomechanical reactions, pedestrian injuries take place in a variety of parts of the body, but most commonly in the initial impact of the leg section or the secondary contact of the head to the automobile windshield or pillars, or the ground surface. Table 1.2 shows the biomechanical parameters or the limits for pedestrian impact studies. The 15% confidence limits for a fractured skull are just like the Head Injury Criterion (HIC) standard for head trauma inside a vehicle.

TABLE 1.2

BIOMECHANICAL LIMITS FOR ASSESSMENT OF PEDESTRIAN IMPACT TESTS [4]

Type of test	Injury Measurement	Units	Biomechanical Limits
	Upper Tibia acceleration	g	<150
Leg Form	Knee shear displacement	mm	<6
	Knee bending angle	degrees	<15
Upper Leg Form	Bending Moment	Nm	<220
	Sum of force	KN	<4
Child Head Form	Head acceleration	HIC	<1000
Adult Head Form	Head acceleration	HIC	<1000

1.2 Pedestrian Injury Biomechanics

The most common pedestrian injuries are thorax injuries to upper and lower parts and also head injuries of the body. This injury is addressed, as well as their biomechanics assessment were explained here.

1.2.1 Head Injury Criterion

Head Injury Criteria (HIC) is often the most difficult standard to reach. J. Versace was the first to introduce the Head Injury Criterion (HIC), which was then updated by the National Highway Traffic Safety Administration NHTSA.

This criterion is dependent on how the Gadd Severity Index is interpreted. HIC is a formula based on experimental results. The HIC represents more than just a maximum data value; it also represents an integration of data over time. The HIC is calculated using data from three mutually perpendicular accelerometers placed in the ATD's head according to the dummy specification. Head Injury Criterion (HIC) is developed as an indicator of the likelihood of severe head injury and is determined by [17].

The Head Injury Criterion, or HIC, by NHTSA is described by the following expression:

$$HIC = \max_{T_0 \le t_1 \le t_2 \le T_F} \left[\left(\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} R(t)dt \right)^n (t_2 - t_1) \right] \le 1000 \qquad \text{....... (1)}$$

where:

- T_0: starting time of the simulation
- T_F: end time of the simulation
- T_1: Initial time (in s) of the interval during which HIC attains maximum value.
- T_2: Final time (in s) of the interval during which HIC attains maximum value.

HIC is utilized to measure head impact in collisions with various zones of the vehicle, as well as to identify connections between the amount of deformation recorded in the vehicle and the strength of the acceleration [18].

HIC is measured in automotive testing regardless of whether or not it is head contact. The HIC should not exceed 1000 for 36ms Δt duration, or 700 for 15 Δt duration, according to the Federal Motor Vehicle Safety Standards (FMVSS) and FAA regulations. Serious injury is considered to be improbable if HIC is held below 1000 [17].

Head Injury Criteria – AIS rating

The numerical value of the AIS scale is determined through studies of accident victims whose injuries had already been classified according to the AIS scale. A more detailed specification is found in the international literature [19].

The correlation HIC-AIS (Table 1.3) is only used on the impact test that covers the head; the experiments for the development of this correlation were performed on dead bodies. It is considered from an example in the research [20, 21].

The AIS scale's numerical value is derived through research on accident victims whose injuries have previously been categorized using the AIS scale. A value of HIC equal to 1000 indicates a severe gravity accident; a value of HIC equal to 2000 indicates a gravity higher than a thousand, but the severity and chance of death of the event are not doubled [18].

TABLE 1.3

RELATION BETWEEN HEAD INJURY CRITERIA AND AIS RATING [19]

AIS	Description
1	Skin and scalp: abrasions, superficial lacerations. Face: fracture of the nose
2	Skin: more abrasion. Simple fractures or broken down in the face, open fractures or displacements of the jaw, jaw fractures
3	Several fractures, total loss of scalp, contusion to the cerebellum.
4	Complex fractures to the face, exposure or loss of brain tissue, small subdural or epidural hematoma.
5	greater penetration of the brain injury, damage to the trunk and hematoma, subdural or epidural compression, diffusion axonal injury
6	mass destruction of both skull and brain

1.2.2 Thorax

In a truck-pedestrian collision, the lateral impact to the thorax is the most frequent. Due to the flat bonnet top or relative flat edge contacting the thorax without intrusion, the pedestrian thorax injury mechanism is commonly associated with blunt trauma. Because of the height and age of the pedestrians, the thorax contact position on the truck front varies. Bonnet-top impacts are the primary cause of thorax injuries in adults and older children. When a small child collides with the truck's bonnet front edge and end front face, they are more likely to suffer thorax injuries. The thorax is accelerated towards the hood in a truck-pedestrian lateral collision, then abruptly decelerated due to a rounded bonnet impact. The tension of the thorax, internal loading to the internal organs, viscous loading inside the thorax cavity are the three mechanisms that cause thorax injuries (as shown in Figure 1.9) [22].

The thorax may be compressed, resulting in rib fractures, sternum fractures, hemothorax, and pneumothorax. Accidental thorax injuries often occur as a result of a combination of the following mechanisms. Many scholars have used volunteers and cadavers to study thorax affect responses. Some of the research has been conducted in a lateral impact scenario involving occupant side-impact responses.

The outcomes of such studies are useful for research into the biomechanical reactions of the pedestrian thorax to a frontal collision with a vehicle. To understand thorax injuries, the thorax trauma index (TTI) was developed after conducting several cadaver tests [23, 24]. TTI (Thoracic Trauma Index) tolerance levels for adults are 85g and 60g for children. The Sternum Acceleration is a result of the MADYMO test that can be used for TTI and can be calculated using Equation 2.

$$TTI = 1.4 * Age + 0.5(RIB_y + T12_y)(M/M_{std}) \ldots\ldots\ldots\ldots (2)$$

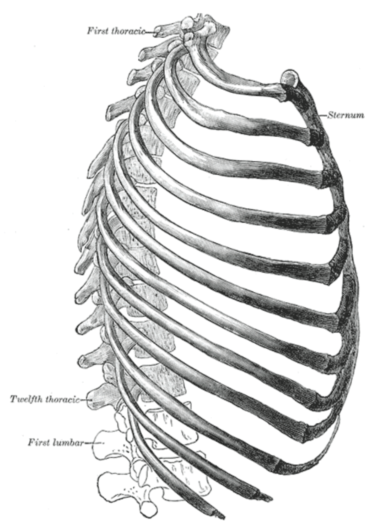


Figure 1.9. Side view of the thorax structure [22]

1.2.3 Pelvis

A lateral impact with a rigid bonnet edge or bonnet top will damage the pelvis (shown in Figure 1.10). The compressive force to the pelvis is the most commonly injured mechanism in truck-pedestrian collisions. Pubis, acetabulum (hip socket), spine, and proximal femur are all important structures involved in injuries to this body part.

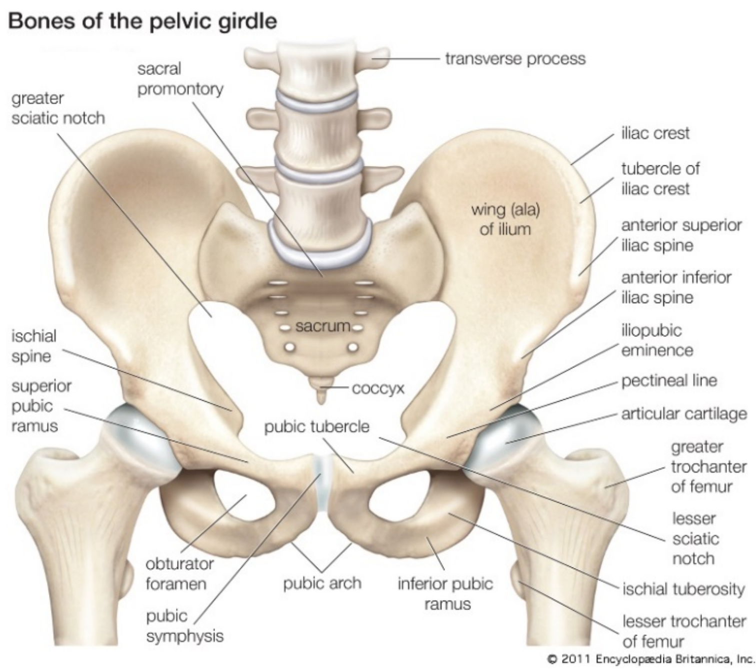


Figure 1.10. The body segments of Pelvis [25]

The responses of the pelvis to lateral impacts were studied using cadaver specimens at various institutes. The lateral responses in these researches were defined in terms of impact force-time histories, pelvis acceleration time histories, and compressive deflection. The 50g to 90g value is the injury threshold for pelvis linear acceleration [26].

1.2.4 Lower Extremities

The MADYMO leg model and a schematic illustration of significant injuries in a truck-pedestrian lateral collision were shown in Figure 1.11. Knee injuries, ankle/foot dislocation, and fractures, and Long bone (Femur and Legs/Thighbone/Fibula-Tibia) fractures, are the most frequent lower extremity injuries in truck-pedestrian collisions. The pedestrian's lower extremities are accelerated after making contact with the truck's front end, resulting in complex injury mechanisms. The two most common injury-related reactions of pedestrian lower extremities to a bumper impact are lateral shearing and bending.

Leg fractures, especially of the lower leg, are common in car-pedestrian collisions. As a result, fracture joints have been mounted at both the second and third upper leg joints, as well as all three lower leg joints [27]. Spherical joints are used in both fractures. They're locked at first, but when the local fracture trigger signal rises above the fracture point, they'll be released. There is no stiffness specified in the unlocked state. To make the rotation of the broken leg section realistic and avoid numerical instability problems, small rotational damping has been defined. It is also possible to turn off the fracture joints.

The occurrence and severity of injuries sustained were associated to impact speed: 54 percent of pedestrians struck at speeds between 0 and 20 kilometers per hour, 85 percent at speeds between 21 and 40 kilometers per hour, and all those struck at speeds above 60 kilometers per hour sustained a pelvic or leg injury. Comparable percentages for non-minor injuries were 4 percent, 42 percent, 63 percent, and 89 percent. This rise in injuries concerning impact speed was attributed primarily to a spike in the severity of automobile impact injuries with speed, with almost all ground contact injuries being moderate [28].

The leg is designed on a physical pedestrian leg model that is similar to the Hybrid III dummy model's leg. Spherical joints have been used to model bending and fracture in both the upper and lower leg [27].

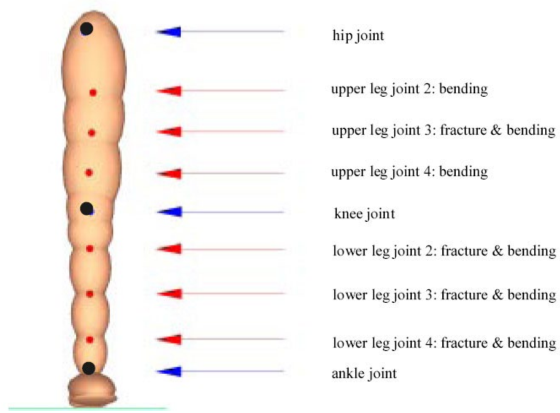


Figure 1.11. MADYMO Pedestrian leg model [22]

1.3 Pedestrian Injury Criteria

The research carried out since the 1970s was focused on various methods with pedestrian replacements such as biological specimens, mathematical models, and mechanical dummies, and also real-world crash samples. In this chapter, injury levels, pedestrian injury biomechanics, injury criteria, and its relationship with the study of real-world car-pedestrian accident reconstruction are described.

The field of injury biomechanics studies the impact of mechanical loads, especially impact loads, on the human body. A body part will undergo physiological or mechanical changes as a result of this mechanical load. All these changes are referred to as biomechanical responses. The process that is involved is called an injury mechanism and the seriousness of the resulting injury is referred to as the injury severity. An injury criterion is the main physical parameter (or a function of many physical parameters) that corresponds with the severity of the injury in the body region under study. Many different approaches to ranking and quantifying the injury have been proposed. Anatomical scales classify injuries according to their anatomical position, their severity, and injury type [29]. The Abbreviated Injury Scale (AIS) is the most widely used anatomical scale in the world. In TABLE 1.4, the AIS describes the essential stages of injury.

TABLE 1.4

Abbreviated Injury Scale (AIS) [29]

AIS Score	Injury
0	No injury
1	minor
2	moderate
3	Serious
4	severe
5	critical
6	Maximum injury
9	unknown

Other than to designate order, the numerical values have no importance. The acceleration forces, displacements, and velocities are included in many injury criteria. A mathematical analysis of a time history signal is needed for certain injury criteria. Some of these injury parameter estimates can be performed using biomedical codes such as MADYMO.

An injury parameter is a physical parameter (or a function of many physical parameters) that is highly correlated with the severity of the injury in the body region being studied. For ranking and quantifying accidents, a variety of schemes have been suggested.

Anatomical scales classify injuries according to their anatomical position, injury type, and severity of the injury. Accelerations, relative velocities or displacements, or joint constraint forces are used to determine most injury parameters. These qualities must be defined in conjunction with standard output methods. A mathematical evaluation of a time history signal is needed for most injury criteria. These injury parameter estimates are performed by MADYMO. The following injury parameters can be calculated by [29]:

- Gadd Severity Index (GSI)
- Head Injury Criterion (HIC)
- Neck Injury Criterion (FNIC)
- 3 ms Criterion (3MS)
- Thoracic Trauma Index (TTI)
- Femur Loads

The HIC, GSI, and 3MS injury parameters are calculated using the linear acceleration signal of a selected body. On the linear acceleration signals of two selected bodies, the TTI calculation is done. All these linear acceleration signals have been defined under LINACC keyword.

1.4 EEVC Criteria

Every year, over 7000 pedestrians and 2000 pedal cyclists are killed in road accidents across the European Union, with billions more wounded. The differences between the various member countries, on the other hand, are surprising. The number of pedestrian deaths per million people varies from Ten in the Netherlands to forty-seven in Greece. The number of pedestrian deaths per 100 traffic accident deaths ranges from Twelve in France to Thirty-two in the United Kingdom [30]. The front of a passenger car has a major effect on pedestrians and cyclists. The European Enhanced Vehicle Safety Committee (formerly the European Experimental Vehicles Committee) identified this, and EEVC Working Groups conducted several types of research in this area [28, 31-34].

Various guidelines for the front structure design of passenger cars were produced based on this study. In addition, test methods and legislation for evaluating pedestrian safety have been proposed. The EEC ad hoc working group 'ERGA Safety' addressed one of these ideas in the spring of 1987 [28, 35]. The proposal's foundation was found to be promising, but extensive research was required to fill in some spaces. The EEVC was asked to coordinate this study, and EEVC Working Group 10 (WG10)µ Pedestrian Protection was established at the end of 1987 [36].

This group aimed to provide us with test methods and approval levels for determining how well the fronts of cars protect pedestrians in an accident. Sub-system measurements, primarily to the bumper, bonnet leading edge, and bonnet top surface, should be used as the basis for the test methods. The air dam should be included in the bumper test; the headlight surround and the leading edge of the wings should be included in the bonnet leading edge test; and the scuttle, the lower edge of the windscreen frame, and the top of the wings should be included in the bonnet top test. At car-to-pedestrian impact speeds of 40 km/h, test methods should be considered that assess the efficiency of each component of the vehicle system with both child and adult pedestrians. Differences in the test conditions should account for the various impact attributes associated with changes in the overall shape of the car front [37].

1.4.1 Biomechanical Thresholds

Table 1.5 and Table 1.6 summarizes the threshold and injury parameters used in pedestrian safety research over the last 30 years [4], based on the research findings of several studies. Almost all of these tolerance levels come from the EEVC proposal as well as the European Passive Safety Network [28]. The injury-related criteria can be used to assess the front-end safety performance of an automobile. For several years, the HIC value has been the most widely used criterion for a head injury in crash safety testing, as well as for assessing the threat of pedestrian head/brain injuries. In addition, institutes such as EEVC are researching the material properties of human tissues under complex conditions [28]. Lower extremities are particularly important to inspect because the main contact with the vehicle model is intense, resulting in a severe injury score. When compared to Side impacts, injury responses of lower extremities are observed more in Front and Rear impacts.

In the case of pedestrian injuries, the biomechanical threshold criteria differ for side, front and rear impacts. In side impacts, along with criteria involved in Front/ Rear impact, pelvis injury, viscous criteria of thorax and Thorax Trauma Index is evaluated. All the values with '*' are proposed by EEVC but are not a part of current regulations.

TABLE 1.5

THE THRESHOLD AND INJURY CRITERIA FOR PEDESTRIAN BODY SEGMENTS IN SIDE IMPACT [4]

Parameter	Body Segements	Tolerance Levels
Force	*Tibia	4 kN
	*Knee	2.5 kN
	Femur	10 kN
	*Pelvis	4 kN
HIC36/HIC15	Head (36/15ms)	1000/700
Linear Acceleration	*Head	80g
	*Pelvis	130g
	*TTI	85g
	*Tibia	150g
Angular Acceleration	*Head	3000 rad/s^2
Rotation Angle	Knee	15 deg
	Neck	60 deg
Bending Moment	*Knee	350 Nm
	*Tibia	200 Nm
	*Femur	220 Nm
Shear Dislocation	*Knee	6 mm
Viscous Criterion	Thorax	1.0 m/s
Nij	Neck	<1.0

TABLE 1.6

THE THRESHOLD AND INJURY CRITERIA FOR PEDESTRIAN BODY SEGMENTS IN REAR AND FRONT IMPACT [4]

Parameter	Body Segements	Tolerance Levels
Force	*Tibia	4 kN
	*Knee	2.5 kN
	Femur	10 kN
HIC36/HIC15	Head (36/15ms)	1000/700
Linear Acceleration	*Head	80g
	Tibia	150g
	Thorax	60g
Rotation Angle	*Knee	15 deg
	*Neck	60 deg
Bending Moment	*Knee	350 Nm
	*Tibia	200 Nm
	*Femur	220 Nm
Shear Dislocation	*Knee	6 mm

1.5 Literature Review

Yang investigated the front shape of a sedan car to reduce the forces on the pedestrian's head in the case of a vehicle-pedestrian collision. The Pedestrian Model of Chalmers of a 50th percentile adult pedestrian (Yang et al., 1997) was included in this analysis, and it was tested in MADYMO 5.4. A joint research study aimed at improving pedestrian safety made this model accessible for simulations. The wayfarer model was in a walking posture with a 15° angle away from the car. The right upper leg was oriented 5° back, while the left upper leg was positioned 6° forward [38].

Research on the creation and evaluation of FE models of impactors for pedestrian tests was proposed by Teng and Nguyen. All static and dynamic crash simulations were used to certify the leg form test [39].

The relationship between motor vehicle category and the threat of seriously wounding a pedestrian was identified by L. J. Paulozzi. The sum of pedestrian deaths per billion miles of automobile travel for each vehicle category in the United States in 2002, was used to calculate the probability of killing a pedestrian, as stated by the National Highway Traffic Safety Administration's Fatality Analysis Reporting System (NHTSA FARS). The aspects in which a vehicle's specifications (front end design, visibility, and mass) and degree of engagement with pedestrians influence its risk per mile are reflected in the outputs. [40].

Gabler and Hollowell looked at how aggressive light trucks and vans became in traffic accidents. This study aims to investigate LTV in vehicle-to-vehicle collisions. The main goals are to identify the scope of the issue by looking at crash statistics and the relationships between crash aggression and vehicle design parameters [2].

The Lower Extremity Damages in Vehicle-Pedestrian Impacts research by Abvabi Nasr [41] utilizes a leg form impactor model in which the researcher changes the properties of the material of the bumper.

The analysis of a pedestrian impact with a small car was studied by Athale. This study focuses on performing a simulation study for a pedestrian collision with a small car and determining the injuries incurred by the head as a consequence of the resulting acceleration. 5th percentile female Hybrid III ATD, 6-year-old infant ATD, and 50th percentile male Hybrid III ATD at three different speeds were used as dummies [27].

A. Ronghe investigated the impact of pedestrians on small cars and SUVs. The kinematic analysis of pedestrian-vehicle accidents for 6-year-old child ATD, 3-year-old child ATD, and 50th percentile male Hybrid III ATD with a compact car, SUV, and van is the subject of this research. Only the pedestrian's side collision with the automobile is considered at two separate speeds [42].

In a vehicle-pedestrian collision, Korrapati [43] contrasted the kinematic behaviors of the pedestrian human model and Hybrid III standing dummy. The focus of this thesis was to see how parameters like pedestrian impact positions, vehicle speed, bonnet height, and angle affected pedestrian contact responses.

Obaidur Rahman Mohammed [37] study presents a technique for evaluating leg form impactor kinematics after an impact by using finite element models of the leg form and sedan cars and relating simulation results to those from a 50th percentile male human pedestrian model and a multi-body leg form model. The results showed a sensible correlation between both the models and also identified that leg form impact study is an important tool to determine the impact behavior and injuries of the pedestrian.

Pedestrian accidents for lightweight truck vehicles were related to passenger car accidents by B.S. Roudsari, C.N. Mock, R. Kaufman, D. Grossman, B. Y. Henary, and J. Crandall. Pedestrian accident profiles have changed over the past 20 years due to improvements in vehicle design and a growing number of vans and lightweight trucks. The objective of this research was to find out which vehicle type has the greatest impact on the risk of serious injury or death among pedestrians [44].

1.6 Motivation

As the total of Vans and light-weighted trucks on US roads continues to climb, a new source of pedestrian safety problems has arisen. LTVs can cause more damage of injury and death for exposed road users such as Wayfarers due to their significantly different parameters than passenger vehicles [8].

Between 1980 - 2019, the percentage of LTVs sold increased from 20 percent to nearly 50 percent of all light cars and trucks sold (Automotive News, 1980-1999). With such a significant shift in the US trucking industry, it's necessary to look at the safety implications for motorists and pedestrians [8].

Head injuries are the leading cause of pedestrian deaths. The Windscreen, A-pillars, Bonnet, and scuttle are the most common causes of serious head injuries (AIS3+). Under the hood of modern vehicles, there are very rigid parts with gaps as small as 20 mm. As a result, the deformation length for the hood is insufficient to allow for the required energy absorption. To hold the HIC value under 1000 for an adult head form, about 55 mm of distortion is needed at an impact velocity of 24.8 miles per hour. In countries like Germany [45], head form-to-hood impact tests revealed that hoods with 70 mm at most of the deflection developed HIC values under 1000 for the adult head. The speed at which a vehicle collides has a significant effect on accident severity. Pedestrians who are hit at less than 25 km/h suffer only minor damages (Ashton 1982). More than 95 percent of all pedestrian traffic accidents happen at speeds less than 37 miles per hour (Otte, 1998). For serious injuries, the mean speed is about 40 kilometers per hour [27].

The kinematic analysis of a pedestrian colliding with a pickup truck differs significantly from those of a car accident, particularly in terms of Head injury, pelvis injury, and thorax (TTI). Trucks used for carrying goods are more likely to damage the pelvis and chest in pedestrian-truck crashes. As a result, it is essential to research on various conditions in truck-pedestrian crash simulations to gain a deeper understanding of pedestrian accidents and pedestrian responses with pickup trucks.

Applied mathematicians, designers, and researchers have recently been able to fix previously complex problems, thanks to advances in computer technology. Pam Crash, LS-DYNA 3D, and MADYMO are simulation methods for predicting passenger or pedestrian kinematics and injury requirements [46].

CHAPTER 2

OBJECTIVES AND METHODOLOGY

2.1 Objectives

The head and thorax injuries caused by a wayfarer-vehicle crash pose a major risk to life, and restoration is often delayed. In countries like Europe, Australia, Japan, and the United States, studies on pedestrian safety and injury mechanisms have also been conducted. Because of the problem's severity, it's essential to have a good knowledge of bio-injury processes and to recognize the factors linked to injury risk. Impact positions on the vehicle and body velocities after collision influence the intensity of pedestrian accidents.

The goal of this research is to analyze a wayfarer collision with a pickup truck and assess the injury suffered by the head, thorax, pelvis, and lower extremities. The crash simulations and models are created using the MADYMO biodynamic simulation program, which is commonly used in the automotive industry.

The research focuses on the following objectives:

- To develop a multibody model of a lightweight pickup truck in MADYMO.
- To evaluate the response of 50th percentile adult male pedestrian as a result of impact with the pickup truck.
- To evaluate the values of injury parameters at five different impact speeds of 15 kmph, 18 kmph, 21 kmph, 24 kmph, and 27 kmph.

- To evaluate the most significant factors affecting pedestrian injuries, like HIC, head, chest, pelvis, and legs injuries.
- To evaluate injury parameters for three different positions i.e., for Side-impact, collision from the Rear, and Front-impact at three different locations.
- To perform Design of Experiments (DOE) analysis for the vehicle/pedestrian geometry and impact parameters.

The test matrix (Table 2.1) on which the analysis is performed is:

TABLE 2.1

TEST MATRIX FOR THIS STUDY

Impact Positioning	15 Kmph	18 Kmph	21 Kmph	24 Kmph	27 Kmph
Center	Side, Front And Rear	Side, Front And Rear	Side, Front And Rear	Side, Front And Rear	Side, Front And Rear
Left Corner	Side, Front And Rear	Side, Front And Rear	Side, Front And Rear	Side, Front And Rear	Side, Front And Rear
Right Corner	Side, Front And Rear	Side, Front And Rear	Side, Front And Rear	Side, Front And Rear	Side, Front And Rear

2.2 Method of Approach

Generally, the pedestrians are hit at the Center and frontal corners of the vehicle. The average speed at which risk of severe injury for a pedestrian struck by a truck is from 12 Kmph to 35 Kmph [47]. This thesis work is developed completely using computational software, such as MADYMO. First, the ellipsoidal pickup truck model was developed (Figure 2.1). The vehicle model consists of four wheels, hood, bumper, windshield, and the roof in form of ellipsoids and a rigid ground as the reference plane. The physical properties are based on the Chevrolet Silverado pickup truck. Then, a 50th percentile male pedestrian is placed at the front end of the truck.

The whole configuration consists of three different systems that include a 50^{th} percentile male pedestrian, the ground plane, and the light pickup truck in space. To forecast the risk of pedestrian injuries in pickup truck accidents and examine the effects of truck front specifications on the threat of pedestrian injuries, wholescale truck-pedestrian impacts were simulated.

The MADYMO simulation software is used to reconstruct a crash involving a pedestrian. The pedestrian is walking and at the time of impact, the wayfarer is at three different locations of the pickup truck frontal profile,

1) In line, at the Center and Corners and facing away from the truck and colliding from the rear of the wayfarer.
2) At perpendicular, at the corners and colliding in side-impact setup to pickup truck.
3) In line, at the Center and Corners and facing towards of the truck and colliding from the front of the wayfarer.

To simulate pedestrian-truck collisions, a full-size pedestrian model was used. In MADYMO, 45 statistical simulations of various vehicle crashes were run to gain a deeper understanding of the relationship between the outcomes. The impact speed and locations of the dummy for the 50^{th} percentile male pedestrian dummy were used to assess the effects of the pickup truck front on pedestrian behaviors. Later on, the Design of Experiments (DOE) is performed for vehicle front-end parameters.

The proposed wayfarer-pickup truck model was compared by collating the results of the MADYMO study for a wayfarer-pickup truck effect for side-impact at 25 kmph with the results of the tests conducted by Narkhede, Department of Mechanical Engineering, Wichita State

University, USA, 2007. The truck model used in that research was Chevrolet C2500. It was a MADYMO ellipsoidal truck model with dimensions similar to the original FE truck model (NCAC) [12].

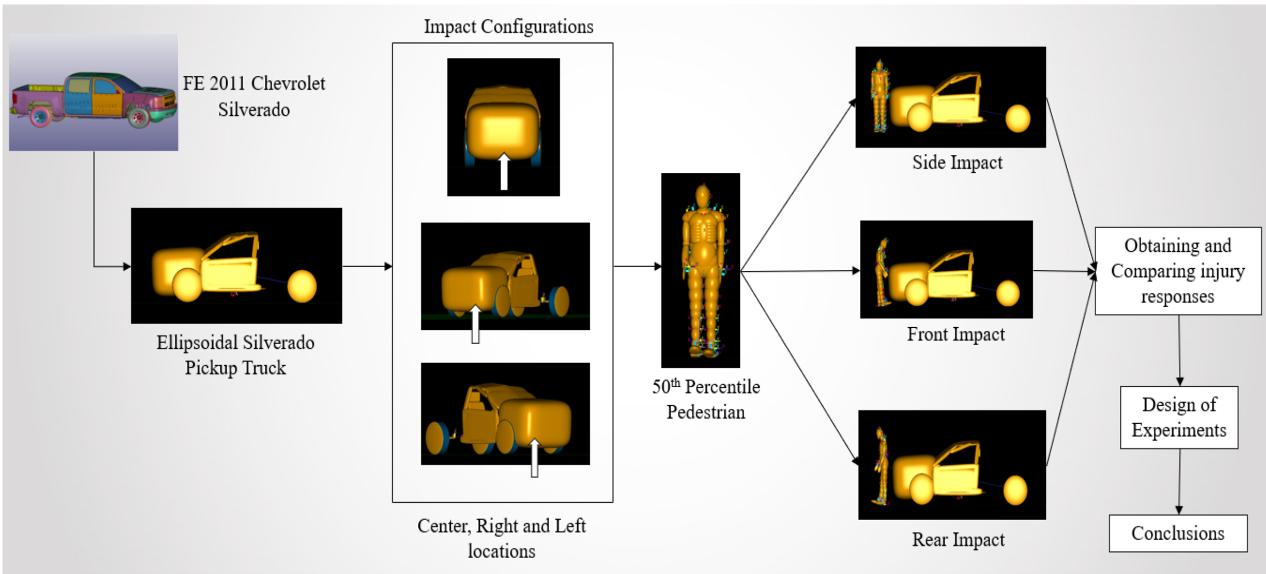


Figure 2.1. Methodology of this study

2.3 Multibody Method MADYMO

2.3.1 Introduction to MADYMO

MADYMO (Mathematical Dynamic Models) is a software package that allows users to design and improve vehicle crash safety efficiency easily, rapidly, and affordably. It is a multibody and finite element technology with several important features for crash simulation. MADYMO performs time-domain analysis using explicit integration methods. It's widely used in engineering and design firms and departments, as well as in research labs and universities. MADYMO has proved its worth in a variety of fields, often assisted by verification research based on experimental test results. MADYMO's major market is automotive safety, but it also works in biomechanical testing, comfort analysis, truck, train and bus safety, sports, and vehicle dynamics [48, 49].

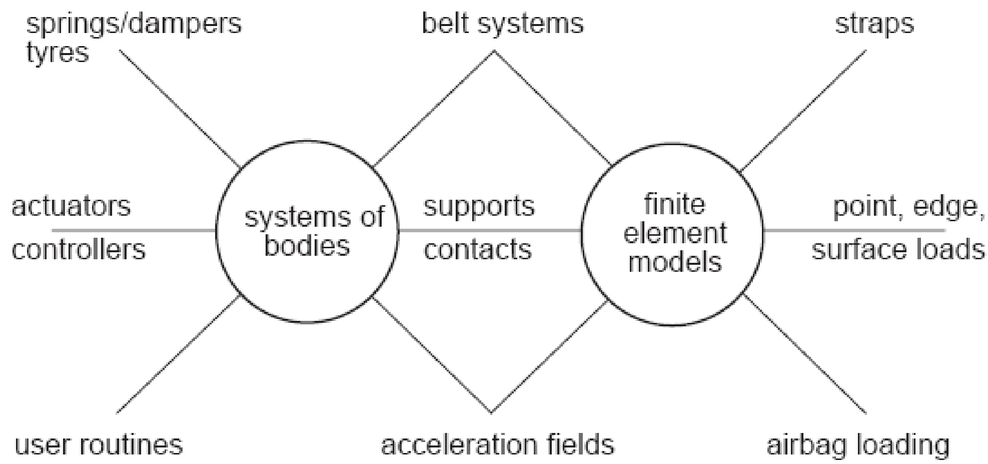


Figure 2.2. MADYMO 3D structure [50]

MADYMO incorporates the capabilities of multi-body (for simulating the gross motion of structures of bodies connected by kinematical joints) and finite element techniques (for simulating structural behavior) into a single simulation program, as shown in Figure 2.2. Only finite element models or only multi-bodies, or both can be used to build a model.

The second time derivatives of the degrees of freedom are derived in an explicit form using MADYMO's multi-body algorithm. If all joints have the same degree of freedom, the number of machine operations is linear in the number of limbs. As a result, a fast algorithm for large systems of bodies emerges. The initial state of the structures of bodies must be defined in terms of joint velocities and position at the starting of the integration. There are several varieties of kinematic joints with dynamic restrictions to account for damping, joint stiffness, and friction. User-defined conditions may cause joints to be removed, locked, or unlocked.

The manner the connection between bodies and finite elements is modeled allows for the use of various time integration methods for the finite element and multi-body equations of motion. Since the integration methods used are conditionally stable, the maximum time step that can be used is limited. The finite element module can be sub-cycled to the multi-body module using different time steps for each module to improve the overall efficiency of the analysis.

The inertial system, multibody system, and null system are the three types of multibody elements found in MADYMO. The inertial framework includes the components used to model the ground, seat, and other non-movable objects. The multibody framework includes elements that are influenced by acceleration fields and contact forces. An example of this is the Anthropomorphic Testing Device (ATD).

To explain a body's form, cylinders, planes and ellipsoids, and facet surfaces can be connected to it. In depicting the occupant's engagement with the interior of the car, the contact surfaces are extremely important. The elastic contact forces that enclose hysteresis are part of the contact surface penetration. Regardless of these factors, damping and friction may also be considered.

An ATD is used as a multibody structure attached to a seat that is part of the inertial space in a standard crash model. Joints are commonly used to bind multibody systems.

2.3.2 Multibody Systems

A system of bodies is referred to as a multi-body system. A single kinematic joint can link any two bodies in the same system. For the system of bodies with a branch structure and systems with closed loops, the MADYMO multi-body formalism for developing equations of motion is appropriate. By eliminating a kinematic joint from any chain, systems with closed loops are simplified to systems with a branch structure. Joints that have been removed are now considered "closing" joints. One body can be bound to the reference space by a kinematic joint for each deducted system with a tree structure, or one body's motion relative to the reference space can be described as a function of time.

MADYMO allows you to describe a variety of multi-body structures. A multibody system is made up of many bodies that are linked together by kinematic joints. If there are no kinematic joints between two different sets of bodies, they are considered different multi-body structures. A multi-body system's connectivity structure is implicitly specified in the input file. Kinematic joints bind the body parts and establish the multi-body structure.

2.3.3 Kinematic Joints

The relative movement of the two bodies connected by a kinematic joint is restricted. The way the relative movement of two bodies is restricted defines a particular form of kinematic joint. Joint degrees of freedom are measurements that explain how much relative motion a joint allows. The number varies according to the kind of joint.

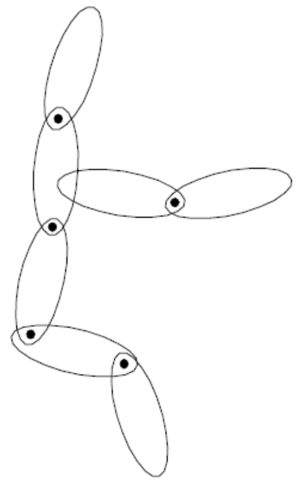


Figure 2.3. Examples of single and multibody systems with tree structure [49]

A structure of bodies is defined by:

- The kinematic joints: Type and bodies they connect.
- The bodies: Inertia matrix, location of Centre of gravity, and the mass.
- Orientation and location.
- Initial conditions.
- Other external parameters on the body

The structure of bodies (Figure 2.3) may also be needed for contact calculations or post-processing works. The force models mentioned in the upcoming chapters can be used to model applied loads on bodies.

Joint degrees of freedom are measurements that explain how much relative motion a joint allows. The number varies according to the kind of joint.

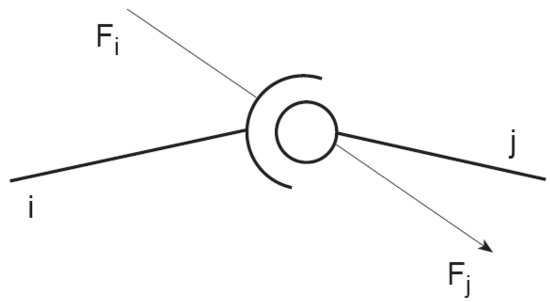


Figure 2.4. Constraint load in a spherical joint [49]

The total child body of the two bodies attached by the joint is known as a kinematic joint. The constraint load (Figure 2.4) is caused by the limitations imposed by a kinematic joint on a couple of linked bodies. The load seems to be that the relative motion of the two bodies is limited to motion that does not break the kinematic joint's restrictions. On different bodies, the constraint loads are similar but opposite. The strength of a joint can be assessed using constraint loads.

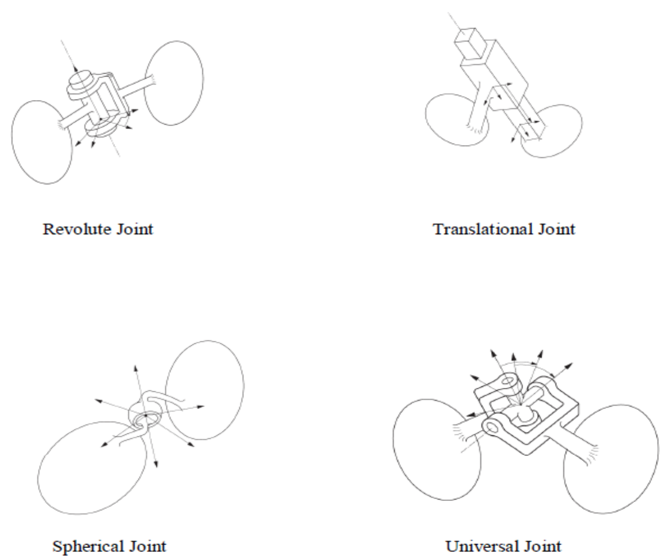


Figure 2.5. Different types of joints [49]

There is a dynamic joint model for any kind of kinematic joint. It's a force model that determines the elastic, damping, and friction loads in a kinematic joint based on relative motions. Each joint degree of freedom can be specified with a damping, friction, and an elastic load for many types of joints (Figure 2.5). Based on if the joint degree of freedom is rotational or translational, the load is either torque or a force.

2.4 Force Interactions

MADYMO provides a standard collection of force accelerations and body interactions with each other and their surroundings. The following subsections go into each of these points. Figure 2.6 depicts this definition in a simple and succinct manner. For the passenger side airbag, the driver, and the knee bolster, FE structures can also be used. The links between the bodies, the mass distribution of the bodies, the joint properties, and finite element structures (FE) are then defined in an input data file.

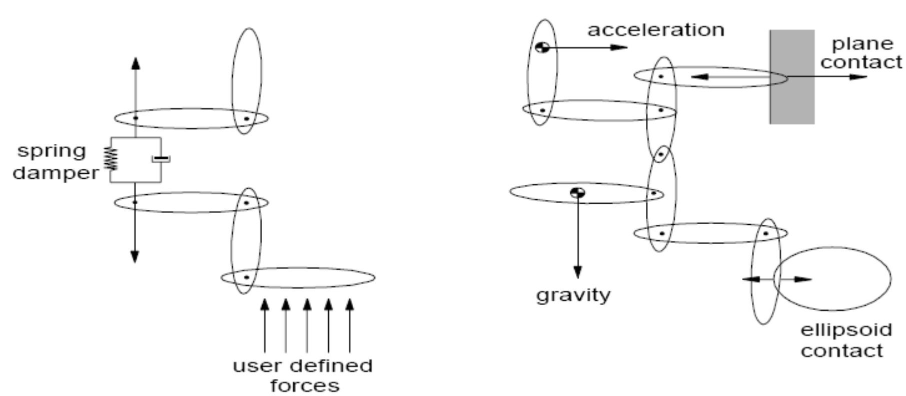


Figure 2.6. Examples of systems of bodies with force interactions [49]

2.4.1 Acceleration Field

Due to the presence of a homogeneous acceleration field, the acceleration field model measures the forces at the point of Centre of Gravity in bodies. Function pairs are used to describe the acceleration field as the function of time. It is not necessary to establish an acceleration field for all systems or bodies. Acceleration is typically applied to the inertial system in an Anthropomorphic Test Dummy (ATD) simulation, and the consequences on different multibody structures are studied. To model pre-simulation motion, such as the FEM belt fastening process, null system motion is being implemented. Figure 2.7 depicts an example of an acceleration field.

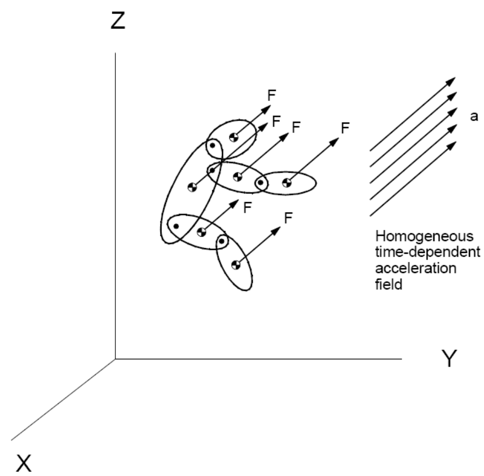


Figure 2.7. A system of bodies in a uniform acceleration field [49]

2.4.2 Spring Damper

To measure forces within two bodies, the corresponding spring-damper models are used: Maxwell element and Kelvin element. The two major types of spring-damper models are as follows:

The Kelvin Element is a model that calculates the forces created by a spring that is parallel to a damper. A Kelvin material is a massless, uniaxial element without any torsion or bending systems. The element's free ends can be connected to any two bodies' arbitrary points. These bodies may be from the same or various systems.

The Maxwell Element is a force model that calculates the forces generated by a spring in series with a damper. A Maxwell element is a massless, uniaxial element without any torsion and bending stiffness. The element's free ends can be connected to any two bodies' arbitrary points. These bodies may be from the same or different systems.

2.4.3 Inertial Space and Null systems

Inertial coordinate system's origin and orientation can be chosen arbitrarily. The positive Z-axis is generally selected to point upwards, in opposition to gravity. The motion of all the systems is expressed in terms of this coordinate system.

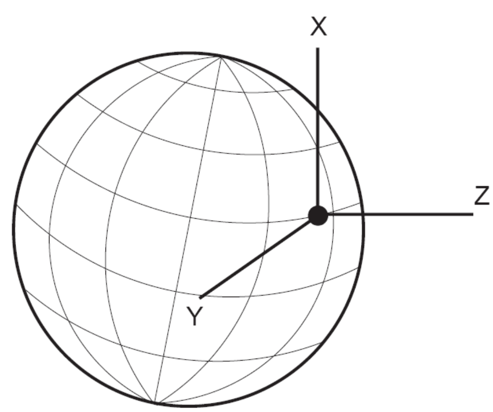


Figure 2.8. Inertial space coordinate system [49]

MADYMO allows you to connect contact surfaces including restraint systems, planes, ellipsoids, spring-damper elements, and nodes of finite element structures to the inertial space. As shown by Figure 2.8, several auxiliary systems with known motion can be described, for instance, to show a vehicle whose motion is known from experimental results. However, using a device of one body with a predetermined motion is the preferred method of modeling this.

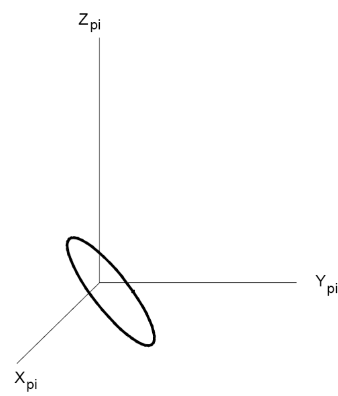


Figure 2.9. Null system coordinate system [49]

A null system (Figure 2.9) may be connected to contact surfaces such as planes, restraint systems, spring-damper elements, ellipsoids, and nodes of finite element structures. A null coordinate system's motion to an inertial coordinate system must be defined as a function of time. This motion is defined by the null system origin (O) coordinates and quantities that form the null system coordinate system's position. A null system's coordinate system is the same as the inertial coordinate system if no motion is defined. The time points at which the origin O's location is defined may vary from the time points at which the location is defined. For example, if the orientation of a null system shifts just slightly, this can be beneficial. To minimize the amount of data input, the orientation can be specified at fewer time points than the location of the origin.

2.5 MADYMO ATD Databases

The simulations are run on ATD databases that have been fully validated. MADYMO provides two-dimensional and three-dimensional databases of ATD models. MADYMO ATD models are available in a variety of shapes and sizes. Dummies such as 3-year-old boy, 6-year-old child, 5th percentile female, 50th percentile male, and 95th percentile male Hybrid III dummy models are the standard models for child and adult hybrid III dummies (Figure 2.10). The 50th percentile male ATD hybrid dummy reflects the “Average” adult male population in the United States (Table 2.2) [49].

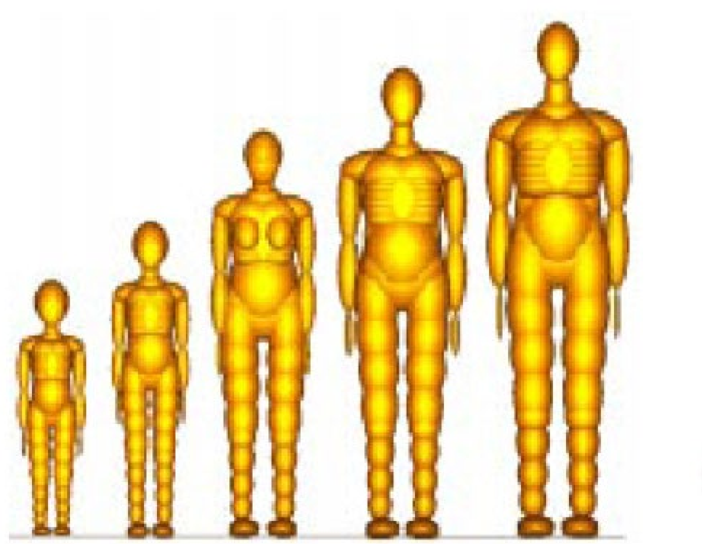


Figure 2.10. Isometric view of the Hybrid III dummies, from left to right: The 3-year-old child, 6 – year – old child, 5th Percentile Female, 50th Percentile Male and 95th Percentile Male [28]

The Hybrid III has been designed in two other versions: the 5th percentile small female and the 95th percentile large male. The 50th percentile Pedestrian model is used in this study.

Every pedestrian model is made up of 52 rigid bodies organized into seven configuration branches. A total of 64 ellipsoids and two planes define the outer surface.

TABLE 2.2

COMPARISON OF WEIGHT TABLE OF DIFFERENT DUMMIES [49]

Comparison of Weight, Sitting Height, and Stature for HYBRID III Family					
	12 mo CRABI	3 YO Child	6 YO Child	5% Female	50% Male
Weight (lbs.)	22.0	34.1	51.6	108.0	172.3.0
Stature (in.)	29.4	37.2	45.0	59.1	69.0
Sitting Height (in)	18.9	21.5	25.0	31.0	34.8

Technical drawings at TNO are used to establish the dimensions of the ellipsoids. If required, the measurements may be adjusted to provide a more accurate representation of the contacts [49]. The features of the child Hybrid III dummy models were generated by scaling those of the 50th percentile male Hybrid III model.

CHAPTER 3

WAYFARER – TRUCK MODEL DEVELOPMENT

To represent a pedestrian in a collision with a vehicle, a mathematical multibody-system model of the vehicle (lightweight pickup truck) and pedestrian is constructed (Figure 3.1). MADYMO is used to develop a pedestrian-vehicle model for simulation. To analyze the Pedestrian-Vehicle model using computer simulation study data, simulations are run in such a way that all of the criteria are applied to the simulations to represent it as Yang [4] specified. Simulation is used to acquire the model's reaction, such as overall pedestrian behavior and accelerations of the head, chest, pelvis, and lower extremities for a certain test configuration.

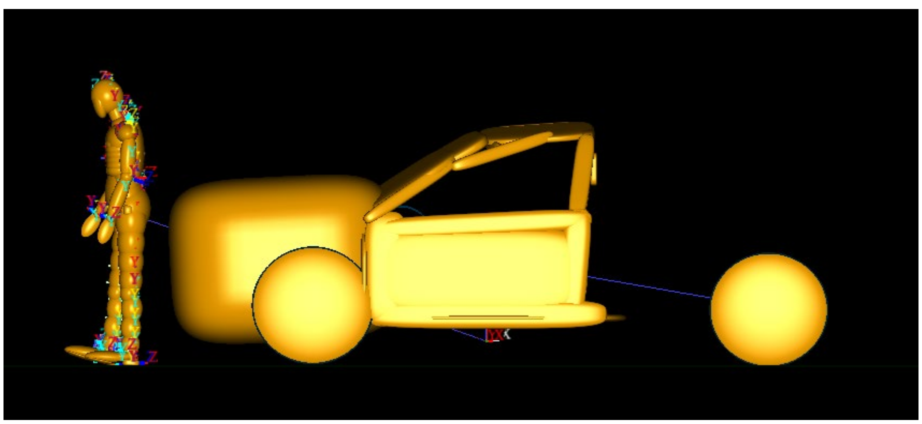


Figure 3.1. 50th Percentile Pedestrian and Lightweight Pickup truck model

3.1 Modeling of Wayfarer – Pickup Truck Impact Model

The accident model between Pedestrian and Lightweight Pickup Truck comprises of three different models as follows,

- Lightweight Pickup Truck Model,

- Adult Pedestrian Model,
- Ground reference plane.

3.1.1 Modeling of Pickup Truck Model

MADYMO employs both multi-body analyses and FE techniques to evaluate structural behavior. Multi-body analyses simulate the overall motion of a system of bodies connected by complex joints. The FE separates a continuous structure into discrete volumes, surfaces, or line segments. Each element distorts in accordance with the load-deformation relationship. The continuum is then evaluated as a complicated system consisting of elements with continuity at all boundaries between them. At a finite number of nodes or points, these elements are linked. Initial nodal locations and velocities, as well as the nodes corresponding to each element, are all necessary for the simulation.

The truck model, depicted in Figure 3.3 and Figure 3.4, is designed that represent the same geometry as the FE model, but with fewer parts on the frontal side and modeling a single body system using planes and ellipsoids. The Light Pickup Truck model is modeled as one body which consists of ellipsoids for bumper, hood, windshield, roof, driver, and passenger seats and four wheels. Rigid models such as the seat and ground, which are later connected to the truck system. The speeds produced in this truck model are 15 kmph, 18 kmph, 21 kmph, 24 kmph, and 27 kmph, respectively. The moment of inertia is centered on the X-axis, which corresponds to the center of gravity. In the case of stiffness, there is an optimum: too stiff, and the hood is injurious; not stiff enough, and the pedestrian’s head bottoms out. The truck's brake deceleration is caused by the friction force between the wheels and the ground, which is indicated by four identical ellipsoids.

The optimal stiffness succeeds in bringing the head to a stand just before the extremely stiff structures are impacted. Stiffness varies with deformation distance, and stiffness can be affected by both speed and deformation. Stiffness fluctuates because stiffness that is ideal at one speed is not ideal at other speeds. Coefficient of friction used for model simulations = 0.5. The stiffness parameters are considered according to Yang. J (2000) [4]. The dimensions of the truck are similar to the dimensions of the FE model of the 2011 Chevrolet Silverado lightweight pickup truck (Figure 3.2) taken from NCAC (National Crash Analysis Center) [51]. The parameters considered for modeling the truck are shown in Table 3.1.

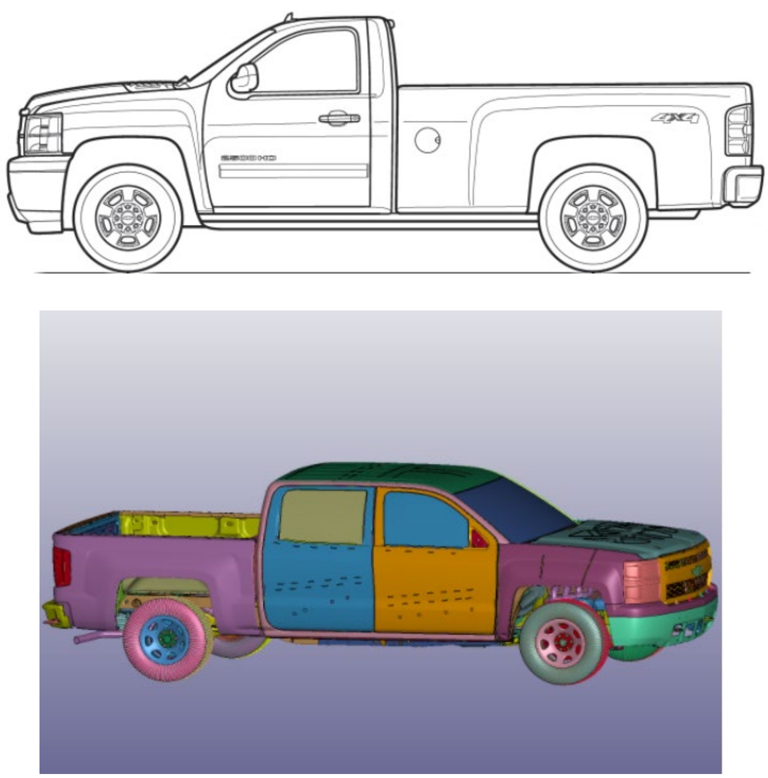


Figure 3.2. Original FE 2011 Chevrolet Silverado [52]

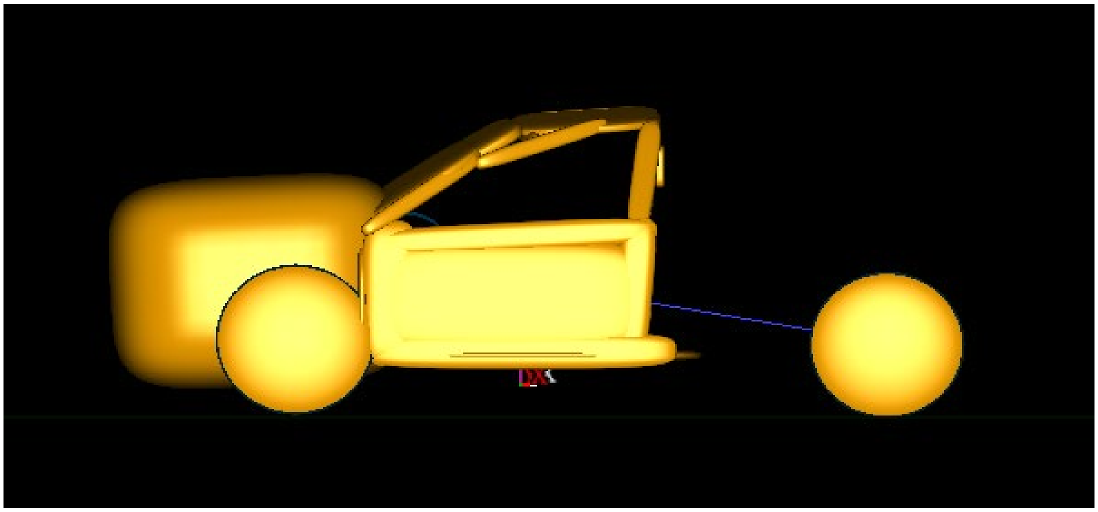


Figure 3.3 Ellipsoidal Lightweight Pickup truck

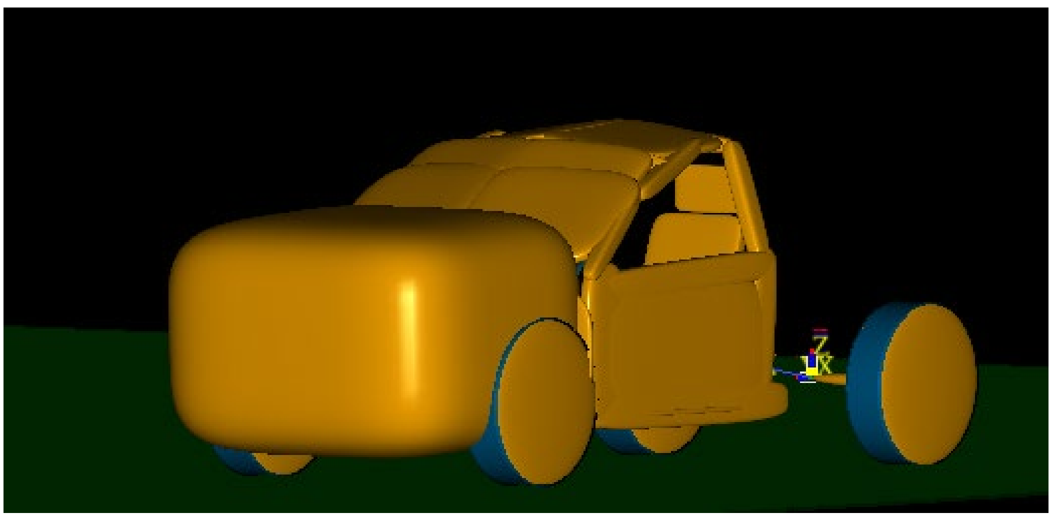


Figure 3.4. Isometric view of the ellipsoidal lightweight pickup truck

For simulations, the ellipsoidal lightweight pickup truck model is constructed to replicate the impact scenario and analyze the injuries that occurred to the pedestrian. The vehicle's dimensions, total weight, and front and rear axle dimensions are all taken from the vehicle catalogs provided by the manufacturers. By assuming that all components are constructed of mild steel, the material qualities of various truck frame parts are expressed in terms of stiffness.

TABLE 3.1

DIMENSIONS OF GEOMETRIC AND STIFFNESS PARAMETERS OF THE PICKUP TRUCK

S.NO	Geometric and Stiffness Parameters	Dimensions
1	Hood edge height	990 mm
2	Hood length	1308 mm
3	Hood Slope angle	19
4	Windshield length	787 mm
5	Windshield Angle	34
6	Weight of truck	1695 kg
7	Hood Surface Stiffness	175 N/mm
8	Hood Edge Stiffness	350 N/mm
9	Windshield Stiffness	500 N/mm

3.1.2 Wayfarer Model Description

This section describes the pedestrian accident investigation using various test conditions to assess injury parameters at various body parts. During vehicle-pedestrian crash dynamic tests, the pedestrian response is calculated under different speed situations. Comparisons of the data are carried out to understand the kinematic behaviors of the dummies used for crash testing when subjected to specific loading circumstances.

Simulations are done using well-validated ATD databases. Two-dimensional and three-dimensional databases of ATD models are available in MADYMO. A broad range of MADYMO ATD models are available [53]. The standard models of the child and adult dummies are- 3-year-old child, 6-year-old child, 5th percentile female, 50th percentile male, and 95th percentile male pedestrian dummy models as shown in Figure 3.5. The 50th percentile male pedestrian represents an “Average” of the USA adult male population [49]. The database of the human model has been validated on the segment as well as on full-body level, against a detailed set of volunteers and PMHS (Postmortem Human Surrogates) tests. Pedestrian models, each consist of 52 rigid bodies in 7 configuration branches. Sixty-four ellipsoids and two planes describe the outer surface. The data for the dimensions of the ellipsoids are determined from technical drawings at TNO [48, 49]. It is possible to adjust the dimensions, if necessary, for an adequate description of the contacts. In this research, the 50th percentile male pedestrian is used (Figure 3.6). The MADYMO pedestrian model is positioned in a walking posture in front of the truck as per the NHTSA study.

Figure 3.5. Database of MADYMO Pedestrian models [49]

Accelerations for various body parts, Impact forces, HIC, dislocations and contact forces, and knee-bending angle are all important injury-related characteristics that may be computed using the model. A frangible joint described in the breakable leg segments can be used to forecast the leg fracture. As a result, MADYMO is regarded to be a useful tool for predicting the chances of pedestrian causalities in accidents. This model will also be utilized to do a parameter analysis on how to improve vehicle front-end design for pedestrian protection [4].

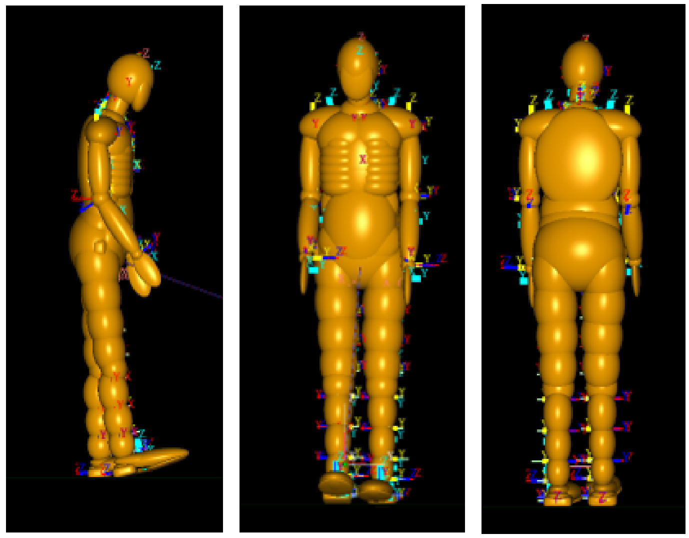


Figure 3.6. Side view, Front view, and Rearview of 50th Percentile Pedestrian model

3.1.3 Ground Reference Plane

A ground reference plane is created in a reference coordinate system with specified stiffness properties. Secondary impact with roadways is taken into account in this situation. Depending on whichever body part strikes the road first and at what speeds, it can cause serious injuries. Secondary contact injuries vary depending on the location. The pickup truck and the pedestrian dummy are placed on the ground reference plane (Figure 3.7).

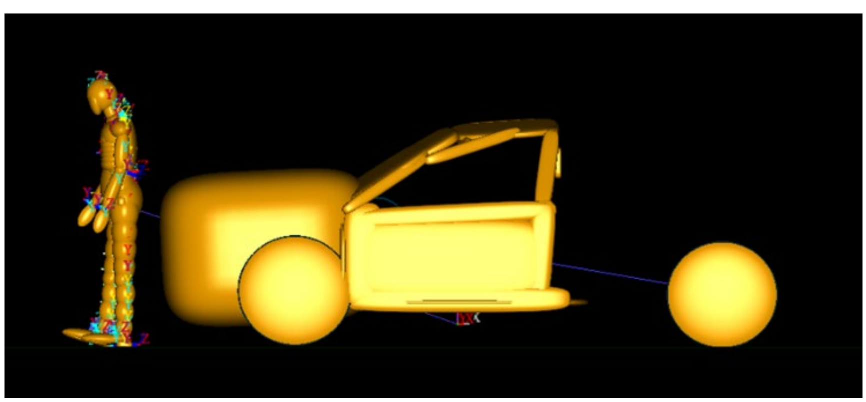


Figure 3.7. Pedestrian – Pickup truck model placed on ground reference plane

3.2 Comparison with the earlier study

The proposed wayfarer-pickup truck model was compared by collating the results of the MADYMO study for a wayfarer-pickup truck effect for side-impact at 25 kmph with the results of the tests conducted by [12]. The injury values are shown and compared in Table 3.2. According to the multi-body model analysis of [12] and multi-body model in this study, it is found that the difference in injury responses were less. The frontal hood design is finer than the ellipsoidal truck of [12]. The truck model used in that research was Chevrolet Silverado C2500. A MADYMO ellipsoidal truck model with dimensions similar to the original FE truck model (NCAC). In this research, the parameters considered for the ellipsoidal model are Similar to the FE truck model.

TABLE 3.2

COMPARISON OF INJURY RESPONSES WITH EARLIER STUDY

MODEL	HIC	HEAD ACCELERATION (g)	HEAD INJURY ON AIS SCALE	THIGH IMPACT FORCE (kN)	PELVIS RES_ACC (g)	KNEE FORCES (kN)
Narkhede, 2007	1013	241	3	6.3	38	1.6
Present model	848	206	2	4.7	35	1.4

CHAPTER 4

ANALYSIS OF WAYFARER IN SIDE IMPACT

4.1 Introduction

After the development and selection of the side impact model in MADYMO, the next stage is to perform the simulation analysis and investigate the kinematics of a specific collision with the pickup truck. In this thesis, side, front and rear impacts with the pickup truck were analyzed at different speeds. For every collision type, injuries and their severity were evaluated and compared at different locations. The injury criterion of the pedestrian dummy is based on levels of the European Experimental Vehicles Committee as well as European Passive Safety Network. The analysis section under Side impact includes three locations,

- Pedestrian – Truck Side Impact Analysis at Center,
- Pedestrian – Truck Side Impact Analysis at Right Corner,
- Pedestrian – Truck Side Impact Analysis at Left Corner.

Pedestrian Side impact (Figure 4.1) were modeled at 5 different pickup truck speeds starting from 15 kmph to 27 kmph with an increment of 3 kmph velocities. The pedestrian dummy model is positioned in a walking posture in front of the truck as per the NHTSA study. The pedestrian is placed at the Center and 0.35m from the center at both left and right corners. All the pickup truck body parts were picked as master surfaces and the pedestrian body parts were picked as slave surfaces. The coefficient of friction between the slave and master surfaces was taken as 0.5 [4] including the ground surface. Simulations were performed at three locations for 500ms and injuries like Head Injury Criteria, Head resultant acceleration, Viscous response, forces on upper and lower extremities of pedestrian are evaluated in the Side collision.

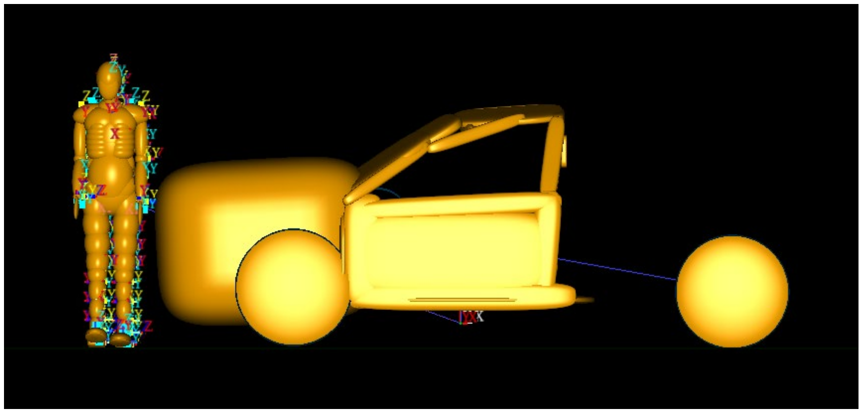


Figure 4.1. Side impact model of 50th percentile pedestrian and pickup truck

4.2 Kinematics of 50th Percentile Pedestrian in Pickup Truck Side Impact at Center

Adult injury risks are evaluated for low and high-speed collisions. The kinematics and tendency of pedestrian injuries are affected by the vehicle's front design, impact speed, and pedestrian height in pedestrian-vehicle collisions. When lightweight pickup trucks like the Chevrolet Silverado, which have a hood height roughly double that of a normal car, strike pedestrians, they cause more injuries, that could lead to death.

At the Center, the kinematics of pedestrian in side-impact differ for every speed parameter. The primary contact for pedestrian observed in the side impact is the truck hood. There are no head injuries at 15 kmph and 18 kmph and minimum injuries for impact speeds 21 kmph and above. Kinematics of the 50th percentile pedestrian in pickup truck side impact at 15 kmph, 18 kmph, 21 kmph, 24 kmph, and 27 kmph are shown in Figures 4.2 through 4.6, respectively.

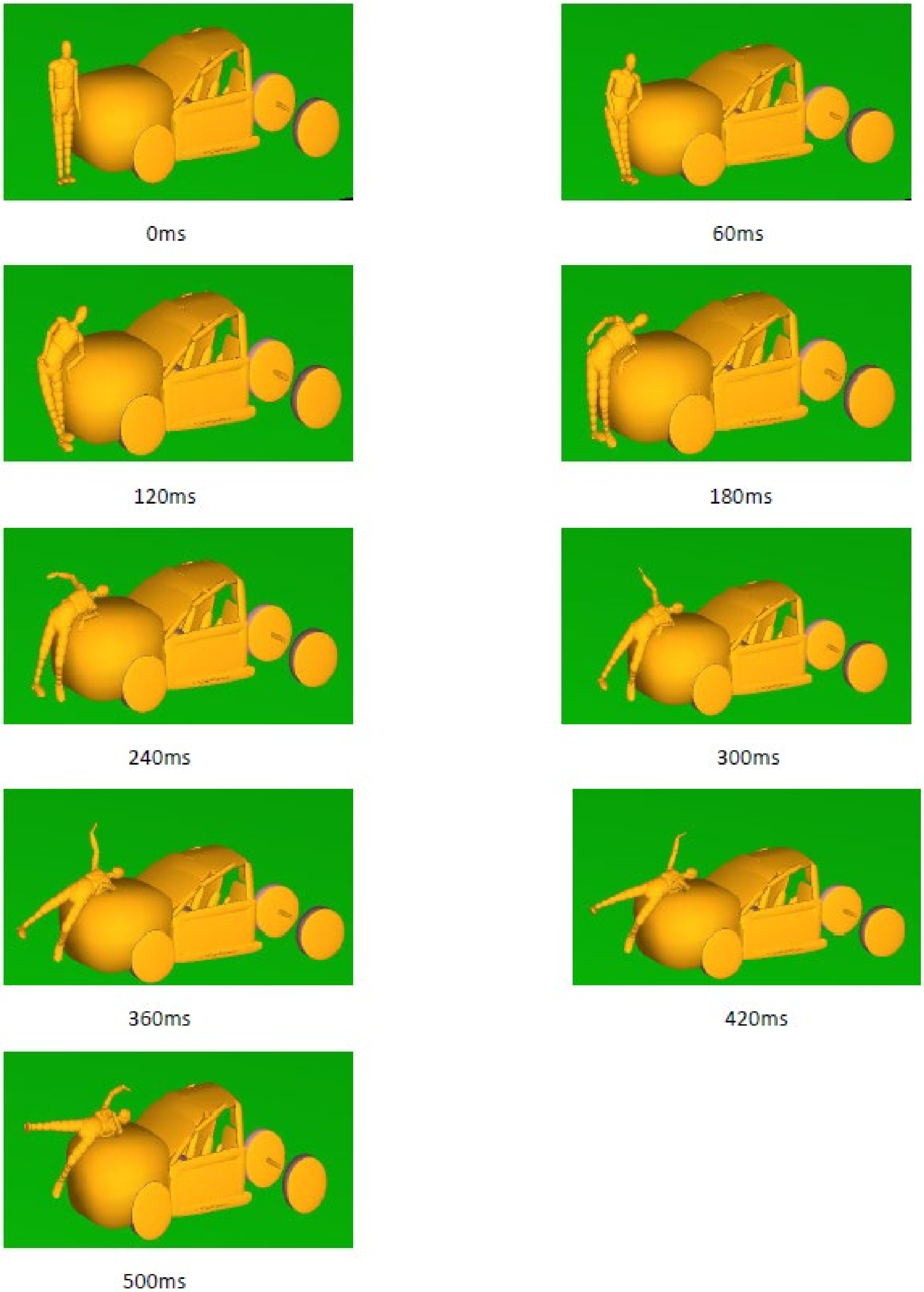


Figure 4.2. Kinematics of the 50th percentile pedestrian in pickup truck side impact at 15 kmph at Center

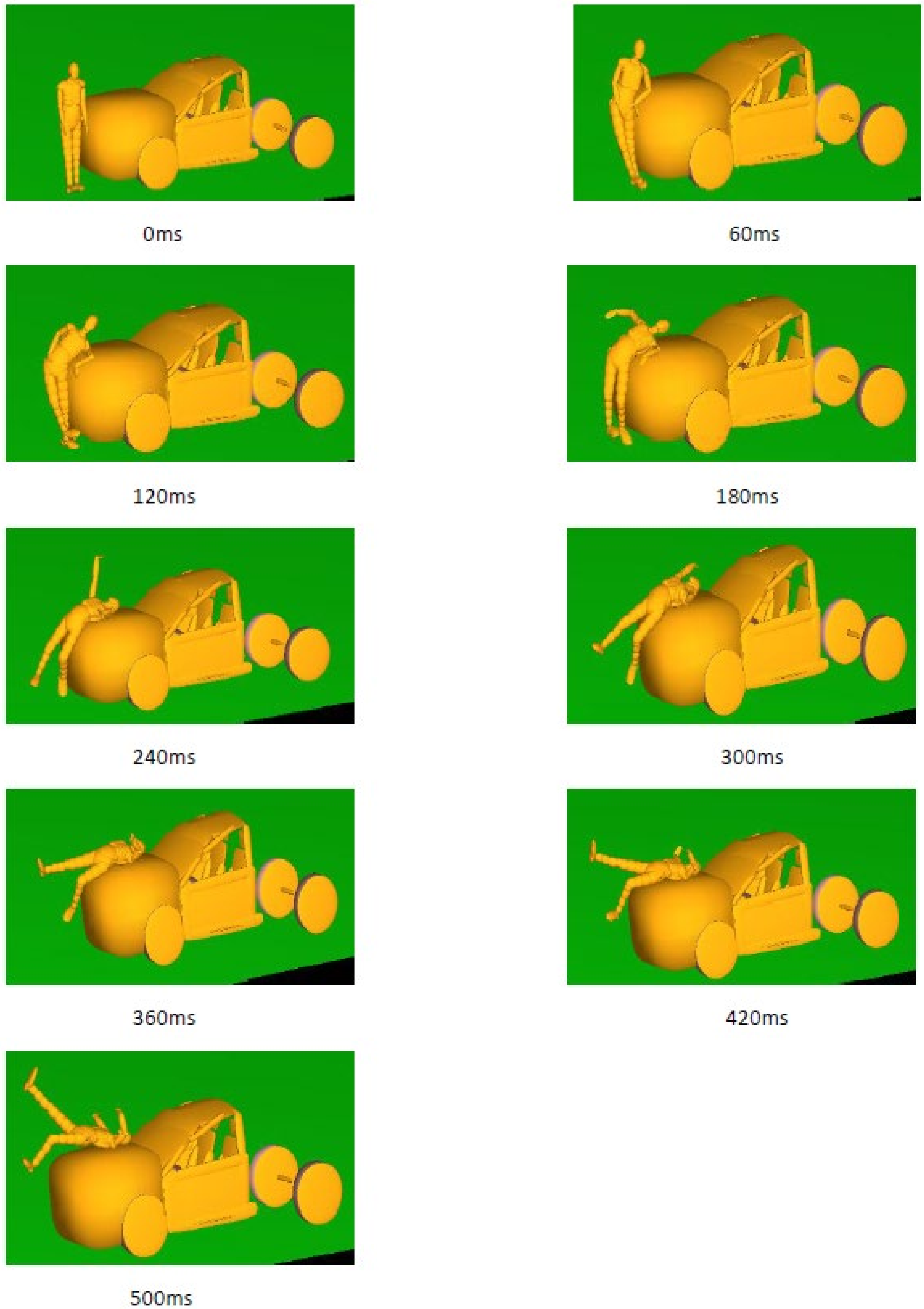


Figure 4.3. Kinematics of the 50th percentile pedestrian in pickup truck side impact at 18 kmph at Center

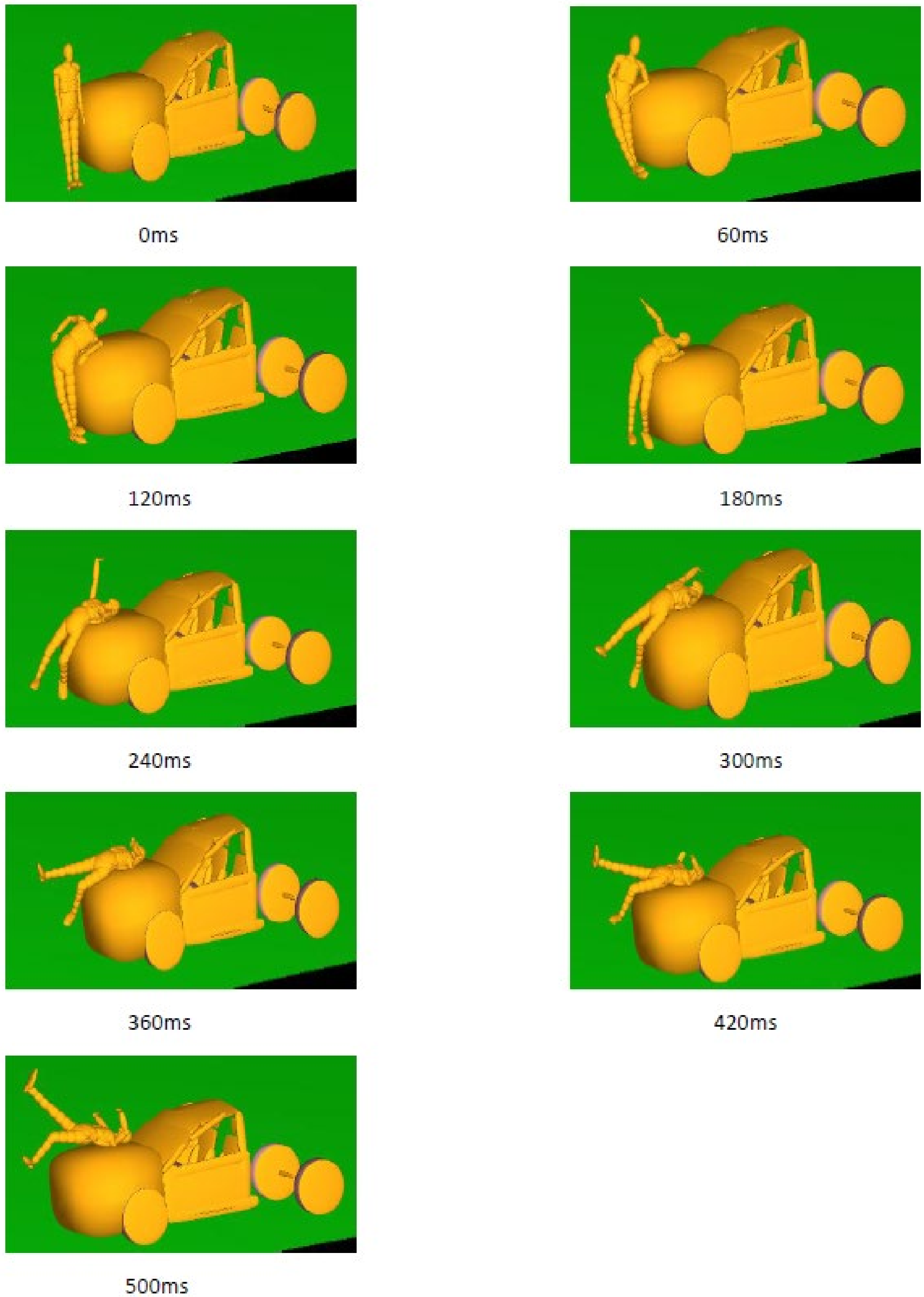


Figure 4.4. Kinematics of the 50th percentile pedestrian in pickup truck side impact at 21 kmph at Center

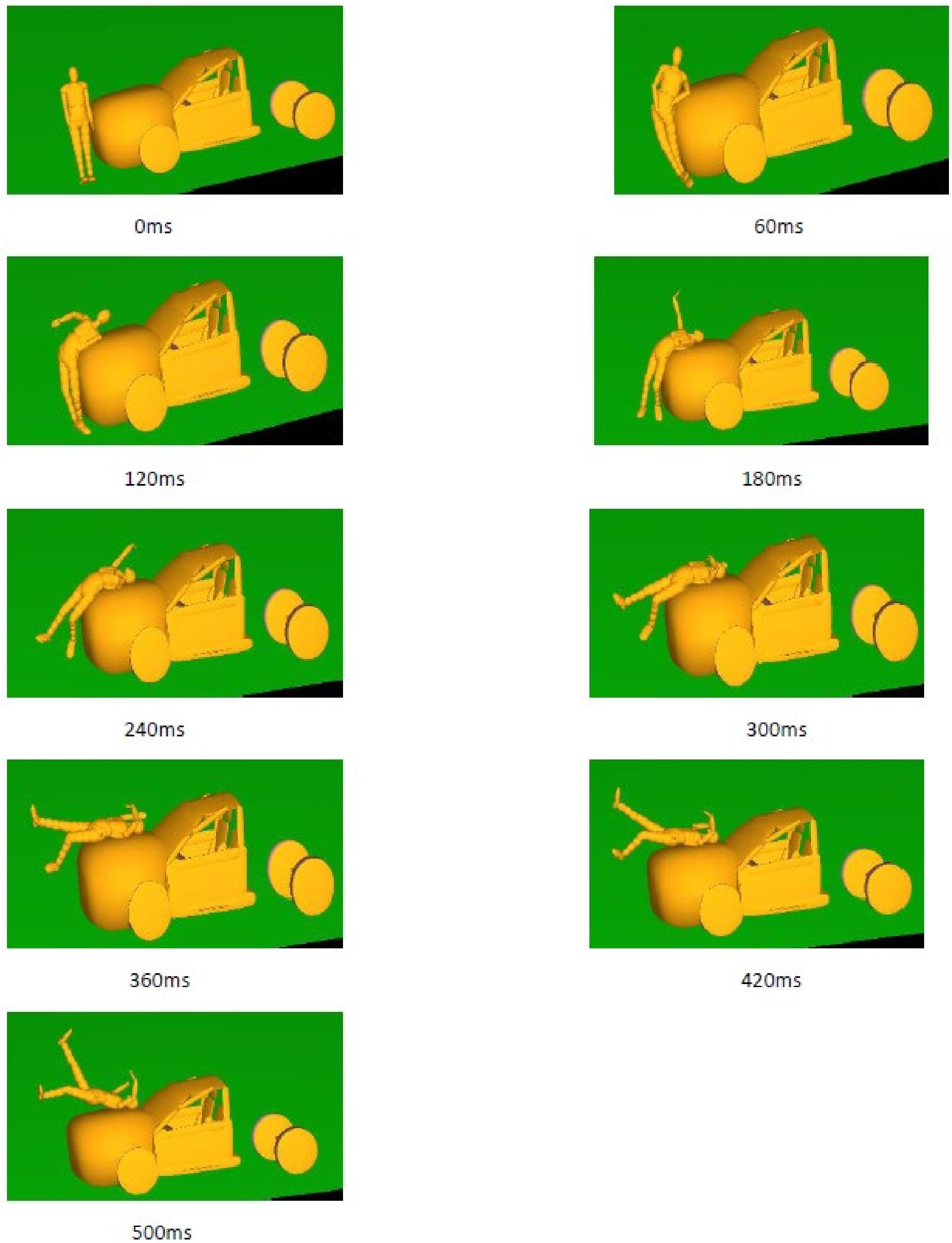


Figure 4.5. Kinematics of the 50th percentile pedestrian in pickup truck side impact at 24 kmph at Center

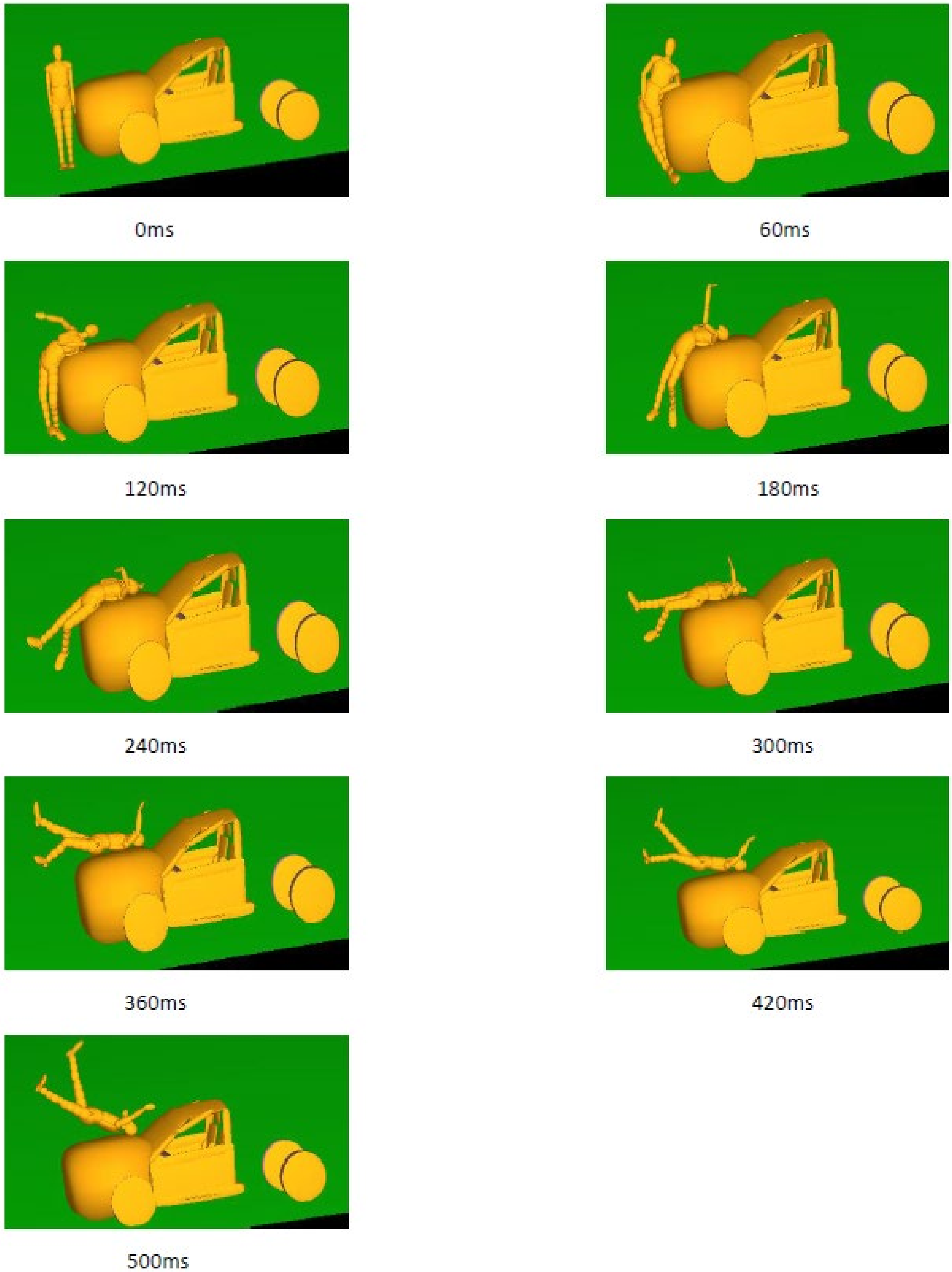


Figure 4.6. Kinematics of the 50th percentile pedestrian in pickup truck side impact at 27 kmph at Center

4.3 Kinematics of 50th Percentile Pedestrian in Pickup Truck Side Impact at Right Corner

Adult injury risks are evaluated for low and high-speed collisions. The kinematics and tendency of pedestrian injuries are affected by the vehicle's front design, impact speed, and pedestrian height in pedestrian-vehicle collisions. When lightweight pickup trucks like the Chevrolet Silverado, which have a hood height roughly double that of a normal car, strike pedestrians, they cause more injuries, that could lead to death.

At Right Corner, the kinematics of pedestrian in side-impact vary for every speed parameter. All the stiffness values of the hood used are the same applied by Yang in his simulation. The coefficient of friction applied for the pedestrian–pickup truck model is 0.5.

Simulations are performed for 5 different speeds (15 kmph, 18 kmph, 21 kmph, 24 kmph, and 27 kmph) at the right corner at 500ms, and injuries are evaluated. The MADYMO 50th percentile pedestrian model is positioned to be walking laterally in the front end of the truck as mentioned in NHTSA research.

The primary contact for pedestrian observed in the side impact is the truck hood. The primary contact for pedestrian observed in front impact is the truck hood. There are no head injuries at 15 kmph and 18 kmph and minimum injuries for impact speeds 21 kmph and above.

Kinematics of the 50th percentile pedestrian in pickup truck impact at 15 kmph, 18 kmph, 21 kmph, 24 kmph, and 27 kmph are shown in Figures 4.7 through 4.11, respectively.

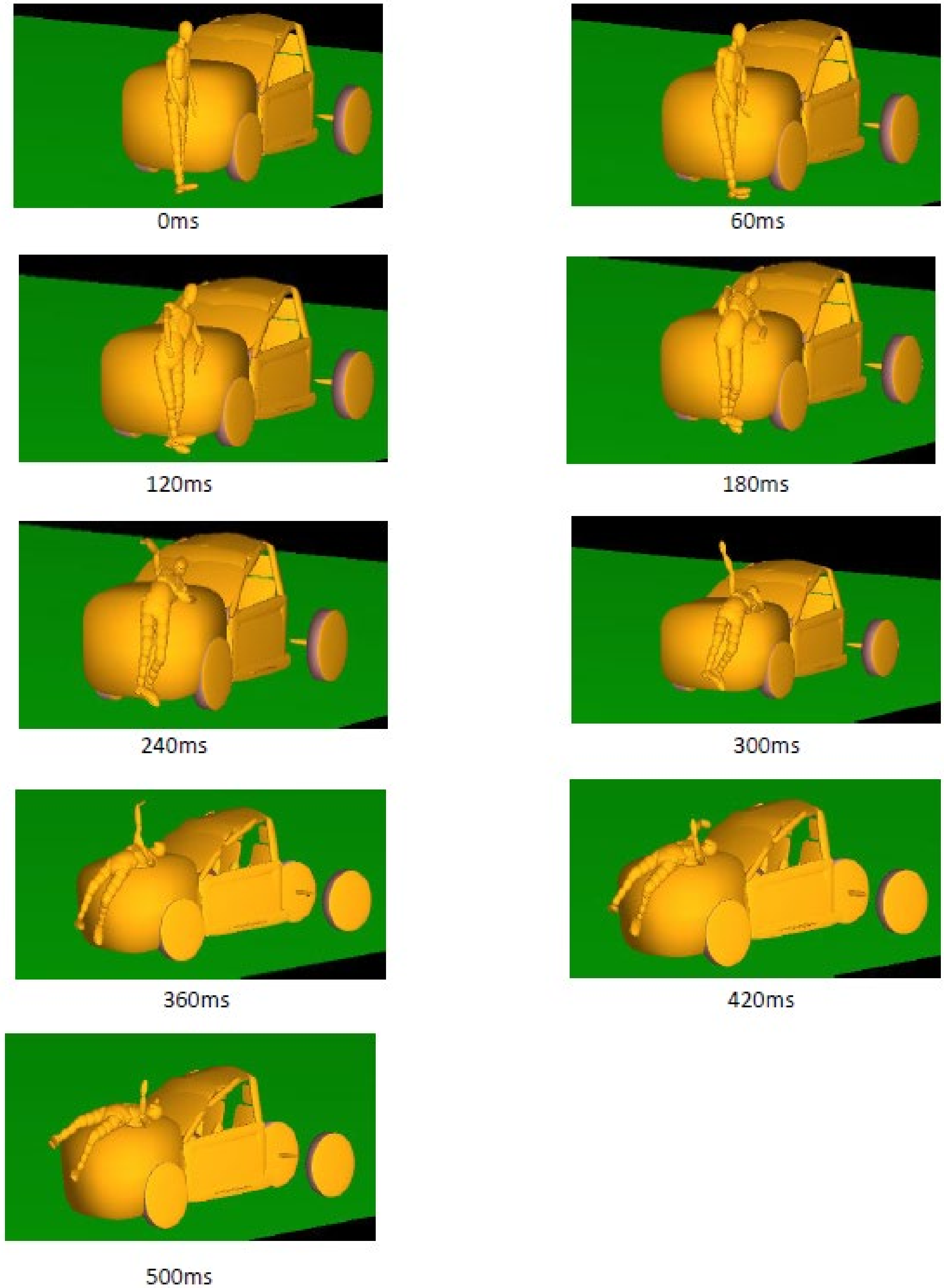


Figure 4.7. Kinematics of the 50th percentile pedestrian in pickup truck side impact at 15 kmph at Right Corner

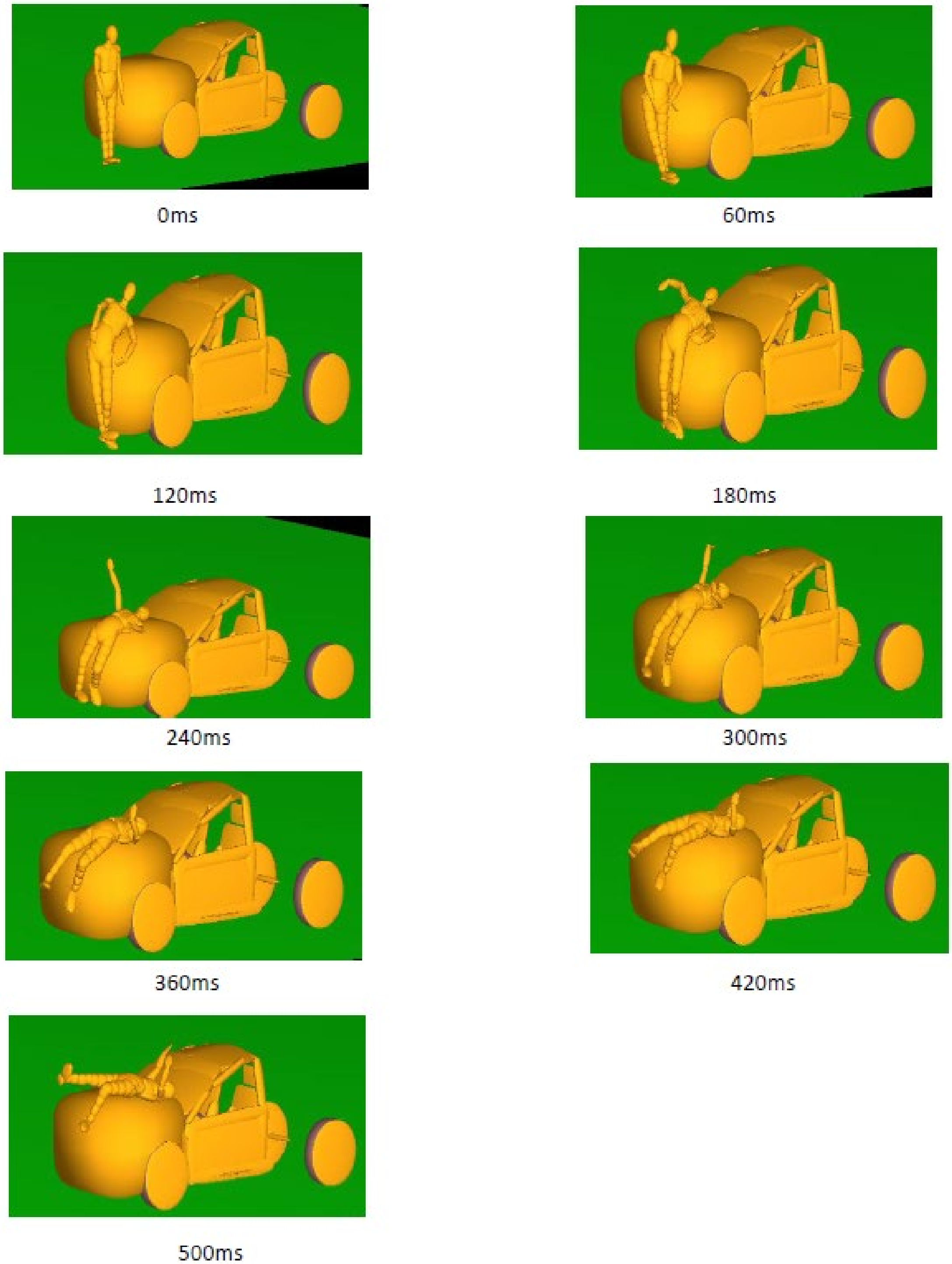


Figure 4.8. Kinematics of the 50th percentile pedestrian in pickup truck side impact at 18 kmph at Right Corner

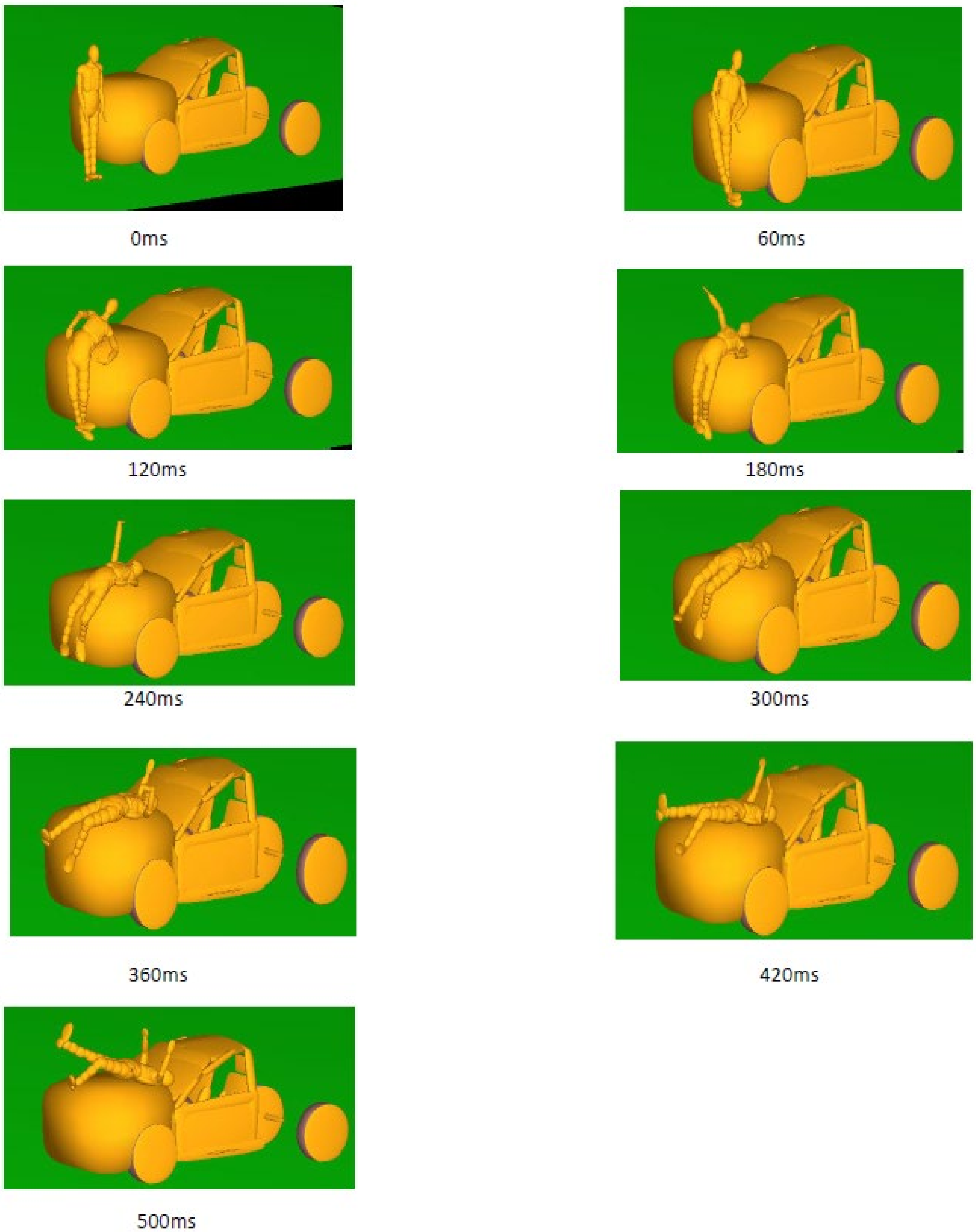


Figure 4.9. Kinematics of the 50th percentile pedestrian in pickup truck side impact at 21 kmph at Right Corner

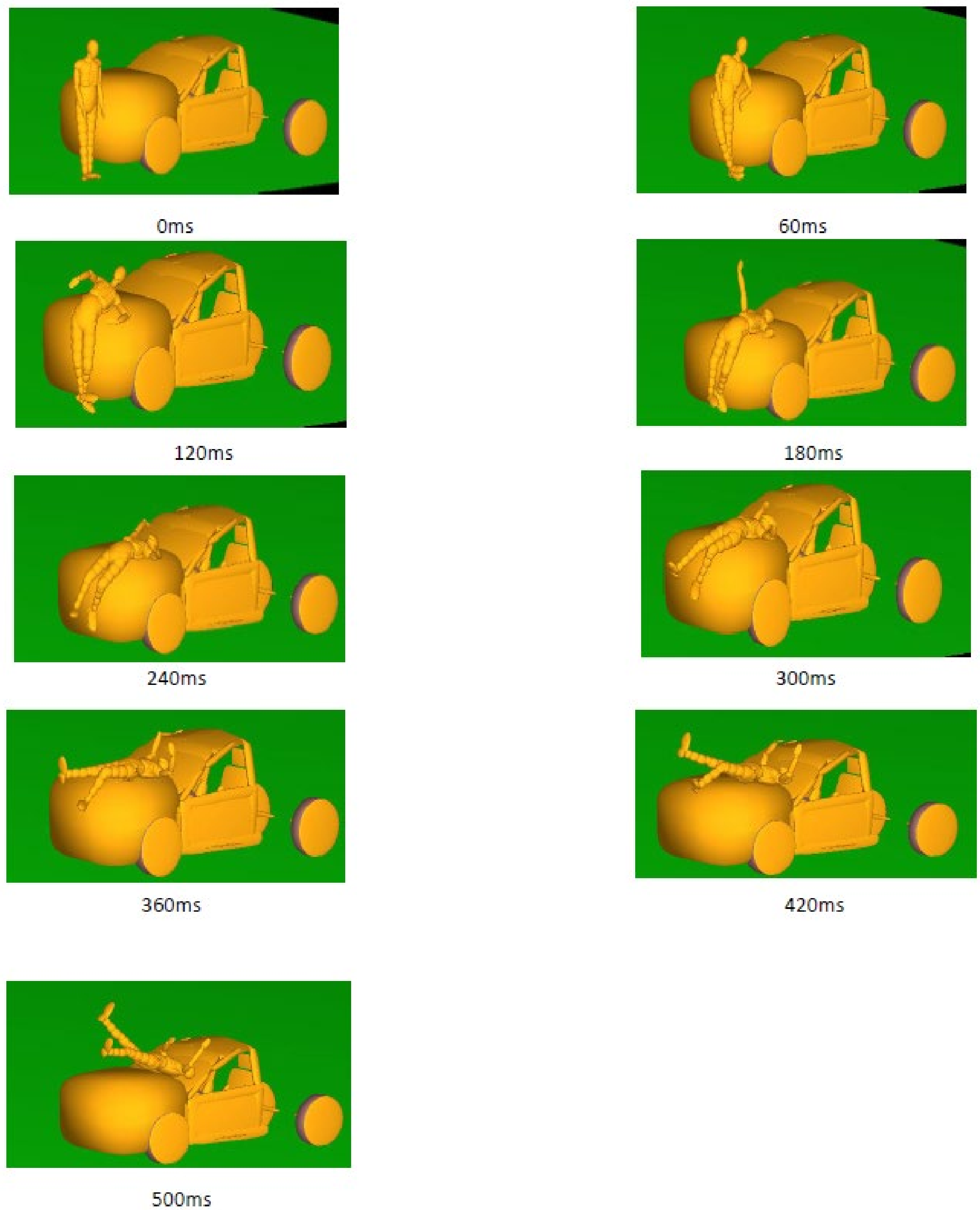


Figure 4.10. Kinematics of the 50th percentile pedestrian in pickup truck side impact at 24 kmph at Right Corner

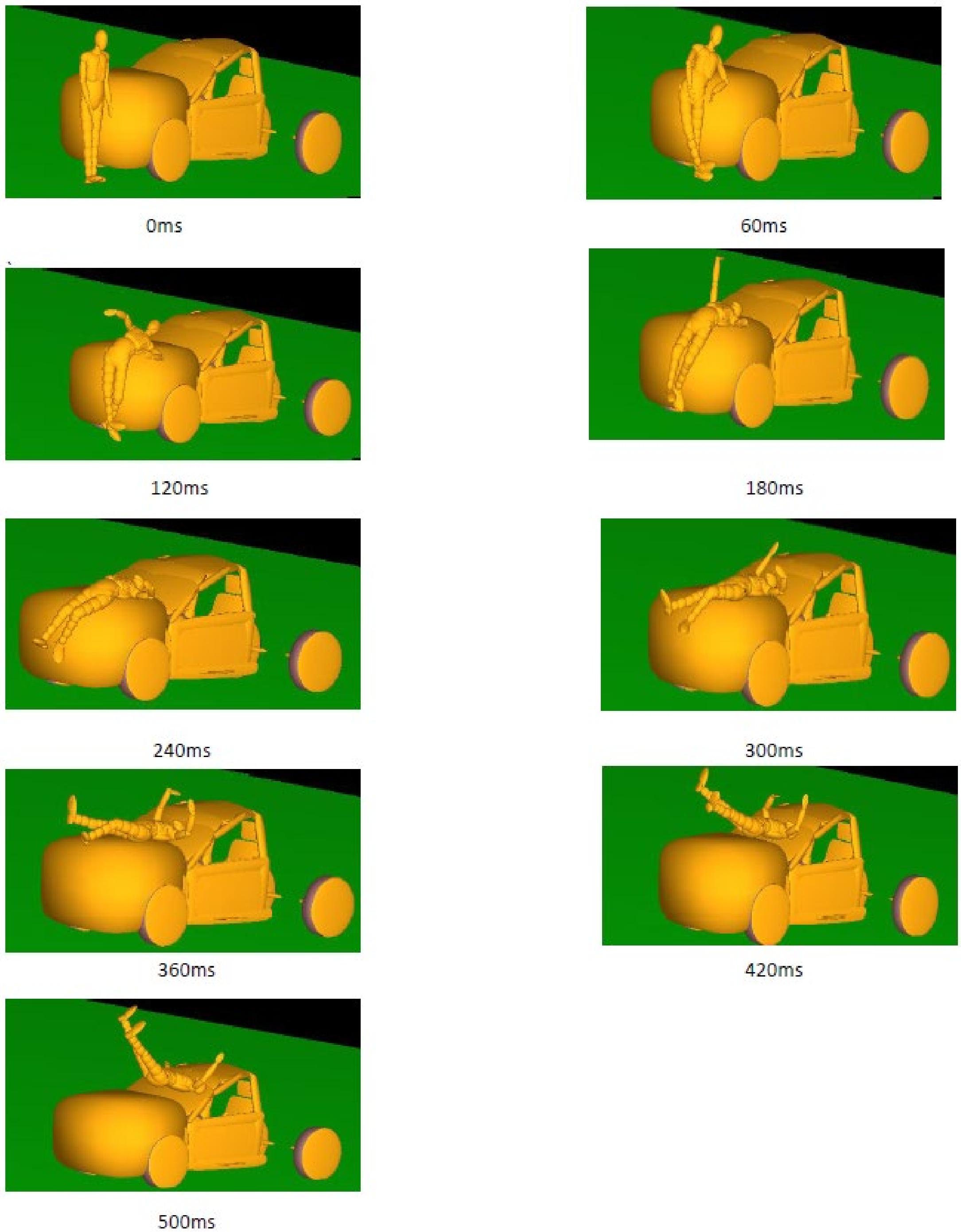


Figure 4.11. Kinematics of the 50th percentile pedestrian in pickup truck side impact at 27 kmph at Right Corner

4.4 Kinematics of 50th Percentile Pedestrian in Pickup Truck Side Impact at Left Corner

Adult injury risks are evaluated for low and high-speed collisions. The kinematics and tendency of pedestrian injuries are affected by the vehicle's front design, impact speed, and pedestrian height in pedestrian-vehicle collisions. When lightweight pickup trucks like the Chevrolet Silverado, which have a hood height roughly double that of a normal car, strike pedestrians, they cause more injuries, that could lead to death.

At the left corner, the kinematics of pedestrian in the side impact varies for every speed parameter. All the stiffness values of the hood used are the same applied by Yang in his simulation. The coefficient of friction applied for the pedestrian–pickup truck model is 0.5.

Simulations are performed for 5 different speeds (15 kmph, 18 kmph, 21 kmph, 24 kmph, and 27 kmph) at the left corner at 500ms, and injuries are evaluated. The MADYMO 50th percentile pedestrian model is positioned to be walking laterally in the front end of the truck as mentioned in NHTSA research.

The primary contact for pedestrian observed in the side impact is the truck hood. There are no head injuries at 15 kmph and 18 kmph and minimum injuries for impact speeds 21 kmph and above.

Kinematics of the 50th percentile pedestrian in pickup truck impact at 15 kmph, 18 kmph, 21 kmph, 24 kmph, and 27 kmph are shown in Figures 4.12 through 4.16, respectively.

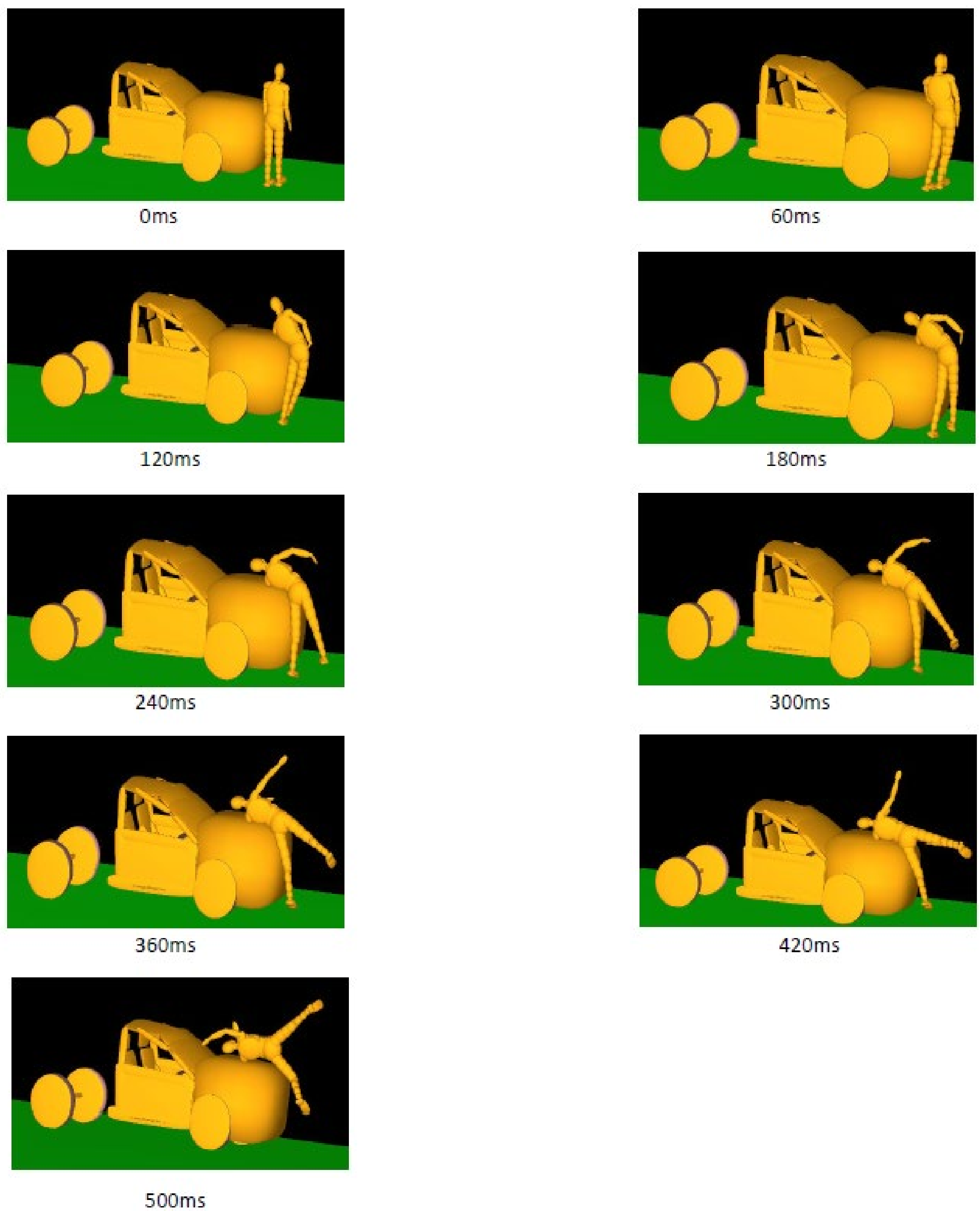
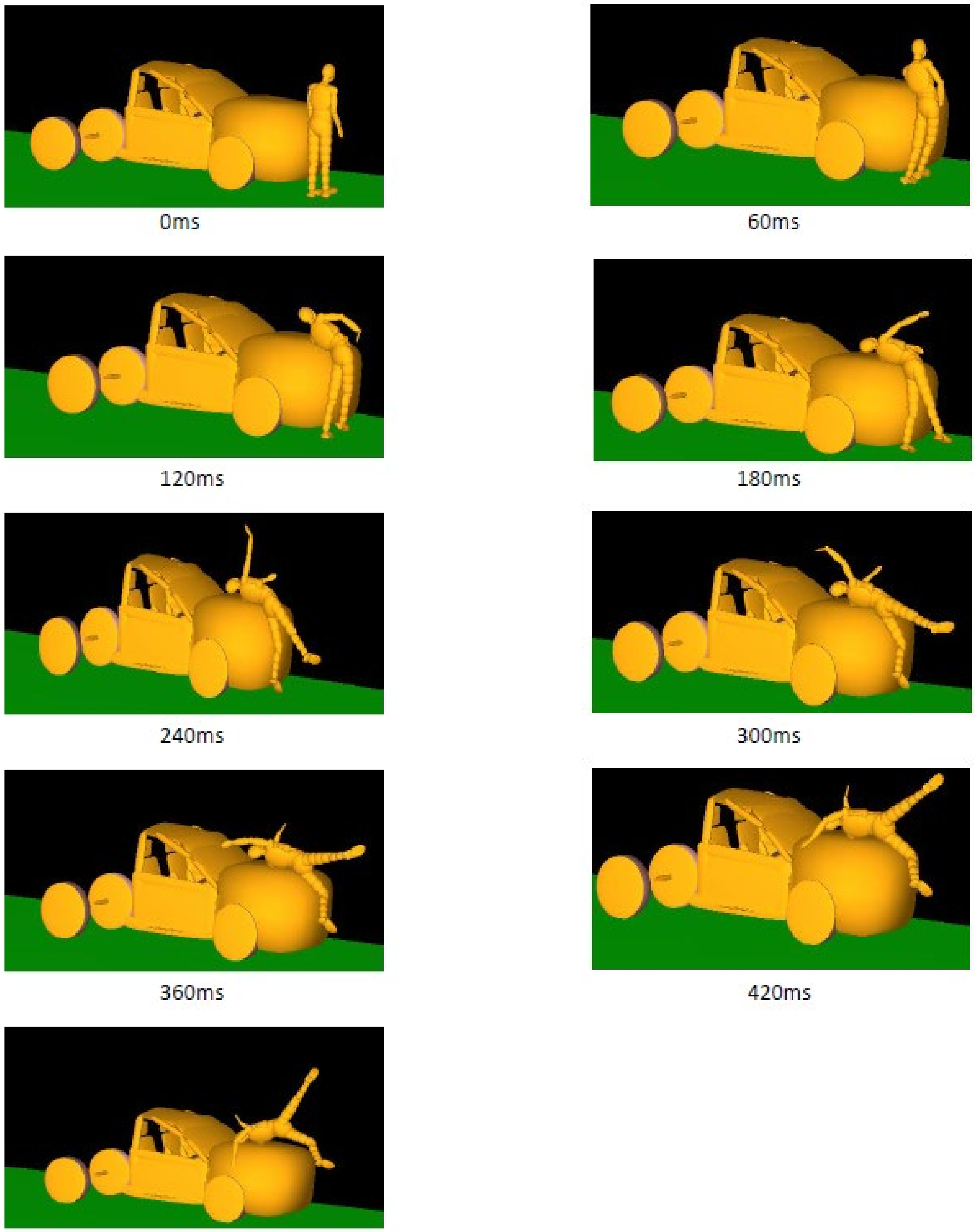


Figure 4.12. Kinematics of the 50th percentile pedestrian in pickup truck side impact at 15 kmph at Left Corner



0ms 60ms

120ms 180ms

240ms 300ms

360ms 420ms

500ms

Figure 4.13. Kinematics of the 50th percentile pedestrian in pickup truck side impact at 18 kmph at Left Corner

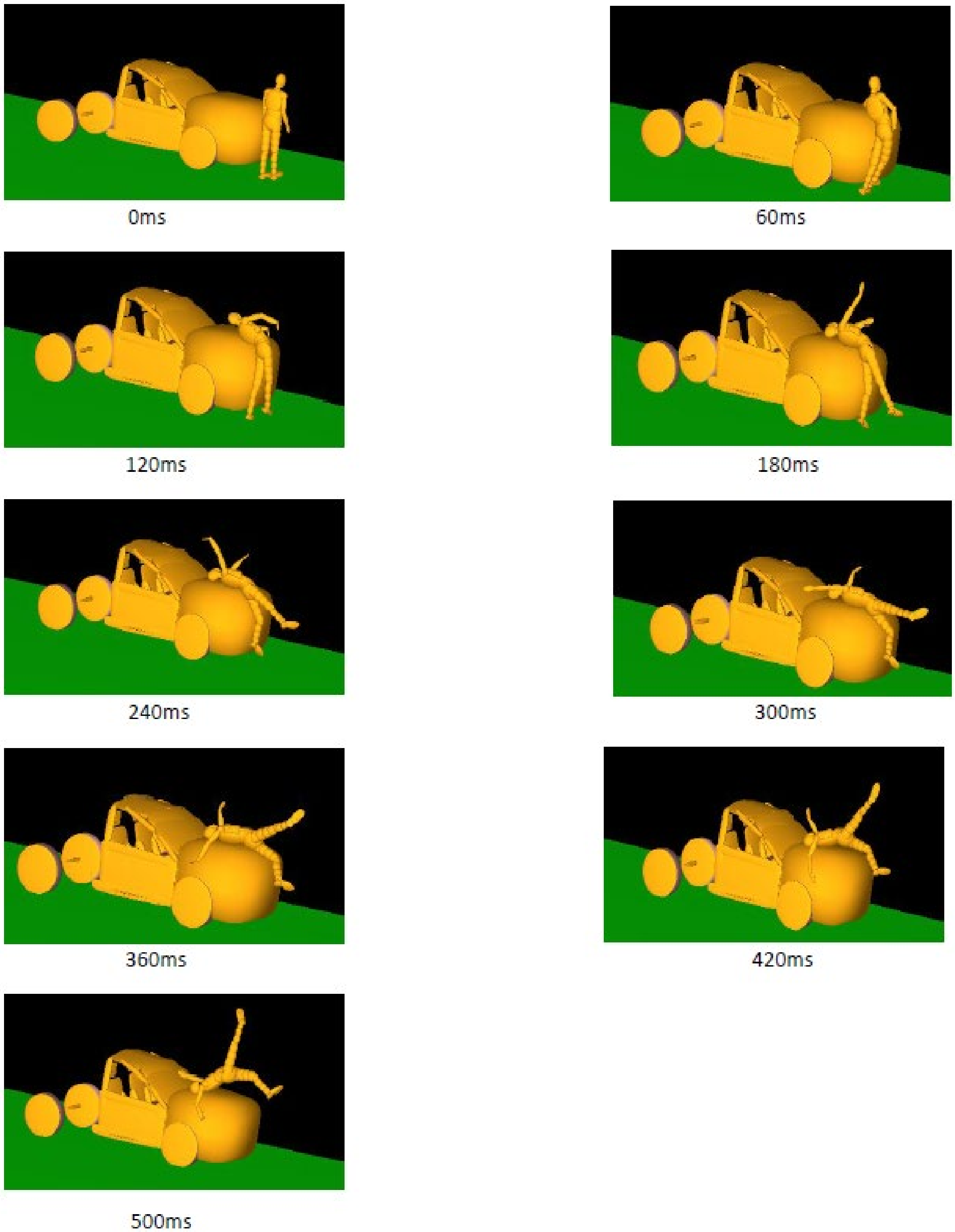


Figure 4.14. Kinematics of the 50th percentile pedestrian in pickup truck side impact at 21 kmph at Left Corner

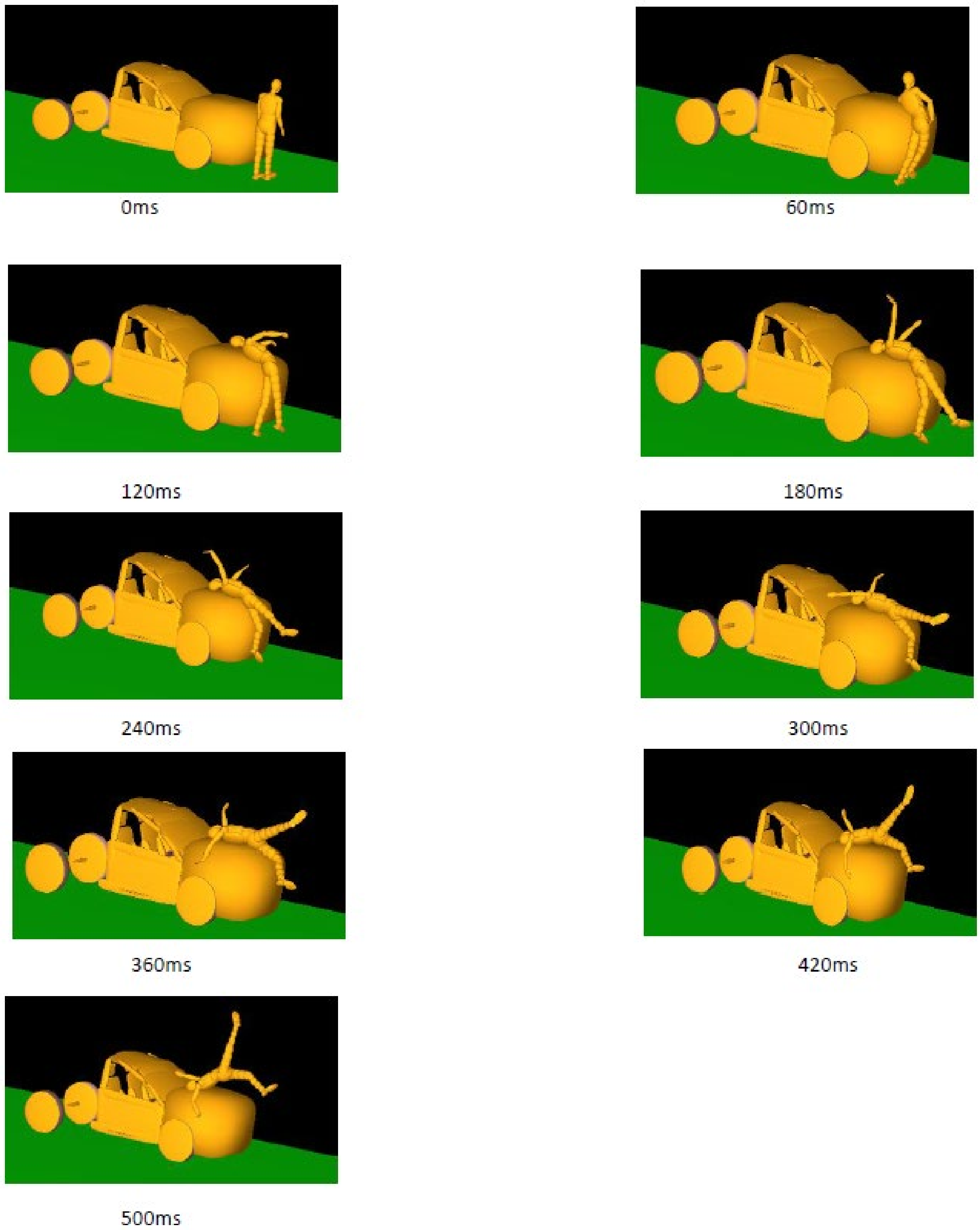


Figure 4.15. Kinematics of the 50th percentile pedestrian in pickup truck side impact at 24 kmph at Left Corner

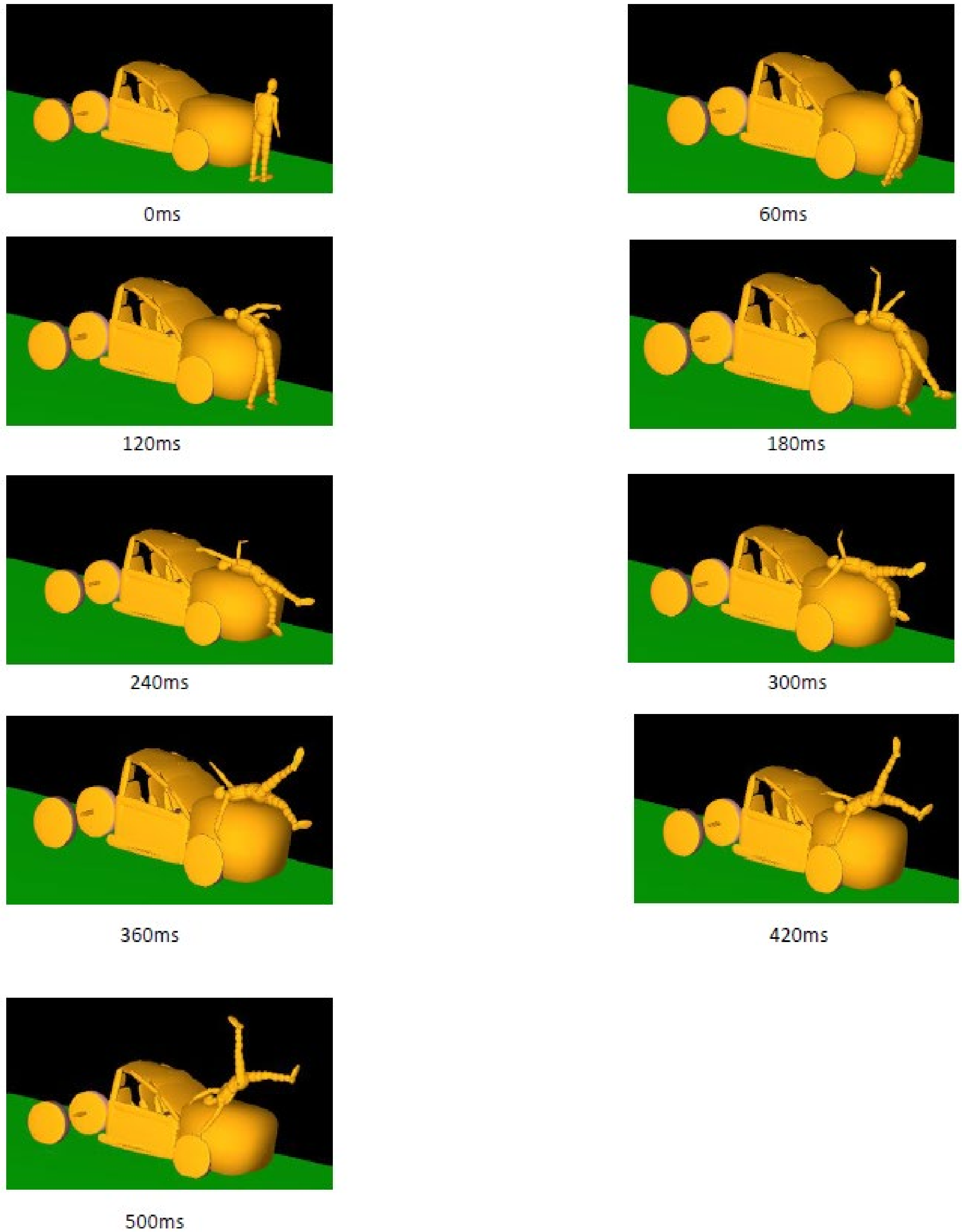


Figure 4.16. Kinematics of the 50th percentile pedestrian in pickup truck side impact at 27 kmph at Left Corner

4.5 Comparison of Kinematic Behavior of 50th Percentile Pedestrian in Pickup Truck Side Impact at Three locations

From the kinematic analysis of 50th percentile pedestrian in side-impact, it is observed that injury severity is high at the right end when compared to the center and left end. In lateral impact, the truck directly strikes at the center of the pelvis and chest of the pedestrian. At the Center, the pedestrian initially strikes the hood and lands on the hood at low speeds, and at higher speeds the pedestrian lands in front of the truck. At the left corner, the pedestrian lands on the hood initially and later on with increasing speed strikes the windshield at secondary impacts. At the right corner, the pedestrian initially strikes the hood, and with increasing speed, the pedestrian lands at a distance away from the truck. In this location, the secondary impact observed is at the ground plane. Injury forces and accelerations are not much critical and no fatality. In this impact, the chest and head accelerations are higher, and severity is more when compared to other body parts of the pedestrian.

4.6 Comparison of Injuries to 50th Percentile Pedestrian in Pickup Truck Side Impact

Responses of side pedestrian – pickup truck impact are compared to understand the dynamic performance and injuries at different locations at various speeds.

<u>Head Injury Criteria (HIC)</u>

On Comparing, the head injuries at the left location are slightly more than injuries at right and center locations. As the hood is higher than the height of the pelvic region of the pedestrian, there are not many head injuries occurred. Table 4.1 and Figure 4.17 show the maximum values obtained for 50th percentile pedestrian at three locations for a run of 500ms. At 15 kmph, the values are almost negligible when compared with tolerance levels, which means, there is no injury at that speed. Only at 27 kmph, the injury value is above the biomechanical limit and pedestrian might occur with fractures. All the values over 24 kmph have exceeded the biomechanical limits ($HIC_{36} < 1000$, $HIC_{15} < 700$), indicating several fractures, loss of skin and scalp. The chances of fatality are low and there are no higher risks of injury. The maximum AIS scale rating of 3, which leads to multiple fractures and contusion to the cerebellum as shown in Table 4.2.

TABLE 4.1

HEAD INJURY CRITERIA FOR 50TH PERCENTILE PEDESTRIAN AT CENTER, RIGHT AND LEFT END IN SIDE IMPACTS

Speeds(kmph)	Frontal Center Side impact	ΔT (ms)	Frontal Left-Side impact	ΔT (ms)	Frontal Right-Side impact	ΔT (ms)
15	17	2.1	20	2.8	15	2.3
18	107	2.6	134	2.3	96	3.2
21	283	2.4	348	2.6	268	2.4
24	713	2.6	765	2.9	673	2.7
27	1411	2.9	1348	2.6	1210	2.4

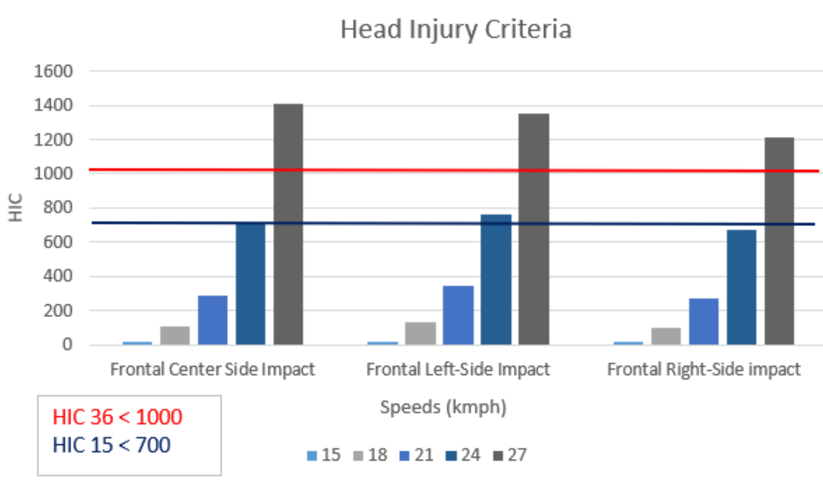


Figure 4.17. Comparison of Head Injury Criteria for 50th Percentile Pedestrian at Center, Right and Left end in Side impacts

TABLE 4.2

AIS RATING FOR SIDE-IMPACT HEAD INJURY

Speeds (kmph)	Side Impact
15	1
18	1
21	1
24	2
27	3

Head Impact locations on Hood

Figure 4.18 shows the initial head impact locations on the hood obtained in a pedestrian Side impact.

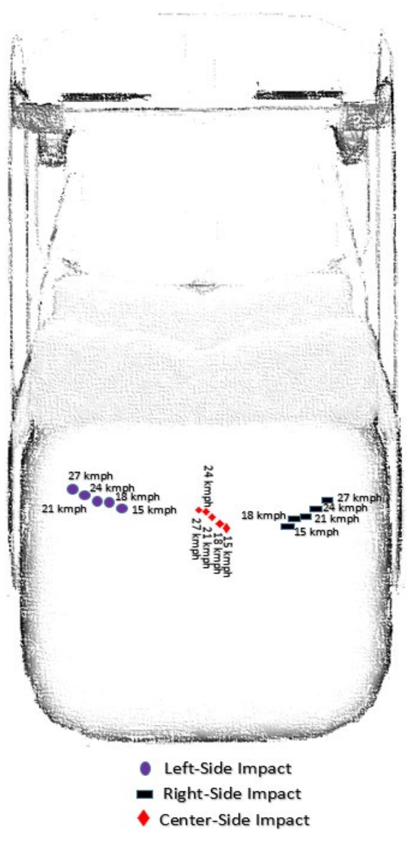


Figure 4.18. Head impact locations of 50th percentile pedestrian on the truck hood in Side impact

Viscous Injury Response (VC)

The tolerance level of the viscous criterion in a side impact should not reach 1 m/s. Table 4.3 indicates all the maximum Viscous Injury Responses obtained by 50th percentile pedestrian during impact for a run of 500ms. In all three locations, the Viscous response is less than 1. The least response is obtained at 15 kmph at the center location and the maximum value is obtained by Frontal right-side impact. There is no major viscous injury for the thorax.

TABLE 4.3

MAXIMUM VISCOUS INJURY RESPONSE IN SIDE-IMPACT AT THREE LOCATIONS

Speeds(kmph)	Frontal Center Side Impact	Frontal Right-Side Impact	Frontal Left-Side impact
15	5.85E-05	4.95E-05	7.14E-05
18	1.18E-04	7.24E-05	1.18E-04
21	1.98E-04	1.00E-04	1.94E-04
24	2.88E-04	1.38E-04	2.93E+00
27	3.80E-04	1.83E-04	4.28E-04

Thoracic Trauma Index (TTI)

In the case of a side impact, the thorax of the pedestrian impacts the hood of the truck, which results in blunt trauma. To understand thorax injuries, the thorax trauma index (TTI) was developed after conducting several tests, the TTI should be less than 85 g for the pedestrian to be safe according to EEVC biomechanical criteria. Table 4.4 and Figure 4.19 indicate the maximum TTI obtained by 50th percentile Pedestrian at all three locations for a run of 500ms. Until 21 kmph, the 50th pedestrian male dummy is safe and below the tolerance limit. For speeds above 24 kmph, the values exceed the limit, and the dummy might occur with severe thorax injury at both locations. On comparing three locations, TTI at left and center impacts are higher than right side impact.

TABLE 4.4

THORAX TRAUMA INDEX AT THREE LOCATIONS FOR SIDE IMPACT

Speeds (kmph)	Frontal Left-Side impact	Frontal Right-Side Impact	Frontal Center-Side Impact
15	55	48	58
18	72	63	69
21	88	75	85
24	109	89	112
27	134	108	126

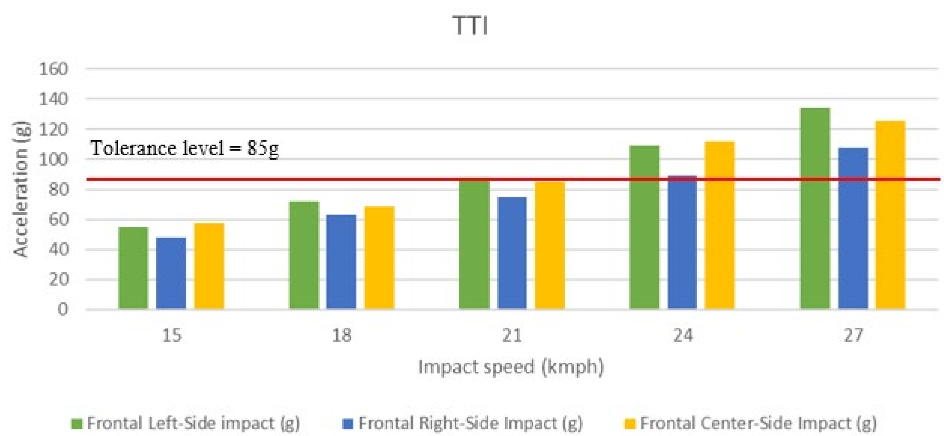


Figure 4.19. Comparison of TTI for 50th percentile pedestrian at Left, Right, and Center ends in Side impact

<u>Pelvic Acceleration</u>

The peak pelvic acceleration shall not exceed 130g according to EEVC biomechanical criteria. Table 4.5 and Figure 4.20 shows the maximum pelvic acceleration values of the 50^{th} percentile pedestrian in side impact for a run of 500ms. At all three locations, the pelvic injuries are within the biomechanical limits, and no major pelvic fractures. The maximum acceleration occurred for the 50th pedestrian male dummy is 62g, 56g, and 71g at left, right corners, and center, respectively at 27 kmph. Comparing the injuries at all the locations, the injuries at the center location are severe than left and right locations as the major force of the truck act at that point and hits the pelvis of pedestrian directly.

TABLE 4.5

PELVIS RESULTANT ACCELERATION OF 50TH PERCENTILE PEDESTRIAN AT LEFT, RIGHT AND CENTER ENDS IN SIDE IMPACT

Speeds (kmph)	Frontal Left-Side impact	Frontal Right-Side Impact	Frontal Center-Side Impact
15	12	9	20
18	16	14	28
21	25	17	36
24	34	28	55
27	62	56	71

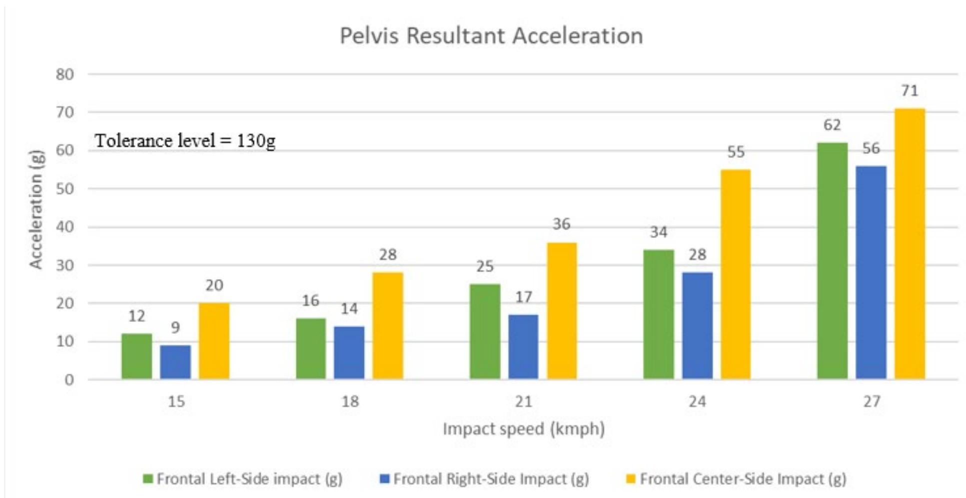


Figure 4.20. Comparison of Pelvis resultant acceleration of 50th percentile pedestrian at Left, Right and Center ends in Side impact

Head Acceleration

The maximum Head acceleration should be 80g for a pedestrian to be safe according to EEVC biomechanical criteria. Table 4.6 and Figure 4.21 show the maximum Head acceleration values obtained by 50th percentile pedestrian for a run of 500ms. At 15 kmph, the values are below biomechanical limit and there are no critical injuries at the left side-impact and right-side impact, respectively. At 18 kmph and above, for the 50th P Pedestrian, the head accelerations are almost

3 - 4 times greater and were fatal. Head accelerations are severe when the pedestrian is struck by a truck at the center location as the head is initially contacted at the hood of the truck.

TABLE 4.6

HEAD RESULTANT ACCELERATION OF 50TH PERCENTILE PEDESTRIAN AT LEFT, RIGHT, AND CENTER ENDS IN SIDE-IMPACT

Speeds(kmph)	Frontal Center Side Impact	Frontal Left-Side Impact	Frontal Right-Side impact
15	73	66	78
18	134	103	155
21	152	131	169
24	206	230	175
27	252	235	192

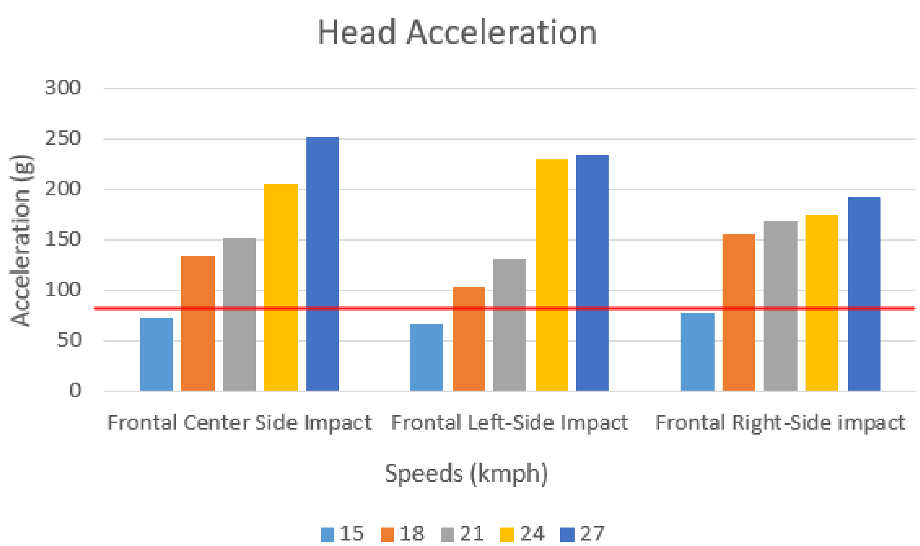


Figure 4.21. Comparison of Head resultant acceleration of 50th percentile pedestrian at Left, Right and Center ends in Side impact

Tibia Acceleration

Femoral and tibial injury is a common injury in pedestrian suffering impacts with vehicles. These injuries are evaluated based on femur and tibia fracture resulting from bending moment of the femur on impact with the hood and the resultant acceleration of tibia [3]. The maximum tolerance level for the Tibia acceleration for a pedestrian is 150g according to EEVC Biomechanical criteria. Table 4.7 and Figure 4.22 indicate the maximum tibia acceleration values obtained by 50th percentile pedestrian for a run of 500ms. Expect for speed 15 kmph, at other all speeds, the values have crossed the tolerance level. Tibia injuries are high indicating fractures at 24 kmph and 27 kmph. Injuries at the left corner have high values when compared with the Center and right corner.

TABLE 4.7

TIBIA RESULTANT ACCELERATION OF 50TH PERCENTILE PEDESTRIAN AT LEFT, RIGHT, AND CENTER ENDS IN SIDE-IMPACT

Speeds(kmph)	Frontal Center Side Impact	Frontal Left-Side Impact	Frontal Right-Side impact
15	127	132	126
18	145	156	142
21	172	187	152
24	186	209	163
27	209	221	189

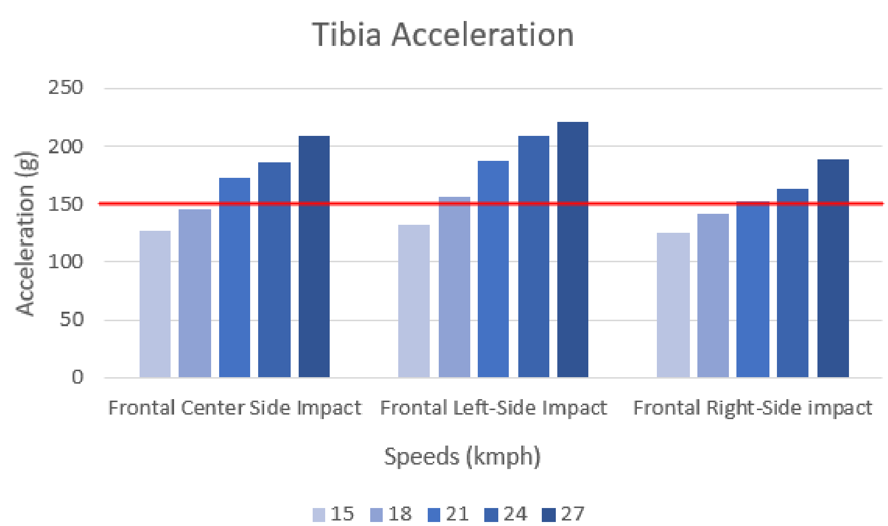


Figure 4.22. Comparison of Tibia resultant acceleration of 50th percentile pedestrian at Left, Right and Center ends in Side impact

Femur Bending Moment

Femoral and tibial injury is a common injury in pedestrian suffering impacts with vehicles. The maximum tolerance level for the Femur bending moment for a pedestrian is 220N.m according to EEVC biomechanical criteria. At all velocities, the value of the tolerance level for forces doesn't exceed the maximum limit. Table 4.8 and Figure 4.23 indicate the maximum femur bending moments for the 50^{th} percentile pedestrian for a run of 500ms. The bending moment at 15 kmph is low and doesn't lead to injury. There are no femur injuries as all values are within the limit.

TABLE 4.8

FEMUR BENDING MOMENTS OF 50TH PERCENTILE PEDESTRIAN AT LEFT, RIGHT, AND CENTER ENDS IN SIDE-IMPACT

Speeds (kmph)	Frontal Center Side Impact	Frontal Left-Side Impact	Frontal Right-Side impact
15	11	6	5
18	35	27	22
21	47	37	31
24	83	78	74
27	104	99	94

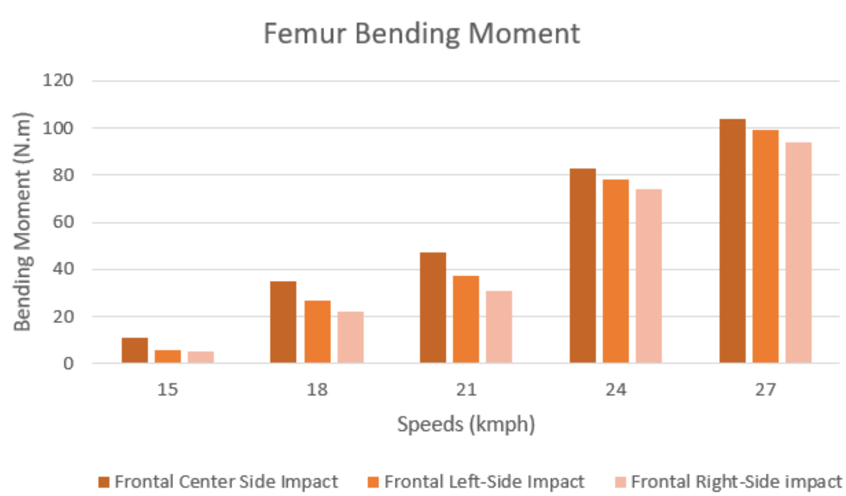


Figure 4.23. Comparison of Femur Bending moments of 50^{th} percentile pedestrian at Left, Right and Center ends in Side impact

Knee Force

The maximum tolerance level for the Knee force for a pedestrian is 2.5 KN according to EEVC biomechanical criteria. Table 4.9 indicates the maximum Knee forces of 50th percentile pedestrian for a run of 500ms. At all velocities, the value of the tolerance level for forces doesn't exceed the maximum limit. At 15 kmph and 18 kmph, the values of forces are least and are negligible at all the locations. As all the values are within the biomechanical limits, there are no knee injuries for the pedestrian.

TABLE 4.9

KNEE FORCES OF 50TH PERCENTILE PEDESTRIAN AT LEFT, RIGHT AND CENTER ENDS IN SIDE-IMPACT

Speeds (kmph)	Frontal Center Side Impact	Frontal Left-Side Impact	Frontal Right-Side impact
15	0.5	0.2	0.3
18	0.8	0.6	0.4
21	1.1	1	0.9
24	1.5	1.2	1.3
27	1.8	1.7	1.6

CHAPTER 5

ANALYSIS OF WAYFARER IN FRONT IMPACT

5.1 Introduction

After the development and selection of the front impact model in MADYMO, the next stage is to perform the simulation analysis and investigate the kinematics of a specific collision with the pickup truck. In this thesis, side, front and rear impacts with the pickup truck were analyzed at different speeds. For every collision type, injuries and their severity were evaluated and compared at different locations. The injury criterion of the pedestrian dummy is based on levels of the European Experimental Vehicles Committee as well as European Passive Safety Network. The analysis section under front impact includes three locations,

- Pedestrian – Truck Front Impact Analysis at Center,
- Pedestrian – Truck Front Impact Analysis at Right Corner,
- Pedestrian – Truck Front Impact Analysis at Left Corner.

Pedestrian front impact (Figure 5.1) was modeled at 5 different pickup truck speeds starting from 15 kmph to 27 kmph with an increment of 3 kmph velocities. The pedestrian dummy model is positioned in a walking posture in front of the truck as per the NHTSA study. A pedestrian is placed at the Center and 0.35m from the center at both left and right corners. The pedestrian is in line, at the Center and Corners and facing towards the truck and colliding from the front. All the pickup truck body parts were picked as master surfaces and the pedestrian body parts were picked as slave surfaces. The coefficient of friction between the slave and master surfaces was taken as

0.5 [4] including the ground surface. Simulations were performed at three locations for a run of 500ms and injuries like Head Injury Criteria, Head resultant acceleration, chest accelerations, forces on upper and lower extremities of pedestrian are evaluated in a front collision.

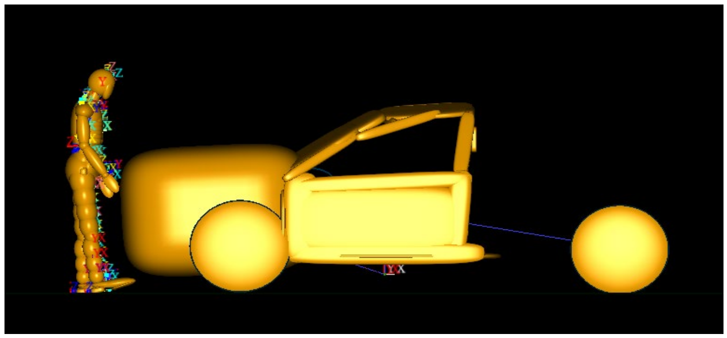


Figure 5.1. Front-impact model of 50th percentile pedestrian and pickup truck model

5.2 Kinematics of 50th Percentile Pedestrian in Pickup Truck Front-Impact at Center

Adult injury risks are evaluated for low and high-speed collisions. The kinematics and tendency of pedestrian injuries are affected by the vehicle's front design, impact speed, and pedestrian height in pedestrian-vehicle collisions. When lightweight pickup trucks like the Chevrolet Silverado, which have a hood height roughly double that of a normal car, strike pedestrians, they cause more injuries, that could lead to death. At the Center, the kinematics of pedestrian in front impact varies for every speed parameter. The primary contact for pedestrian observed in front impact is the truck hood. There are no severe head injuries at 15 kmph. The truck directly strikes the pelvis and chest of the pedestrian in this case. At 18 kmph, head and chest injuries have occurred. At 21 kmph and above, injuries are severe at the head, pelvis, chest, and lower extremities. Kinematics of the 50th percentile pedestrian in pickup truck impact at 15 kmph, 18 kmph, 21 kmph, 24 kmph, and 27 kmph are shown Figures 5.2 through 5.6, respectively.

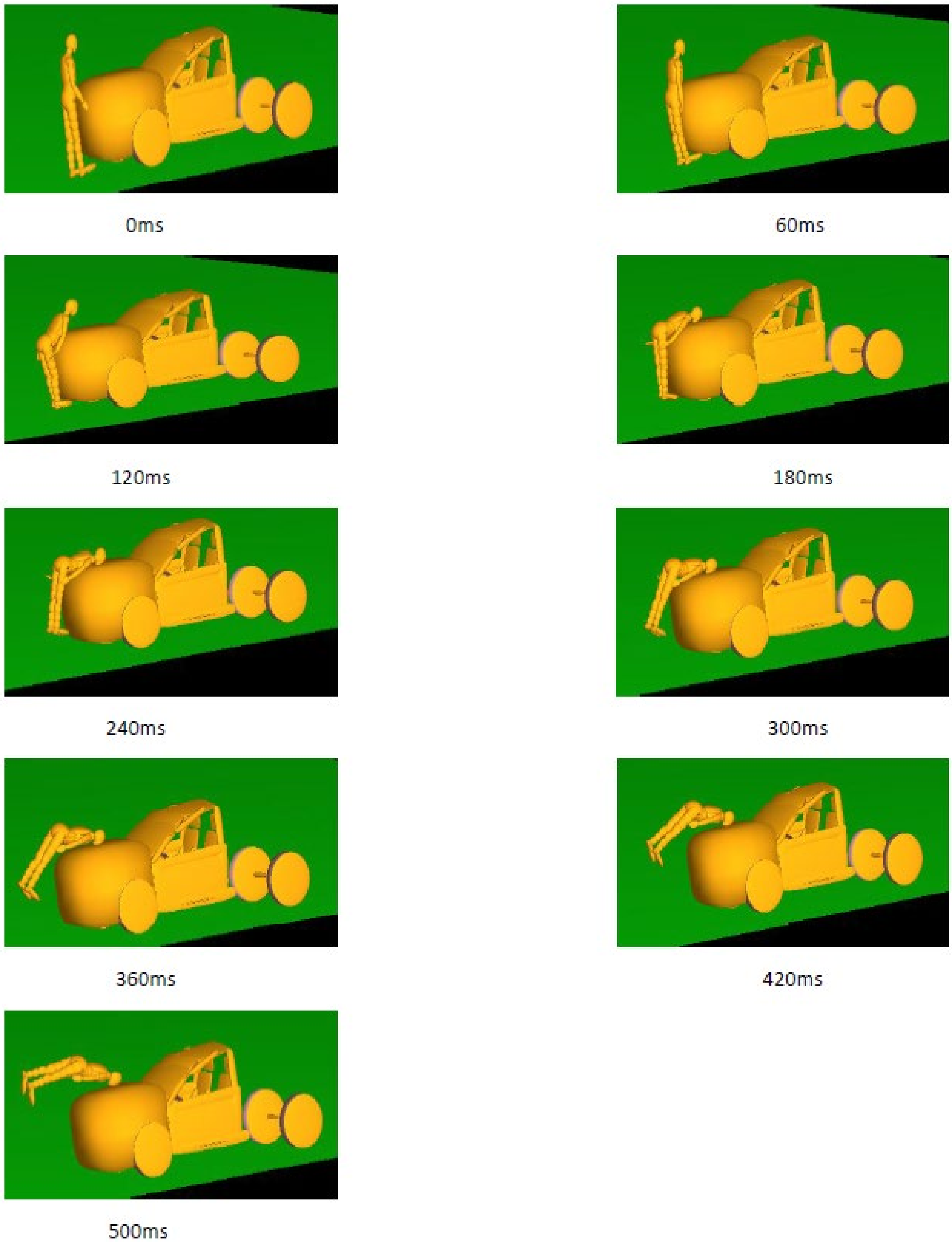


Figure 5.2.Kinematics of the 50th percentile pedestrian in pickup truck Front-impact at 15 kmph at Center

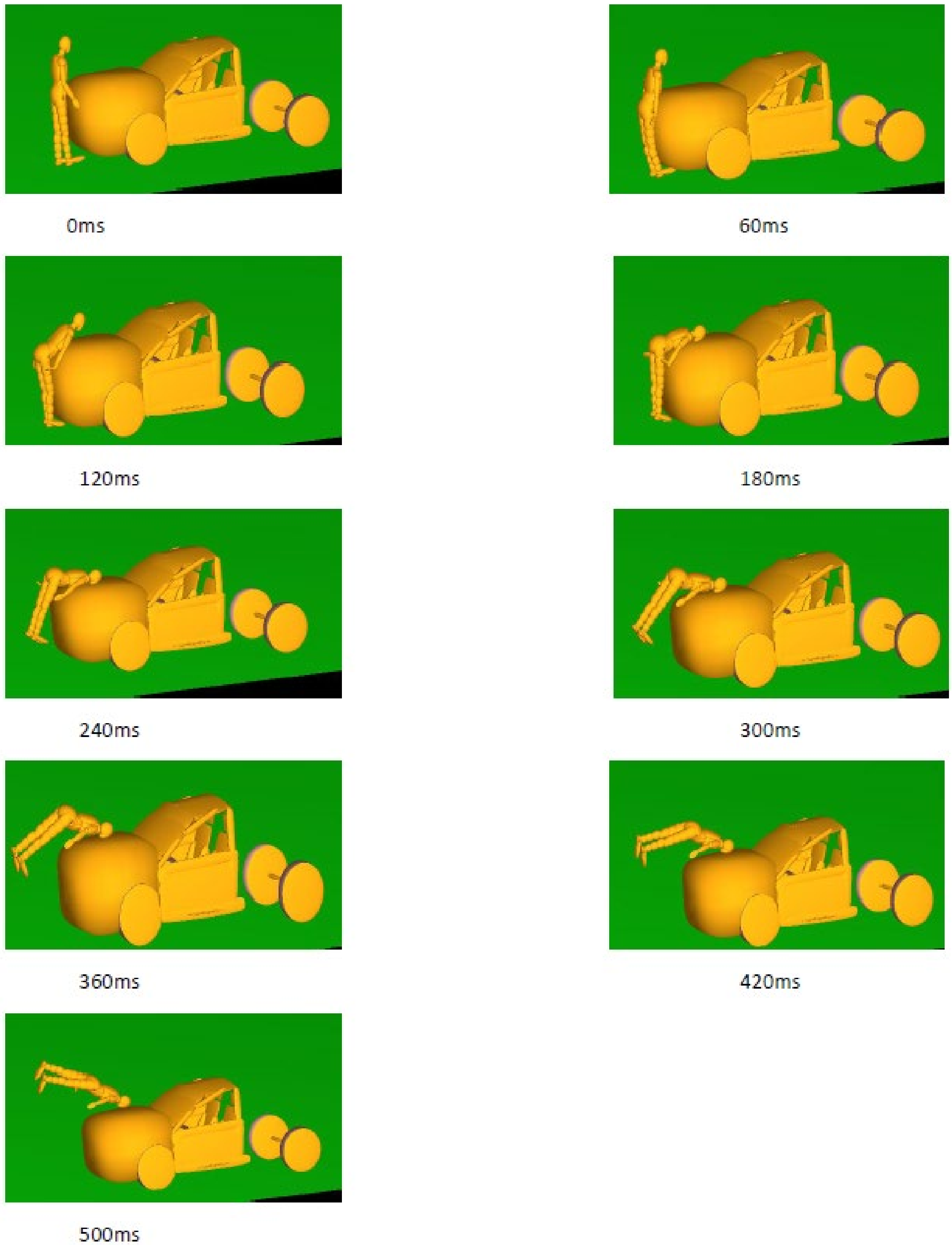


Figure 5.3. Kinematics of the 50th percentile pedestrian in pickup truck Front impact at 18 kmph at Center

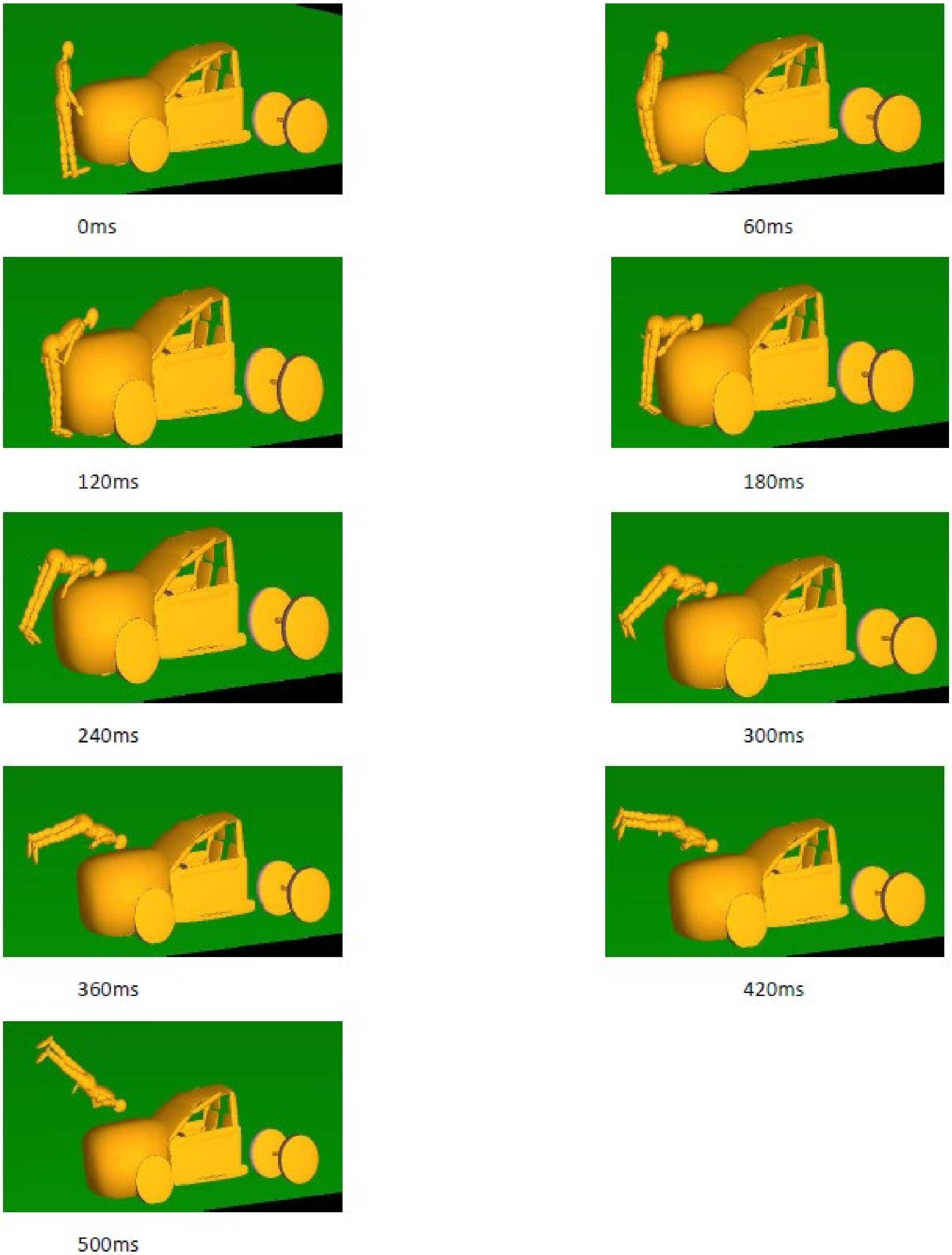


Figure 5.4. Kinematics of the 50th percentile pedestrian in pickup truck Front impact at 21 kmph at Center

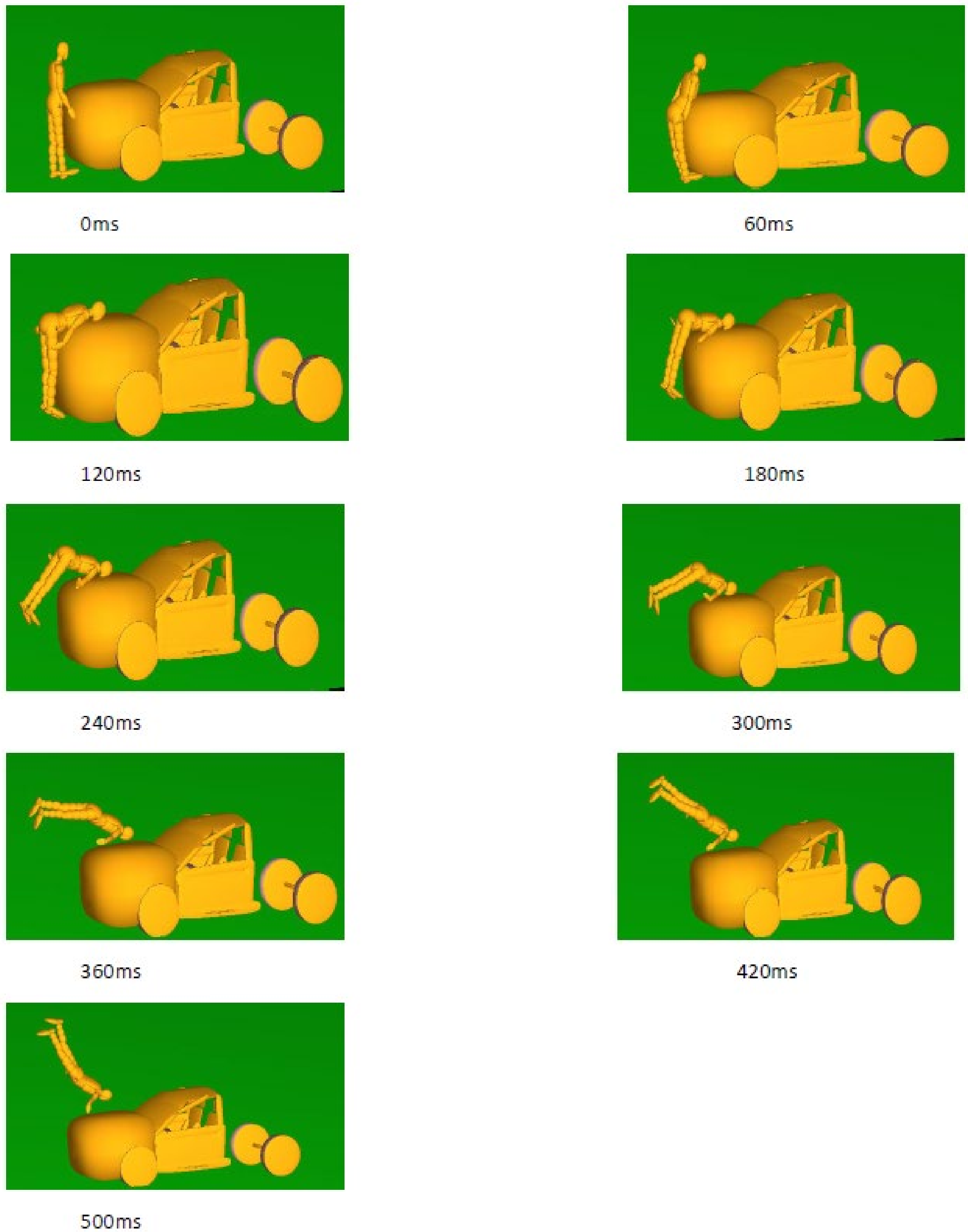


Figure 5.5. Kinematics of the 50th percentile pedestrian in pickup truck Front impact at 24 kmph at Center

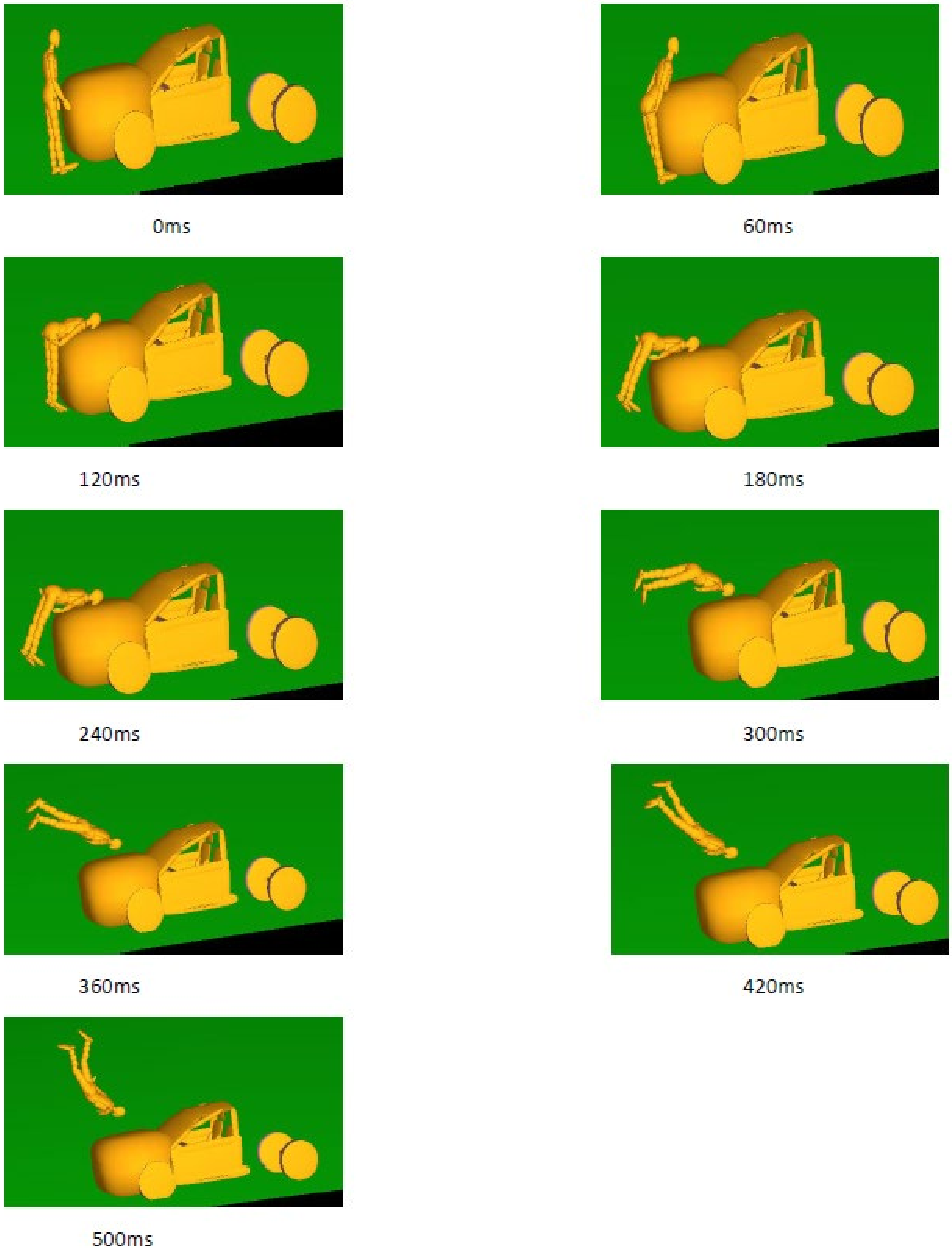


Figure 5.6. Kinematics of the 50th percentile pedestrian in pickup truck Front impact at 27 kmph at Center

5.3 Kinematics of 50th Percentile Pedestrian in Pickup Truck Front-Impact at Right Corner

Adult injury risks are evaluated for low and high-speed collisions. The kinematics and tendency of pedestrian injuries are affected by the vehicle's front design, impact speed, and pedestrian height in pedestrian-vehicle collisions. When lightweight pickup trucks like the Chevrolet Silverado, which have a hood height roughly double that of a normal car, strike pedestrians, they cause more injuries, that could lead to death.

At Right Corner, the kinematics of pedestrian in front impact varies for every speed parameter. All the stiffness values of the hood used are the same applied by Yang in his simulation. The coefficient of friction applied for the pedestrian–pickup truck model is 0.5. Simulations are performed for 5 different speeds (15 kmph, 18 kmph, 21 kmph, 24 kmph, and 27 kmph) at the right corner at 500ms, and injuries are evaluated. The MADYMO 50th percentile pedestrian model is positioned to be walking towards in front end of the truck as mentioned in NHTSA research.

The primary contact for pedestrian observed in front impact is the truck hood. There are no severe head injuries at 15 kmph. The truck directly strikes the pelvis and chest of the pedestrian in this case. At 18 kmph, head and chest injuries have occurred. At 21 kmph and above, injuries are severe at the head, pelvis, chest, and lower extremities

Kinematics of the 50th percentile pedestrian in pickup truck impact at 15 kmph, 18 kmph, 21 kmph, 24 kmph, and 27 kmph are shown in Figures 5.7 through 5.11, respectively.

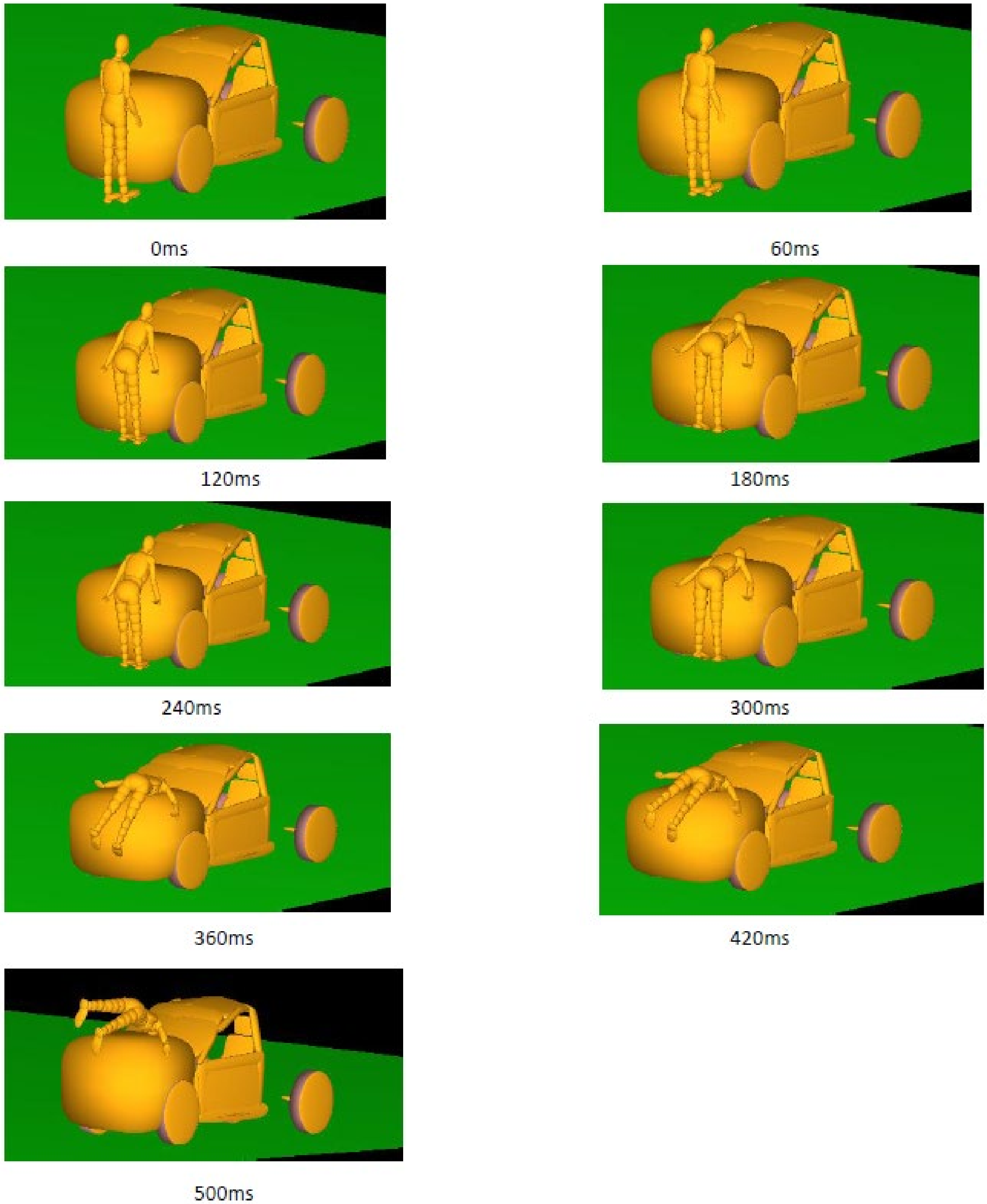


Figure 5.7. Kinematics of the 50th percentile pedestrian in pickup truck Front impact at 15 kmph at Right Corner

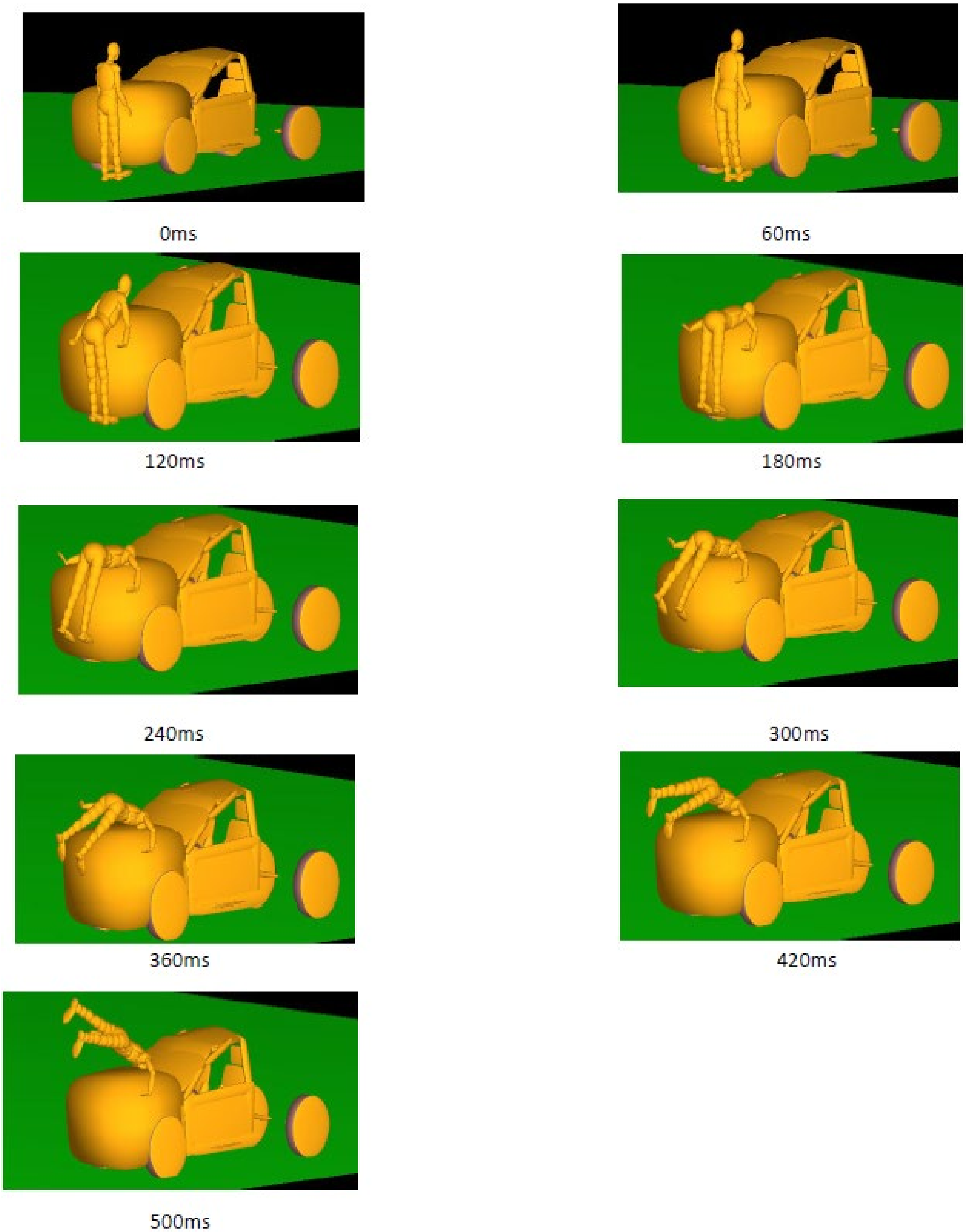


Figure 5.8. Kinematics of the 50th percentile pedestrian in pickup truck Front-impact at 18 kmph at Right Corner

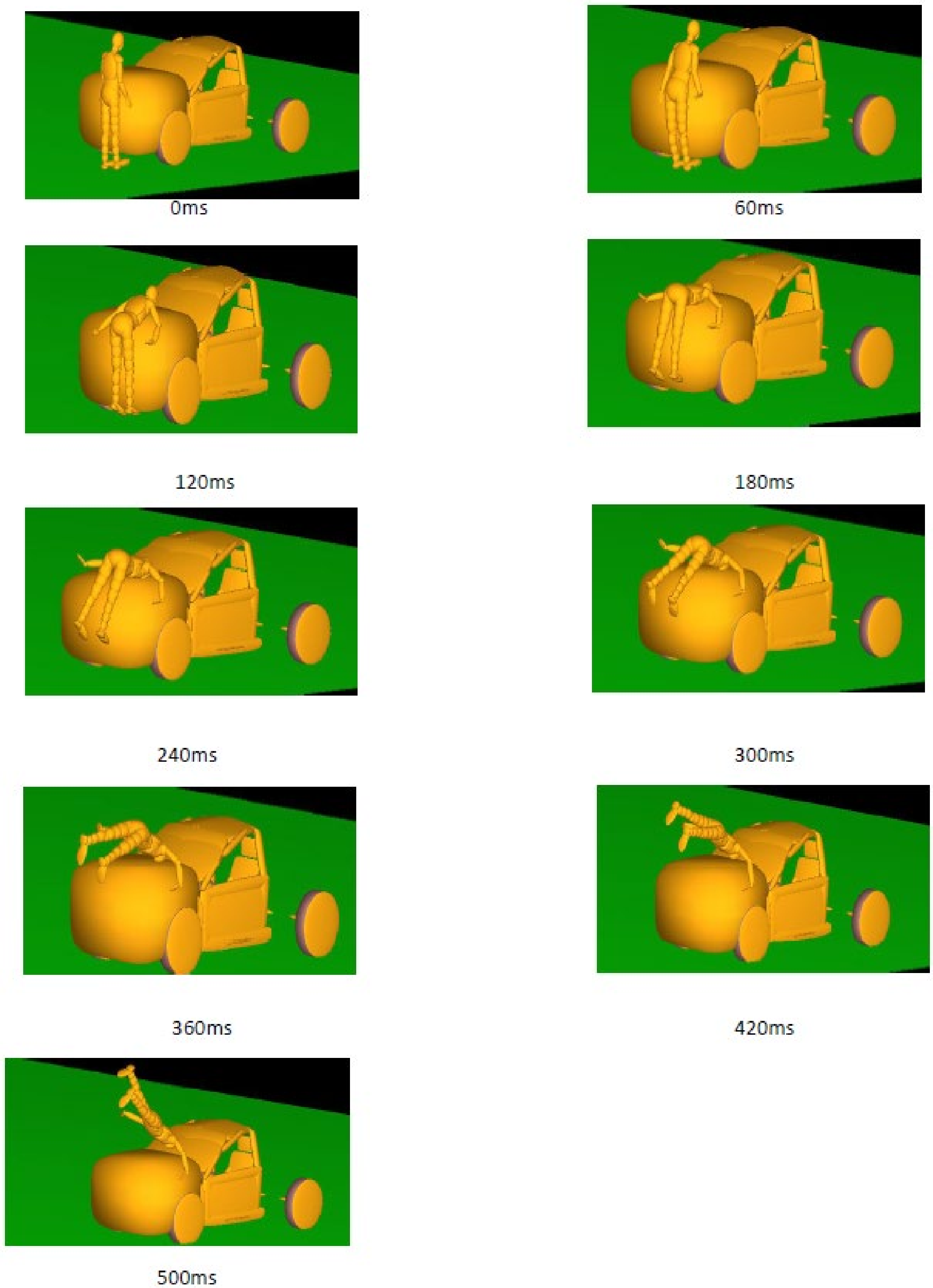


Figure 5.9. Kinematics of the 50th percentile pedestrian in pickup truck Front impact at 21 kmph at Right Corner

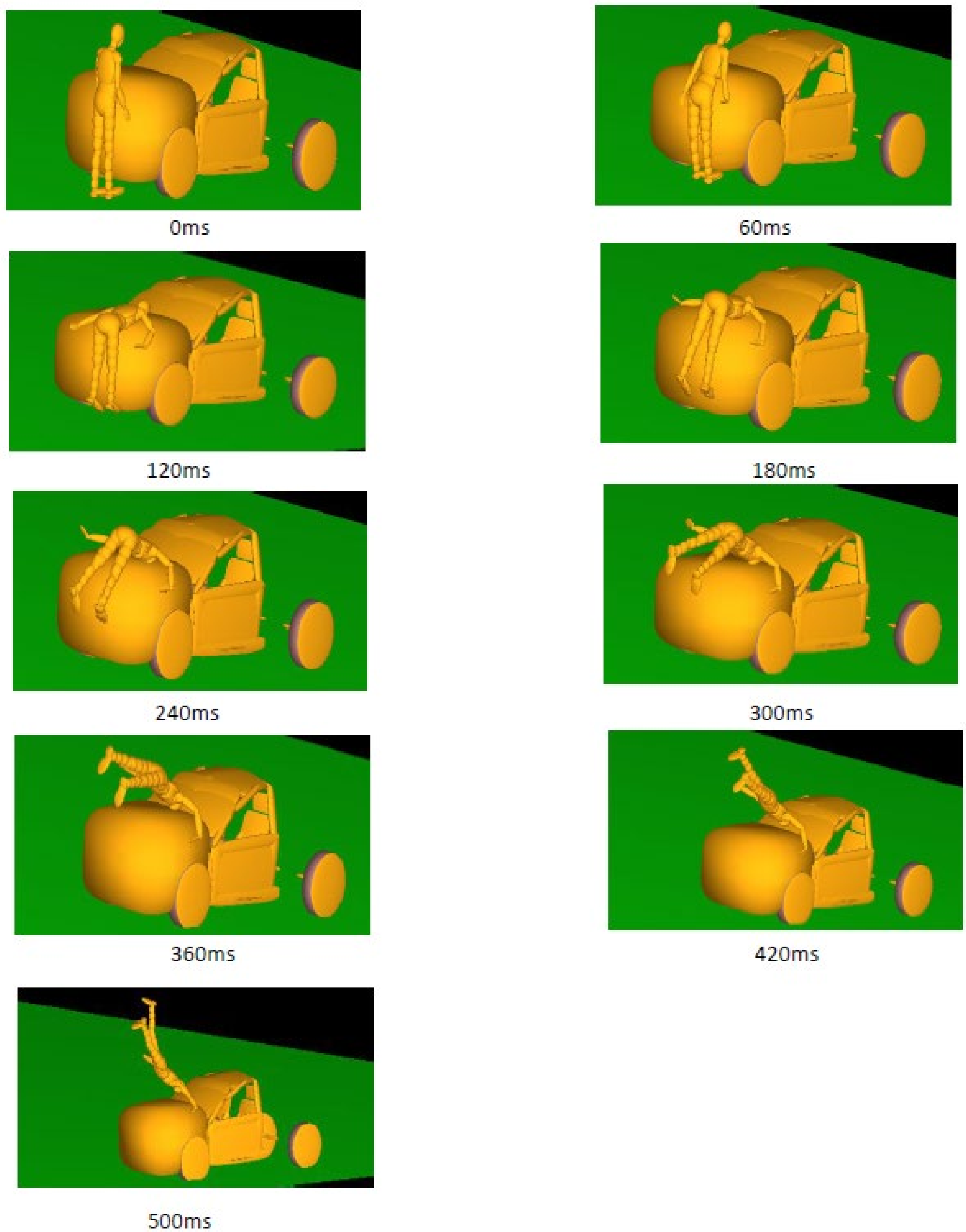


Figure 5.10. Kinematics of the 50th percentile pedestrian in pickup truck Front impact at 24 kmph at Right Corner

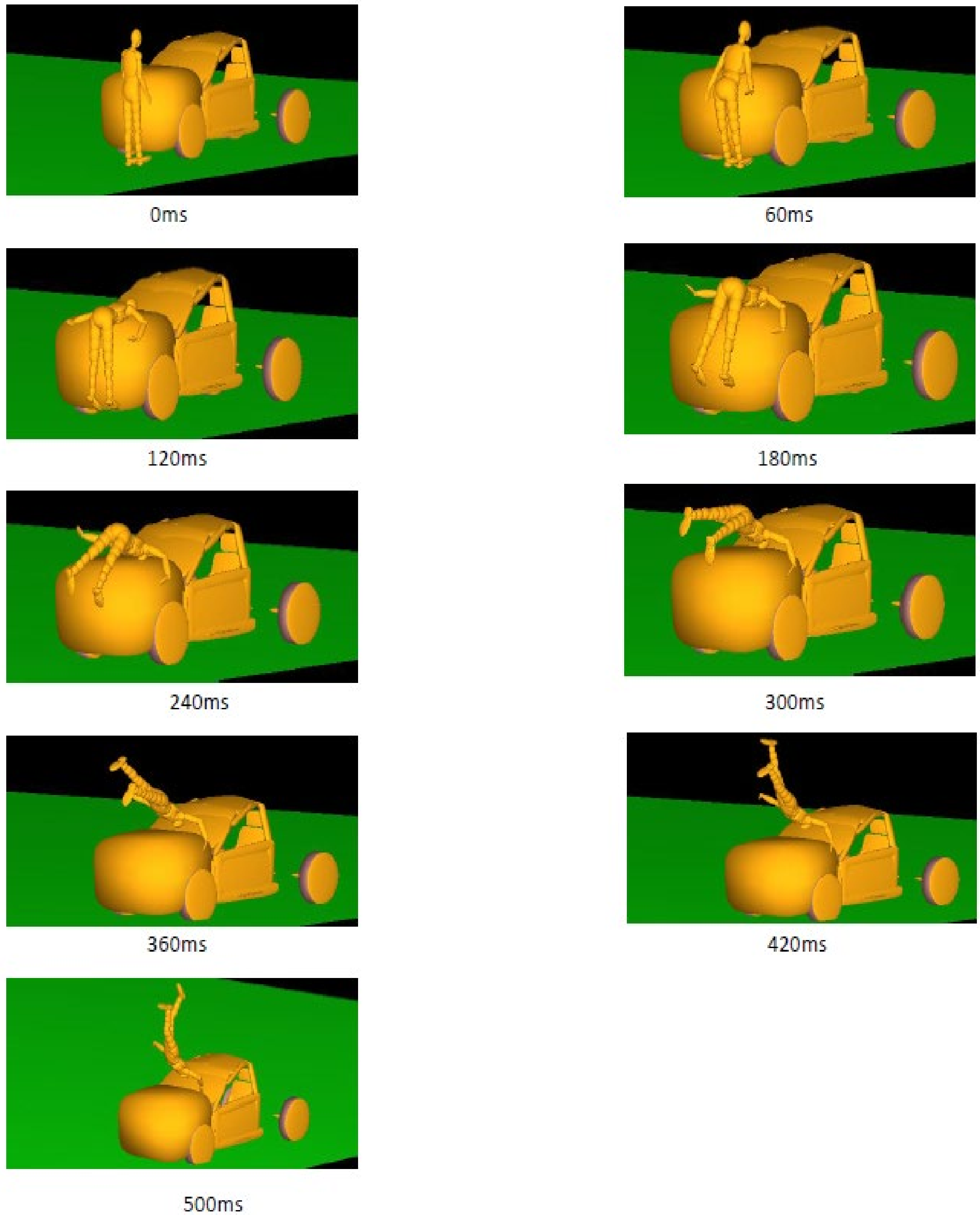


Figure 5.11. Kinematics of the 50th percentile pedestrian in pickup truck Front impact at 27 kmph at Right Corner

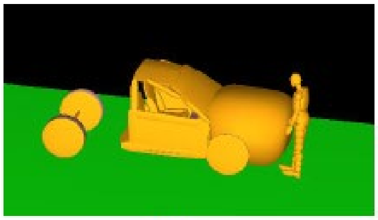
5.4 Kinematics of 50^{th} Percentile Pedestrian in Pickup Truck Front-Impact at Left Corner

Adult injury risks are evaluated for low and high-speed collisions. The kinematics and tendency of pedestrian injuries are affected by the vehicle's front design, impact speed, and pedestrian height in pedestrian-vehicle collisions. When lightweight pickup trucks like the Chevrolet Silverado, which have a hood height roughly double that of a normal car, strike pedestrians, they cause more injuries, that could lead to death.

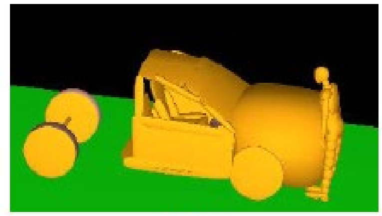
At the left corner, the kinematics of pedestrian in front impact varies for every speed parameter. At Right Corner, the kinematics of pedestrian in front impact varies for every speed parameter. All the stiffness values of the hood used were the same applied by Yang in his simulation. The coefficient of friction applied for the pedestrian–pickup truck model is 0.5. Simulations are performed for 5 different speeds (15 kmph, 18 kmph, 21 kmph, 24 kmph, and 27 kmph) at the left corner at 500ms, and injuries are evaluated. The MADYMO 50th percentile pedestrian model is positioned to be walking towards in front end of the truck as mentioned in NHTSA research.

The primary contact for pedestrian observed in front impact is the truck hood. There are no severe head injuries at 15 kmph. The truck directly strikes the pelvis and chest of the pedestrian in this case. At 18 kmph, head and chest injuries have occurred. At 21 kmph and above, injuries are severe at the head, pelvis, chest, and lower extremities.

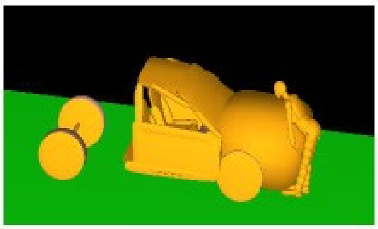
Kinematics of the 50^{th} percentile pedestrian in pickup truck impact at 15 kmph, 18 kmph, 21 kmph, 24 kmph, and 27 kmph are shown in Figures 5.12 through 5.16, respectively.



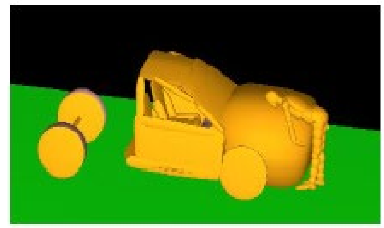
0ms



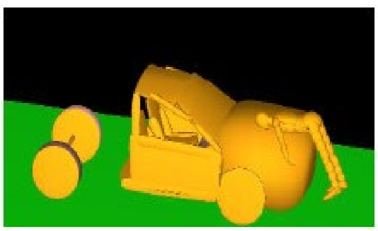
60ms



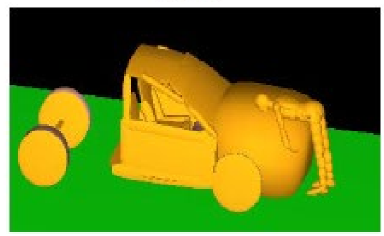
120ms



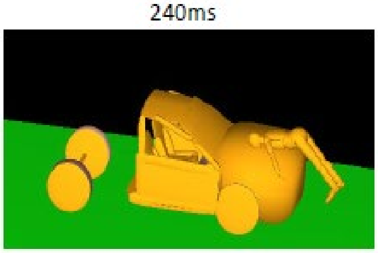
180ms



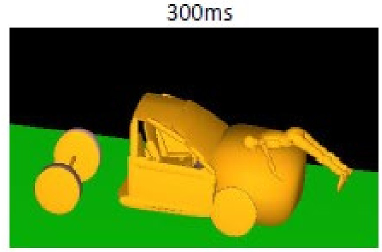
240ms



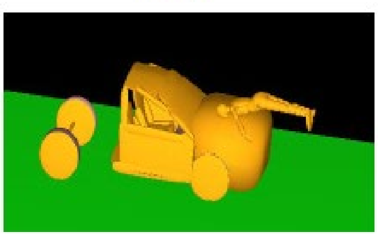
300ms



360ms



420ms



500ms

Figure 5.12. Kinematics of the 50th percentile pedestrian in pickup truck Front impact at 15 kmph at Left Corner

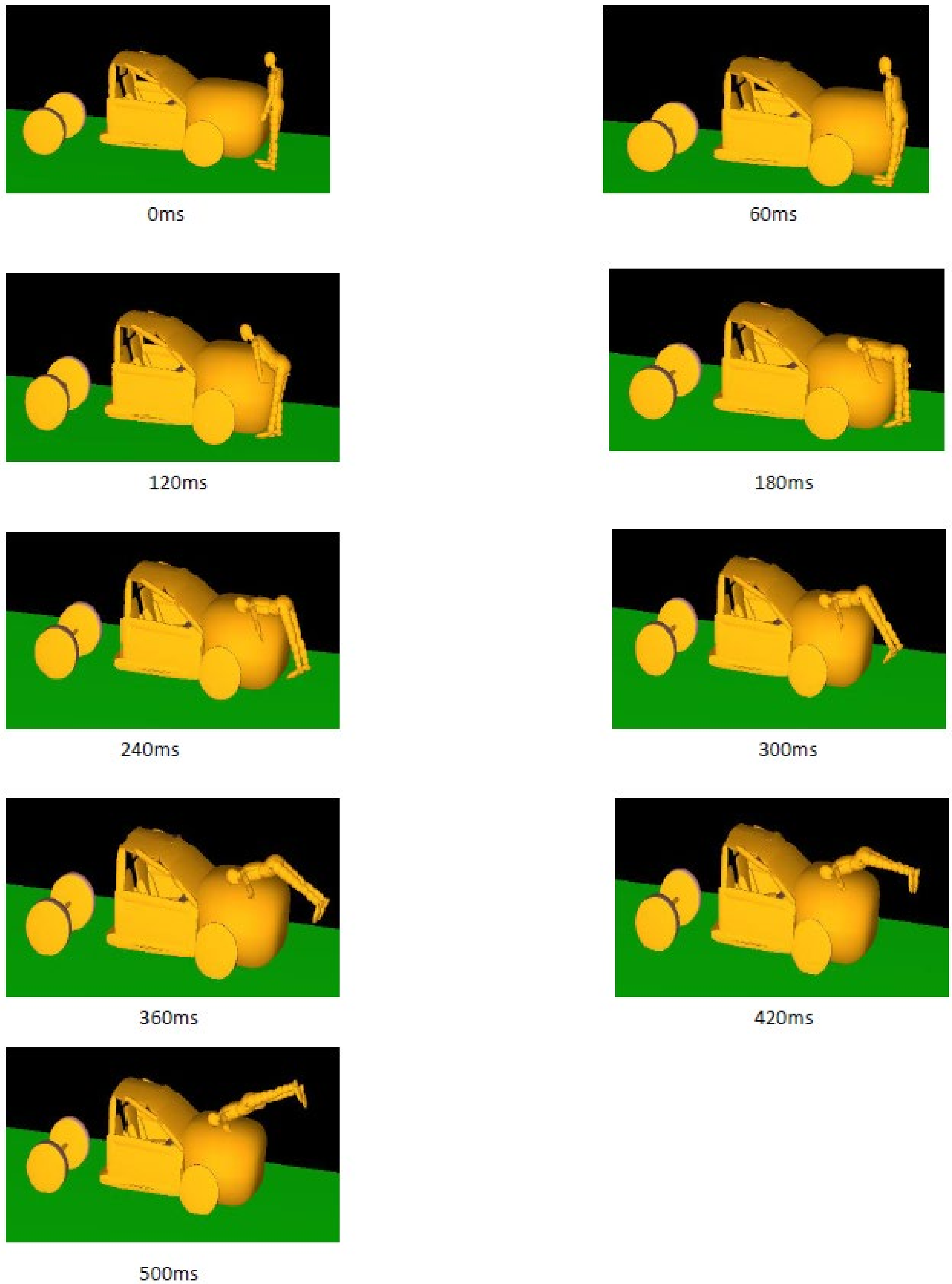


Figure 5.13. Kinematics of the 50th percentile pedestrian in pickup truck Front impact at 18 kmph at Left Corner

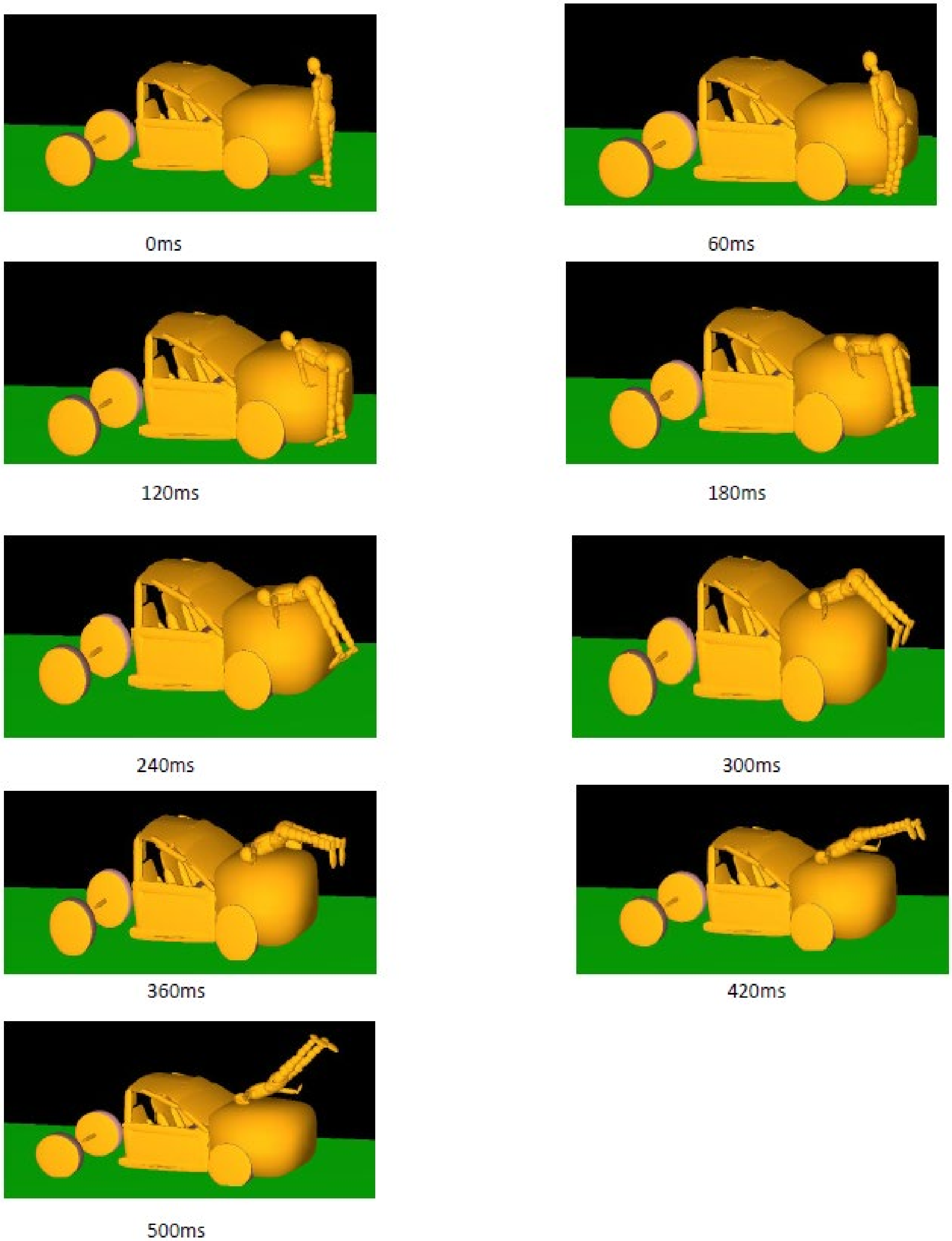


Figure 5.14. Kinematics of the 50th percentile pedestrian in pickup truck Front impact at 21 kmph at Left Corner

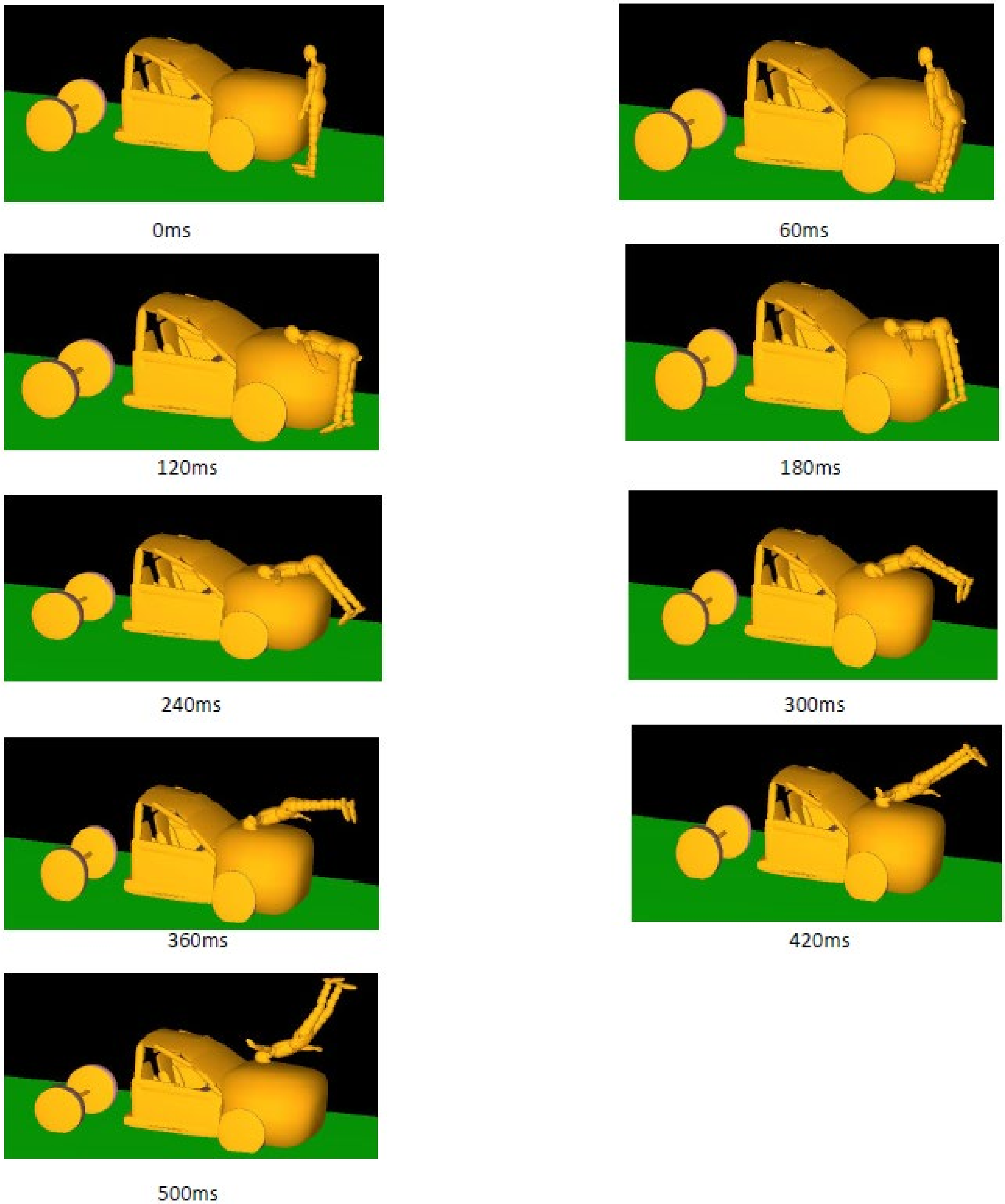


Figure 5.15. Kinematics of the 50th percentile pedestrian in pickup truck Front impact at 24 kmph at Left Corner

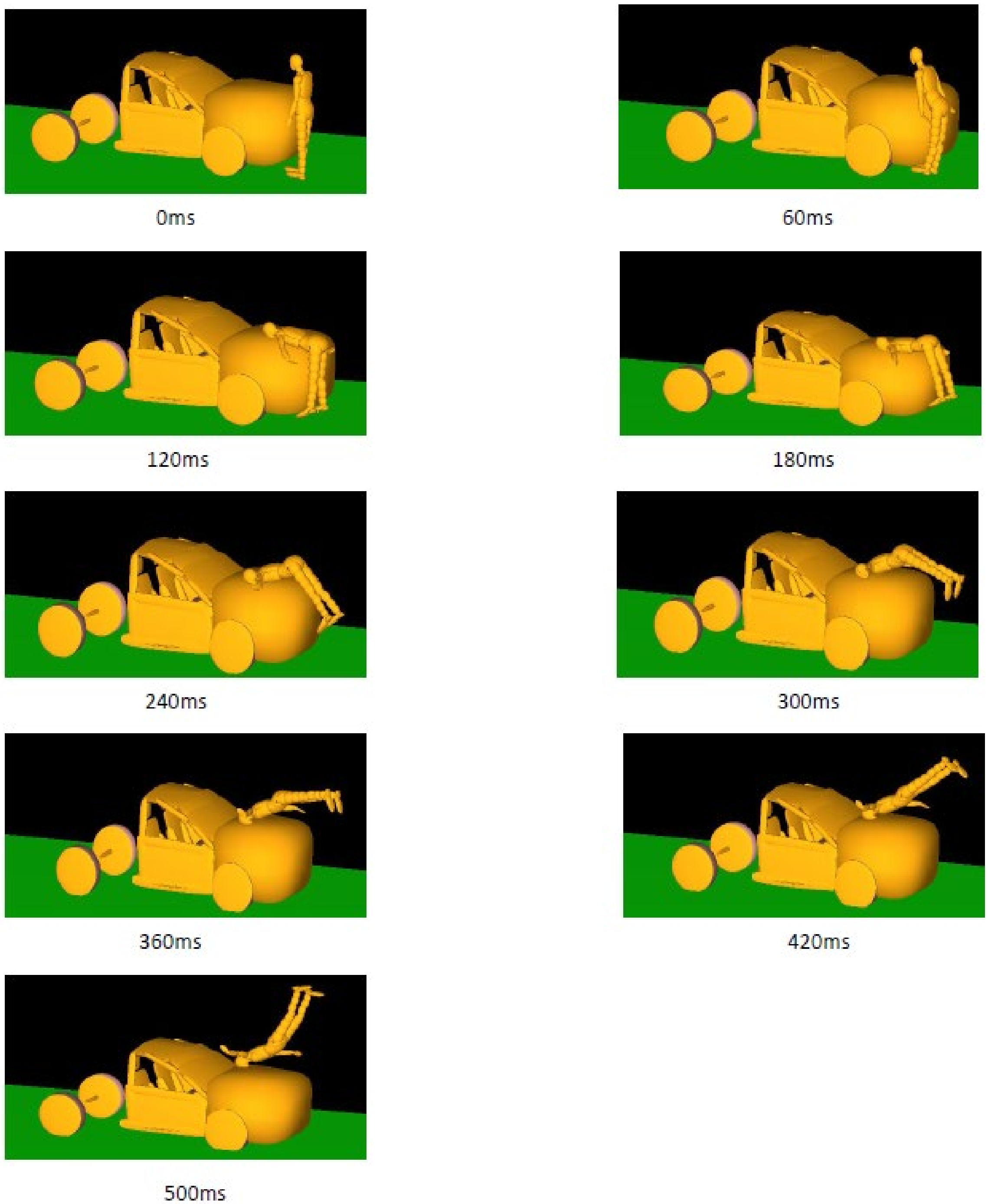


Figure 5.16. Kinematics of the 50th percentile pedestrian in pickup truck Front impact at 27 kmph at Left Corner

5.5 Comparison of Kinematic Behavior of 50th Percentile Pedestrian in Pickup Truck Front-Impact at Three Locations

From the kinematic analysis of 50th percentile pedestrian in front impact, it is observed that injuries are severe at the right end when compared to the center and left end. In front impact, the truck hood directly strikes at the center of pelvis and chest of pedestrian from the front. At the Center, the pedestrian initially strikes the hood and lands in front of the truck at low speeds, and at higher speeds the pedestrian lands away from the truck with high projection. At the left corner, the pedestrian lands in front of the hood initially and later on with increasing speed lands behind the truck with high projection. At the right corner, the pedestrian initially strikes the hood and lands at a distance far away from the truck, and with increasing speed, the pedestrian lands at a distance besides the truck with increased projection trajectory. In this case, the secondary impact observed is at the ground plane. Injury forces and accelerations are more critical and lead to fatality. In this impact, the chest, head, and lower extremity accelerations are more, and the severity of injuries is high.

5.6 Comparison of Injuries to 50th Percentile Pedestrian in Pickup Truck Front Impact

Responses of front pedestrian – pickup truck impact are compared to understand the dynamic performance and injuries at different locations at various speeds.

Head Injury Criteria (HIC)

Table 5.1 and Figure 5.17 show the maximum values obtained for 50th percentile pedestrian at three locations for a run of 500ms. Severe head injury obtained is for the 50th P pedestrian at 27 kmph on the right side. At 27 kmph, for rear impact at both ends, the biomechanical limits ((HIC-36 < 1000, HIC-15 < 700) exceed almost 7-8 times and are fatal. The 50th P pedestrian is at higher risk after 18 kmph and above in rear impacts and might be fatal. The maximum AIS scale rating is 6, leading to mass destruction of both skull and brain as shown in Table 5.2. Except for minimum speed, the injuries that occurred are complex fractures on the face, greater penetration of the brain, damage to the trunk, and mass destruction of the head. On comparing, injuries at the center are severe than injuries at left and right corners.

TABLE 5.1

HEAD INJURY CRITERIA OF 50TH PERCENTILE PEDESTRIAN AT LEFT, RIGHT, AND CENTER ENDS IN FRONT IMPACT

Speeds (kmph)	Frontal Center Front impact	ΔT (ms)	Frontal Left-Front impact	ΔT (ms)	Frontal Right-Front impact	ΔT (ms)
15	1644	2.4	1280	2.9	1565	1.8
18	2781	2.1	2164	2.5	2641	2.3
21	4465	2.9	3476	2.6	4164	2.6
24	6892	2.5	5538	2.3	6762	2.9
27	8934	2.3	7095	2.5	8618	2.8

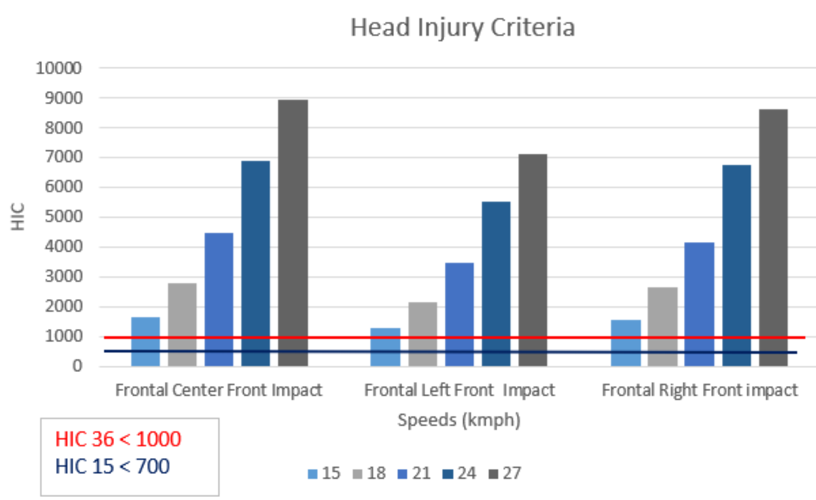


Figure 5.17. Comparison of Head Injury Criteria of 50th percentile pedestrian at Left, Right and Center ends in Front impact

TABLE 5.2

AIS RATING FOR HEAD INJURY IN FRONT IMPACT

Speeds(kmph)	Front Impact
15	3
18	4
21	5
24	6
27	6

Head Acceleration

The maximum Head acceleration should be 80g for a pedestrian to be safe according to EEVC biomechanical criteria. The head acceleration values increase with the increase in the impact speed when the strength of the lightweight pickup truck is high. The head of the pedestrian is the initial body part that is injured in an impact and its severity is based on the impact speed and strength of the truck. Table 5.3 and Figure 5.18 show the maximum Head acceleration values obtained by 50th percentile pedestrian for a run of 500ms.

At three locations, for 50th P Pedestrian, the values are above biomechanical limits for all the velocities. At 18 Kmph and above, the head accelerations are almost 4-5 times greater than the actual value and are fatal.

At 27 kmph on both sides, the value is higher of 1184g, and the pedestrian would have an AIS 6+ injury (mass destruction of both skull and brain). Injuries at the right location are severe than injuries at the center and left locations.

TABLE 5.3

HEAD RESULTANT ACCELERATION OF 50TH PERCENTILE PEDESTRIAN AT LEFT, RIGHT AND CENTER ENDS IN FRONT IMPACT

Speeds(kmph)	Frontal Center Front Impact	Frontal Left Front Impact	Frontal Right Front impact
15	216	201	238
18	379	334	424
21	624	578	697
24	802	712	949
27	1078	1010	1184

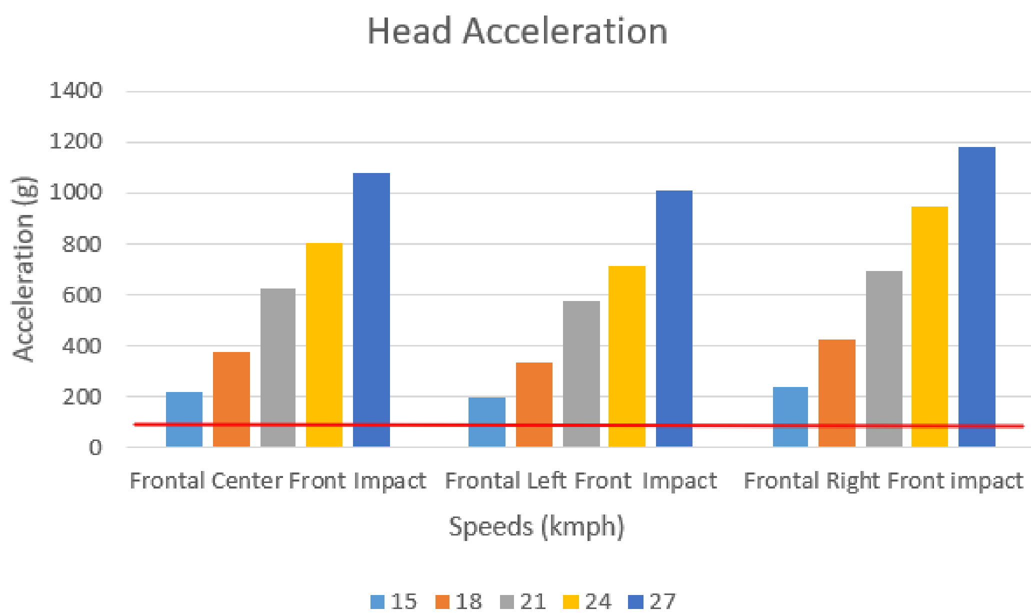


Figure 5.18. Comparison of Head resultant acceleration of 50th percentile pedestrian at Left, Right and Center ends in Front impact

Head Impact locations on Hood

Figure 5.19 shows the initial head impact locations on the hood obtained in a pedestrian front impact.

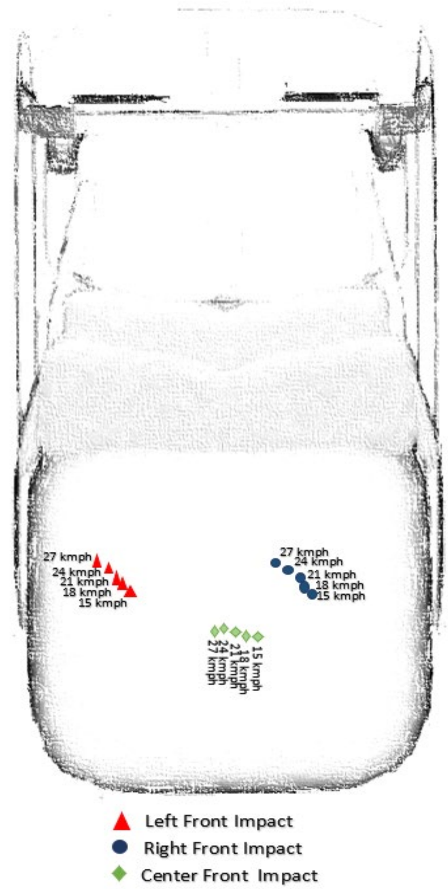


Figure 5.19. Head impact locations of 50th percentile pedestrian model on the truck hood in Front impact

<u>3ms Torso Up Acceleration</u>

The maximum 3ms torso up acceleration should be 60g for a pedestrian to be safe according to EEVC biomechanical criteria. Table 5.4 and Figure 5.20 show the maximum Torso Up acceleration values obtained by 50th percentile pedestrian for a run of 500ms. At all the velocities, the Torso injuries have exceeded the biomechanical limits. At 27 kmph, the value is almost 5-6 times greater than the maximum torso acceleration. As all the values are above the tolerance levels, severe fractures are observed for the pedestrian at the chest.

TABLE 5.4

3MS TORSO-UP ACCELERATION OF 50TH PERCENTILE PEDESTRIAN AT LEFT, RIGHT AND CENTER ENDS IN FRONT IMPACT

Speeds(kmph)	Frontal Center Front Impact	Frontal Left Front Impact	Frontal Right Front impact
15	102	84	117
18	154	132	174
21	207	183	222
24	248	226	270
27	325	301	344

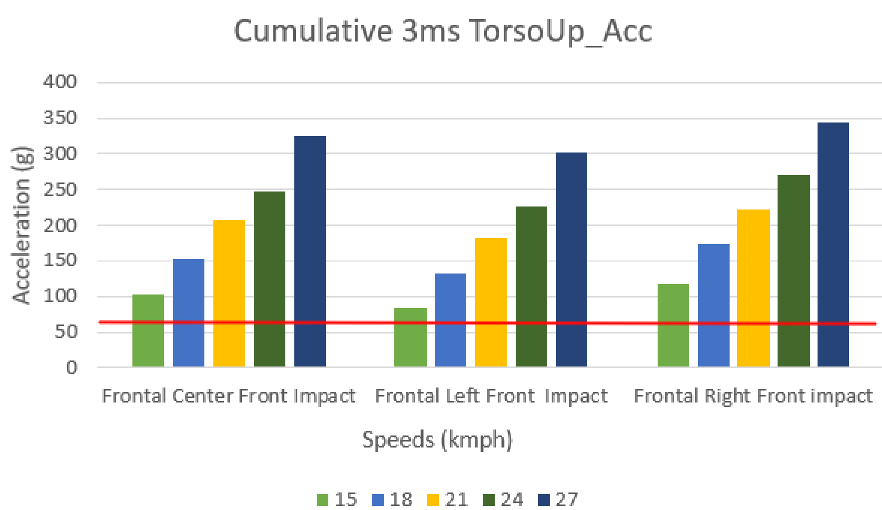


Figure 5.20. Comparison of 3ms Torso-Up acceleration of 50th percentile pedestrian at Left, Right and Center ends in Front impact

Tibia Acceleration

Femoral and tibial injury is a common injury in pedestrian suffering impacts with vehicles. These injuries are evaluated based on femur and tibia fracture resulting from bending moment of the femur on impact with the hood and the resultant acceleration of tibia [3]. The maximum tolerance level for the tibia acceleration for a pedestrian is 150g according to EEVC biomechanical criteria. Table 5.5 and Figure 5.21 show the maximum tibia acceleration values obtained by 50th percentile pedestrian for a run of 500ms. For all velocities, the values exceeded the maximum tolerance level, indicating potential tibia injuries.

TABLE 5.5

TIBIA RESULTANT ACCELERATION OF 50TH PERCENTILE PEDESTRIAN AT LEFT, RIGHT AND CENTER ENDS IN FRONT IMPACT

Speeds(kmph)	Frontal Center Front Impact	Frontal Left Front Impact	Frontal Right Front impact
15	192	186	190
18	213	206	202
21	241	224	232
24	280	266	279
27	309	295	304

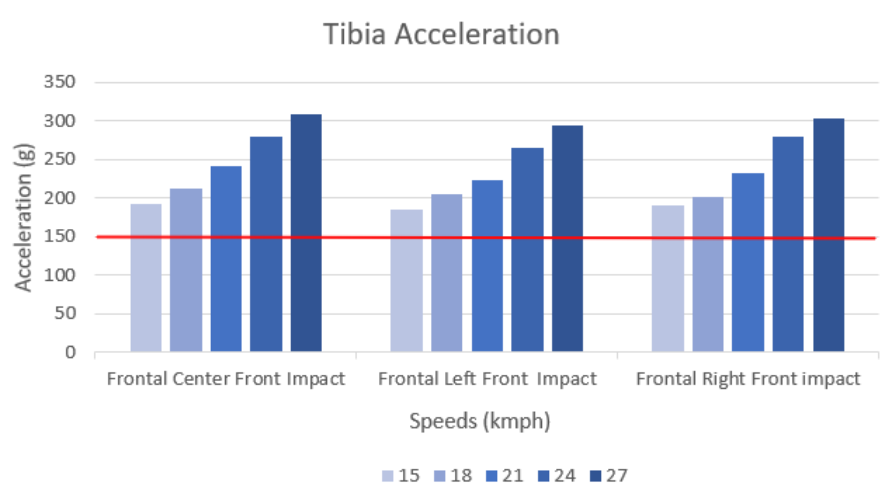


Figure 5.21. Comparison of Tibia resultant acceleration of 50th percentile pedestrian at Left, Right and Center ends in Front impact

Femur Bending Moment

Femoral and tibial injury is a common injury in pedestrian suffering impacts with vehicles. The maximum tolerance level for the Femur bending moment for a pedestrian is 220N.m according to EEVC biomechanical criteria. Table 5.6 and Figure 5.22 indicate the maximum femur bending moments for the 50th percentile pedestrian for a run of 500ms. Until 21 kmph, the bending moment for 50th P pedestrian are within the biomechanical limit. For velocities above 21 kmph, the values of forces are 1-2 times greater than the maximum tolerance limit. At 27 kmph, the bending moment for the 50th P pedestrian is very severe and might suffer multiple fractures. When comparing at locations, femur injuries at the right location are more than center and left locations.

TABLE 5.6

FEMUR BENDING MOMENTS OF 50TH PERCENTILE PEDESTRIAN AT LEFT, RIGHT AND CENTER ENDS IN FRONT IMPACT

Speeds(kmph)	Frontal Center Front Impact	Frontal Left Front Impact	Frontal Right Front impact
15	104	95	111
18	161	155	172
21	218	210	245
24	271	267	276
27	301	292	315

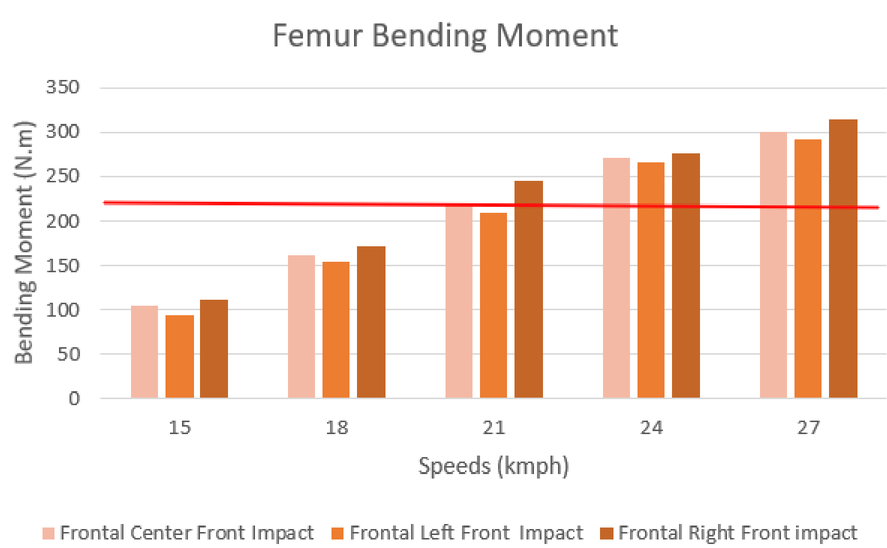


Figure 5.22. Comparison of Femur Bending moments of 50th percentile pedestrian at Left, Right and Center ends in Front impact

Knee Force

The maximum tolerance level for the Knee force for a pedestrian is 2.5 KN according to EEVC biomechanical criteria. Table 5.7, below indicates the maximum Knee forces of 50th percentile pedestrian for a run of 500ms. Until 15 kmph, the knee forces for the 50th P Hybrid male pedestrian are within the biomechanical limit. For velocities above 21 kmph, the values of forces are 2-3 times greater than the maximum tolerance limit. At 27 kmph, the tolerance level for the 50th P Hybrid male dummy is very severe and is amputated. Comparing knee injuries at three locations, injuries at the right end are high than the Center and Left end.

TABLE 5.7

KNEE FORCES OF 50TH PERCENTILE PEDESTRIAN AT LEFT, RIGHT AND CENTER ENDS IN FRONT IMPACT

Speeds(kmph)	Frontal Center Front Impact	Frontal Left Front Impact	Frontal Right Front impact
15	1.4	1.3	1.5
18	3.5	3.3	3.9
21	4.4	3.8	5.1
24	6.2	5.7	7.1
27	8.3	8.5	8.8

CHAPTER 6

ANALYSIS OF WAYFARER IN REAR IMPACT

6.1 Introduction

After the development and selection of the Rear impact model in MADYMO, the next stage is to perform the simulation analysis and investigate the kinematics of a specific collision with the pickup truck. In this thesis, side, front and rear impacts with the pickup truck were analyzed at different speeds. For every collision type, injuries and their severity were evaluated and compared at different locations. The injury criterion of the pedestrian dummy is based on levels of the European Experimental Vehicles Committee as well as European Passive Safety Network. The analysis section under front impact includes three locations,

- Pedestrian – Truck Rear Impact Analysis at Center,
- Pedestrian – Truck Rear Impact Analysis at Right Corner,
- Pedestrian – Truck Rear Impact Analysis at Left Corner.

Pedestrian Rear impacts (Figure 6.1) were modeled at 5 different pickup truck speeds starting from 15 kmph to 27 kmph with an increment of 3 kmph velocities. The pedestrian dummy model is positioned in a walking posture in front of the truck as per the NHTSA study. A pedestrian is placed at the Center and 0.35m from the center at both left and right corners. In line, at the Center and Corners and facing away of the truck and colliding from the rear of the pedestrian. All the pickup truck body parts were picked as master surfaces and the pedestrian body parts were picked as slave surfaces. The coefficient of friction between the slave and master surfaces was taken as

0.5 [4] including the ground surface. Simulations were performed at three locations for 500ms and injuries like Head Injury Criteria, Head resultant acceleration, chest accelerations, forces on upper and lower extremities of pedestrian are evaluated in a rear collision.

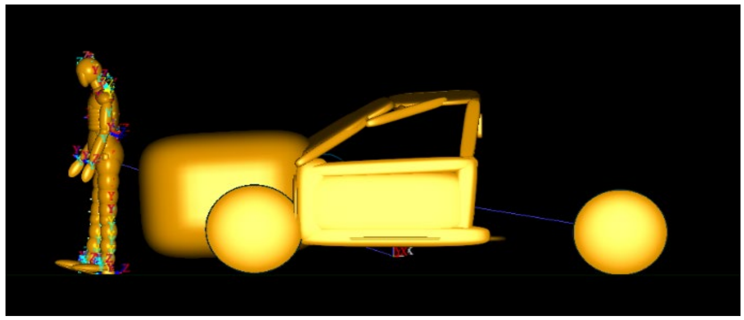


Figure 6.1. Rear impact model of 50th percentile pedestrian and pickup truck model

6.2 Kinematics of 50th Percentile Pedestrian in Pickup Truck Rear Impact at Center

Adult injury risks are evaluated for low and high-speed collisions. The kinematics and tendency of pedestrian injuries are affected by the vehicle's front design, impact speed, and pedestrian height in pedestrian-vehicle collisions. When lightweight pickup trucks like the Chevrolet Silverado, which have a hood height roughly double that of a normal car, strike pedestrians, they cause more injuries, that could lead to death. At the Center, the kinematics of pedestrian in rear impact varies for every speed parameter. The primary contact for pedestrian observed in rear impact is the truck hood. There are severe head injuries at 15 kmph. The truck directly strikes the pelvis and chest of the pedestrian in this case. At 18 kmph, head and chest injuries occur. At 21 kmph and above, injuries are severe at the head, pelvis, chest, and lower extremities. Kinematics of the 50th percentile pedestrian in pickup truck impact at 15 kmph, 18 kmph, 21 kmph, 24 kmph, and 27 kmph are shown in Figures 6.2 through 6.6, respectively.

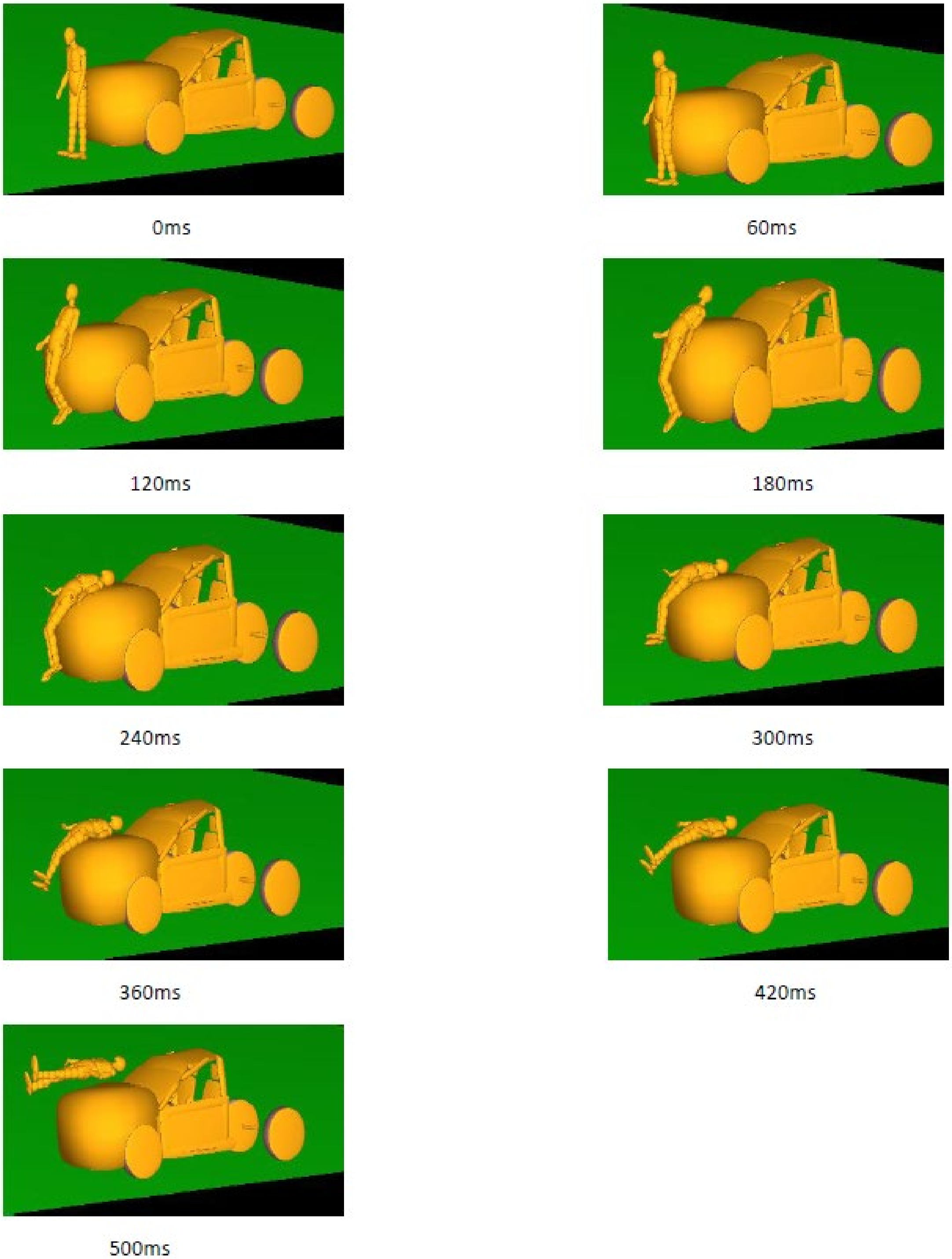


Figure 6.2. Kinematics of the 50th percentile pedestrian in pickup truck Rear impact at 15 kmph at Center

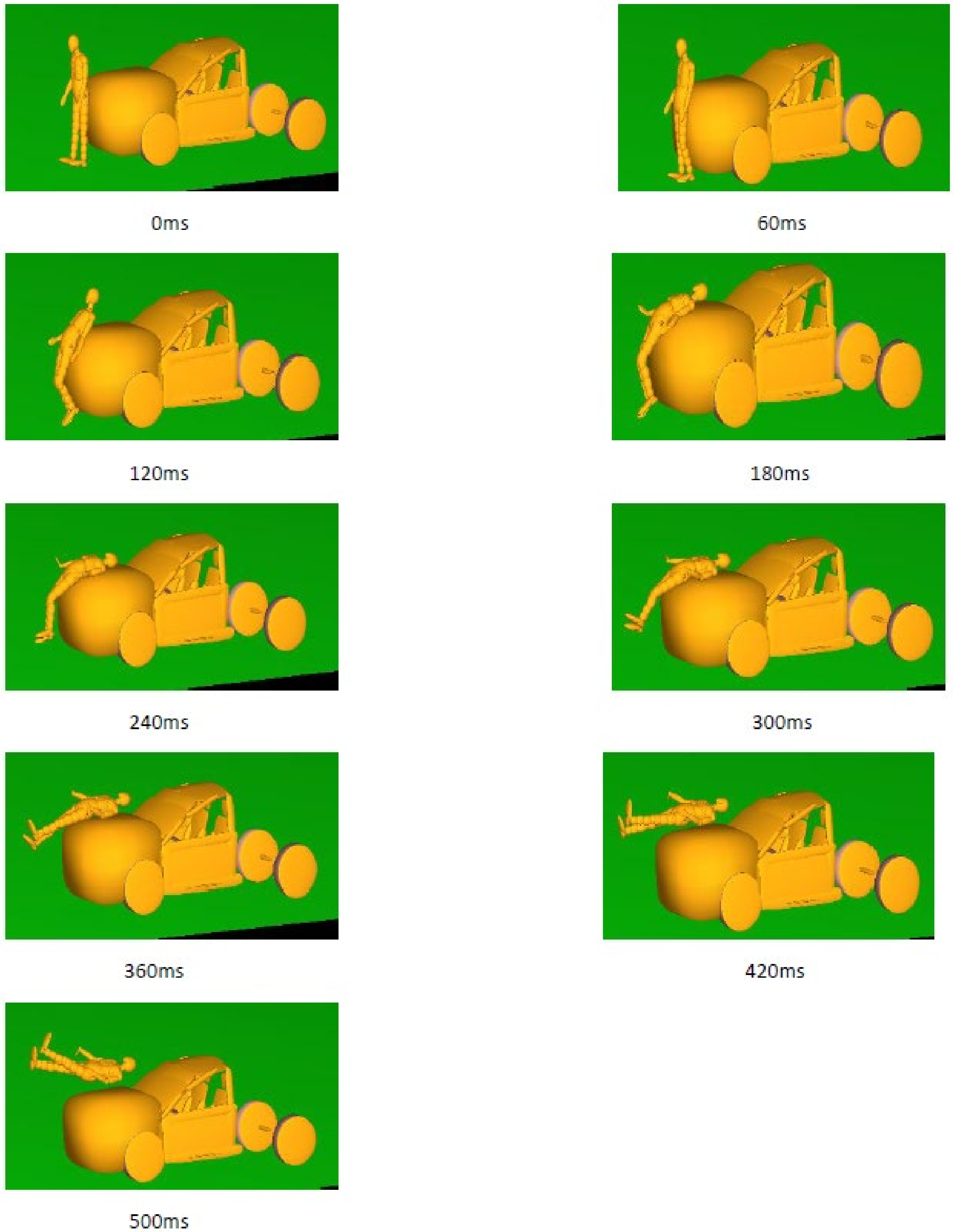
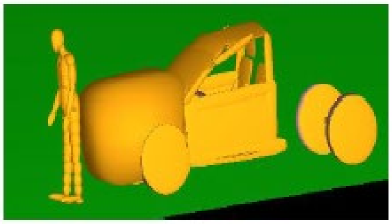
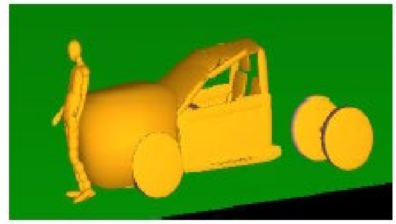


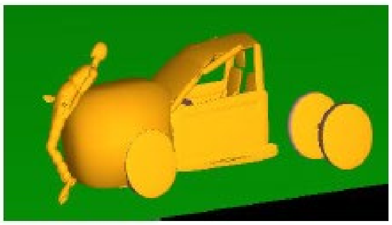
Figure 6.3. Kinematics of the 50th percentile pedestrian in pickup truck Rear impact at 18 kmph at Center



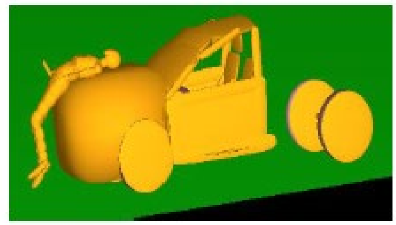
0ms



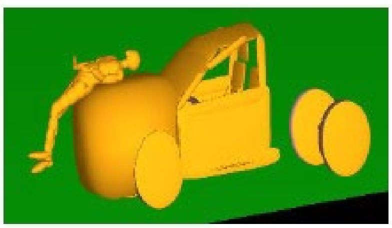
60ms



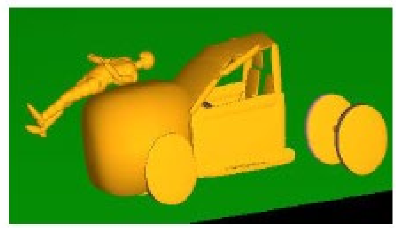
120ms



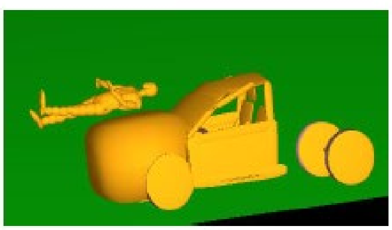
180ms



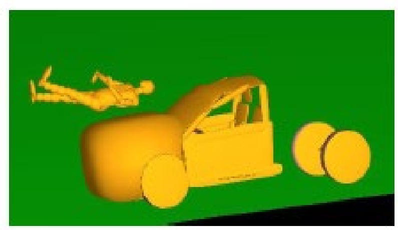
240ms



300ms



360ms



420ms

500ms

Figure 6.4. Kinematics of the 50th percentile pedestrian in pickup truck Rear impact at 21 kmph at Center

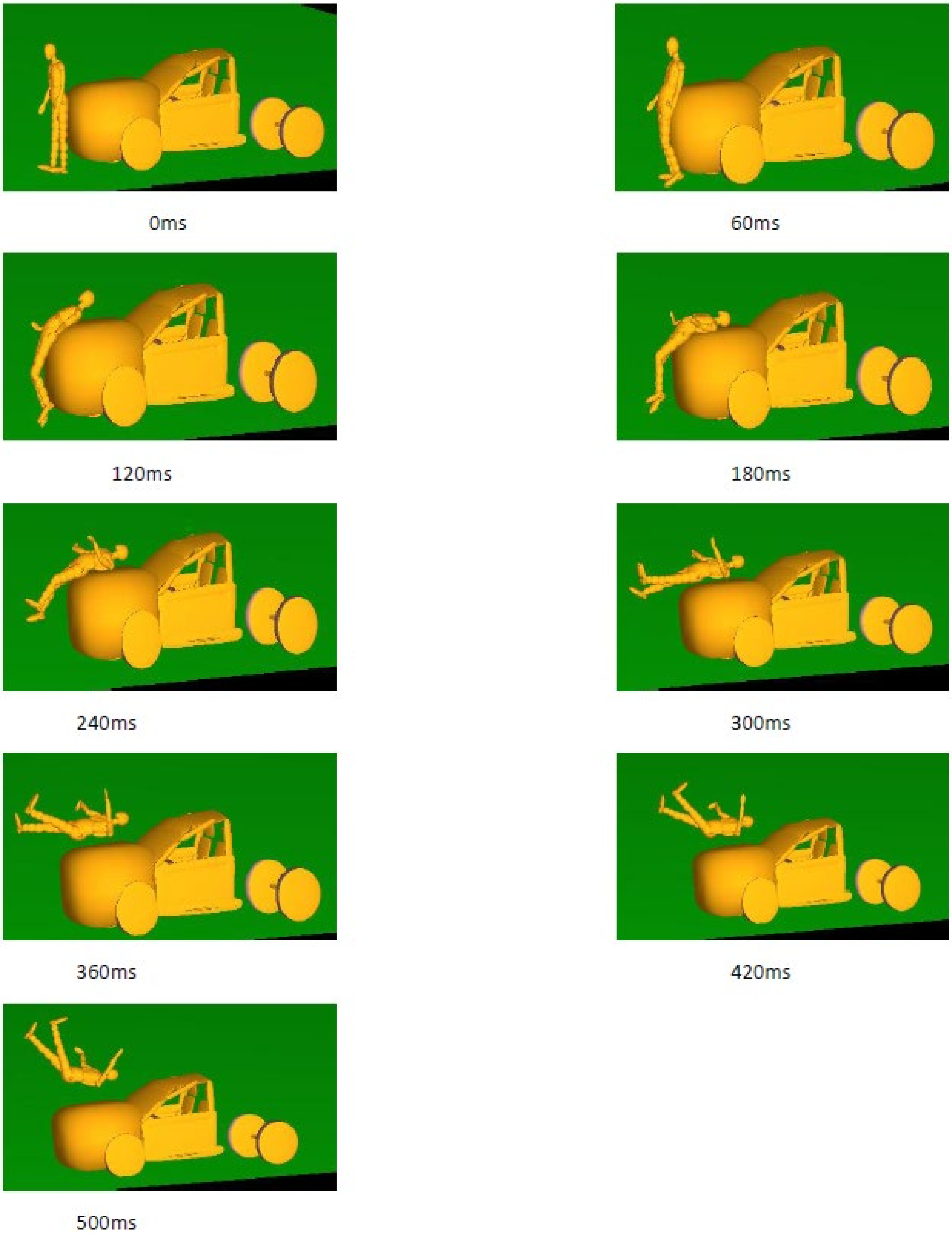


Figure 6.5. Kinematics of the 50th percentile pedestrian in pickup truck Rear impact at 24 kmph at Center

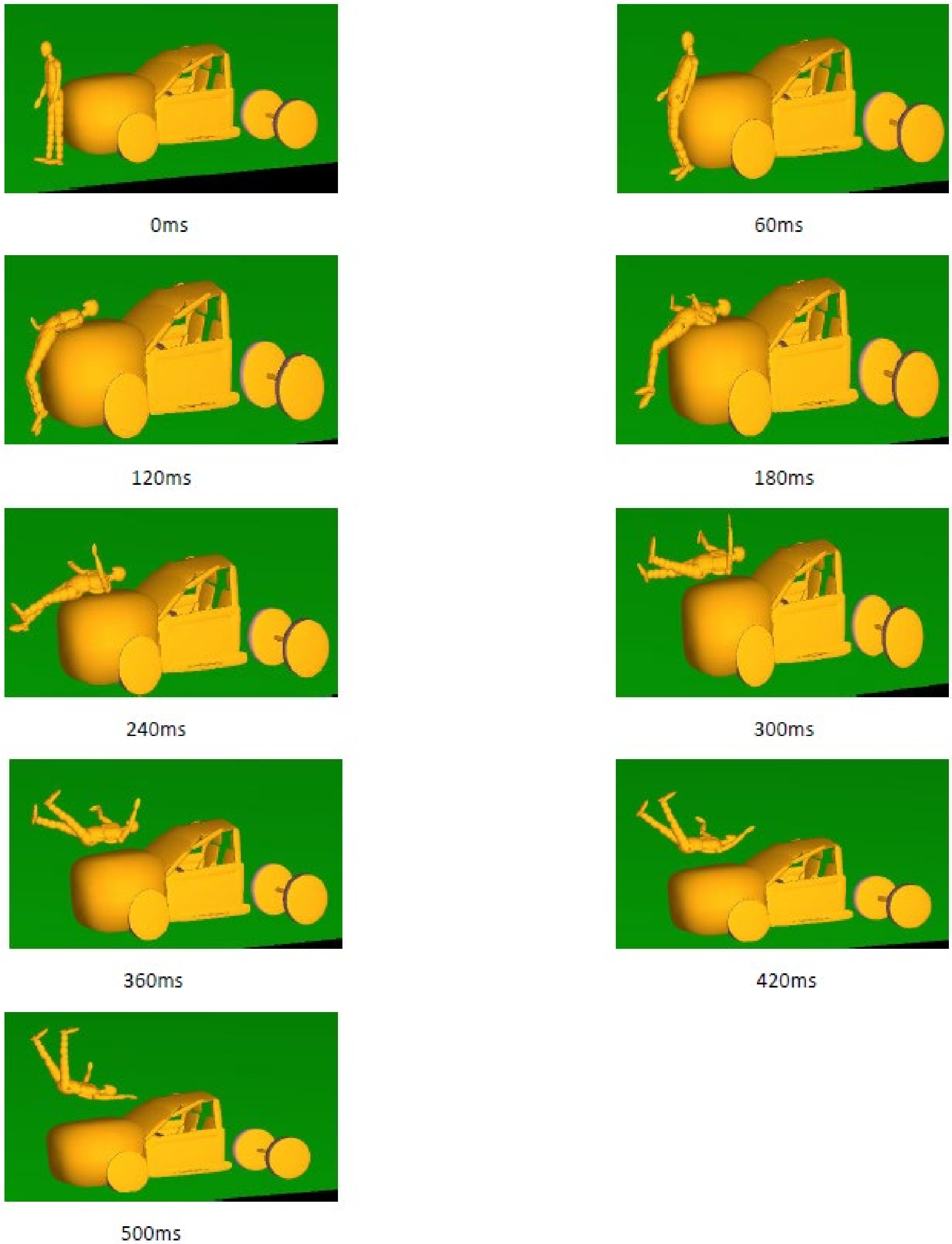


Figure 6.6. Kinematics of the 50th percentile pedestrian in pickup truck Rear impact at 27 kmph at Center

6.3 Kinematics of 50th Percentile Pedestrian in Pickup Truck Rear Impact at Right Corner

Adult injury risks are evaluated for low and high-speed collisions. The kinematics and tendency of pedestrian injuries are affected by the vehicle's front design, impact speed, and pedestrian height in pedestrian-vehicle collisions. When lightweight pickup trucks like the Chevrolet Silverado, which have a hood height roughly double that of a normal car, strike pedestrians, they cause more injuries, that could lead to death.

At Right Corner, the kinematics of pedestrian in rear impact varies for every speed parameter. At Right Corner, the kinematics of pedestrian in front impact varies for every speed parameter. All the stiffness values of the hood used are the same applied by Yang in his simulation. The coefficient of friction applied for the pedestrian–pickup truck model is 0.5. Simulations are performed for 5 different speeds (15 kmph, 18 kmph, 21 kmph, 24 kmph, and 27 kmph) at the right corner at 500ms, and injuries are evaluated. The MADYMO 50th percentile pedestrian model is positioned to be walking away in the front end of the truck as mentioned in NHTSA research.

The primary contact for pedestrian observed in rear impact is the truck hood. There are severe head injuries at 15 kmph. The truck directly strikes the pelvis and chest of the pedestrian in this case. At 18 kmph, head and chest injuries have occurred. At 21 kmph and above, injuries are severe at the head, pelvis, chest, and lower extremities.

Kinematics of the 50th percentile pedestrian in pickup truck impact at 15 kmph, 18 kmph, 21 kmph, 24 kmph, and 27 kmph are shown in Figures 6.7 through 6.11, respectively.

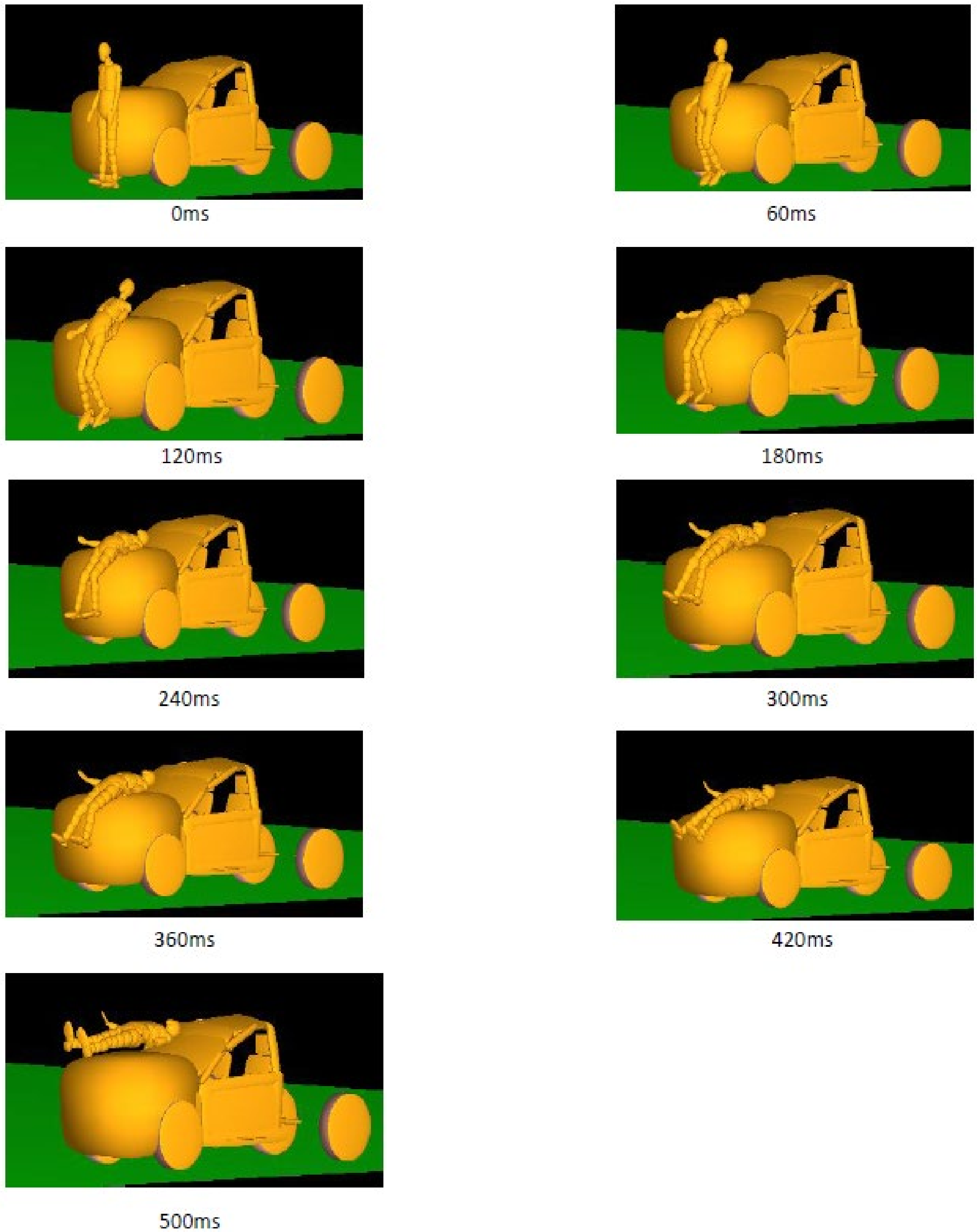


Figure 6.7. Kinematics of the 50th percentile pedestrian in pickup truck Rear impact at 15 kmph at Right Corner

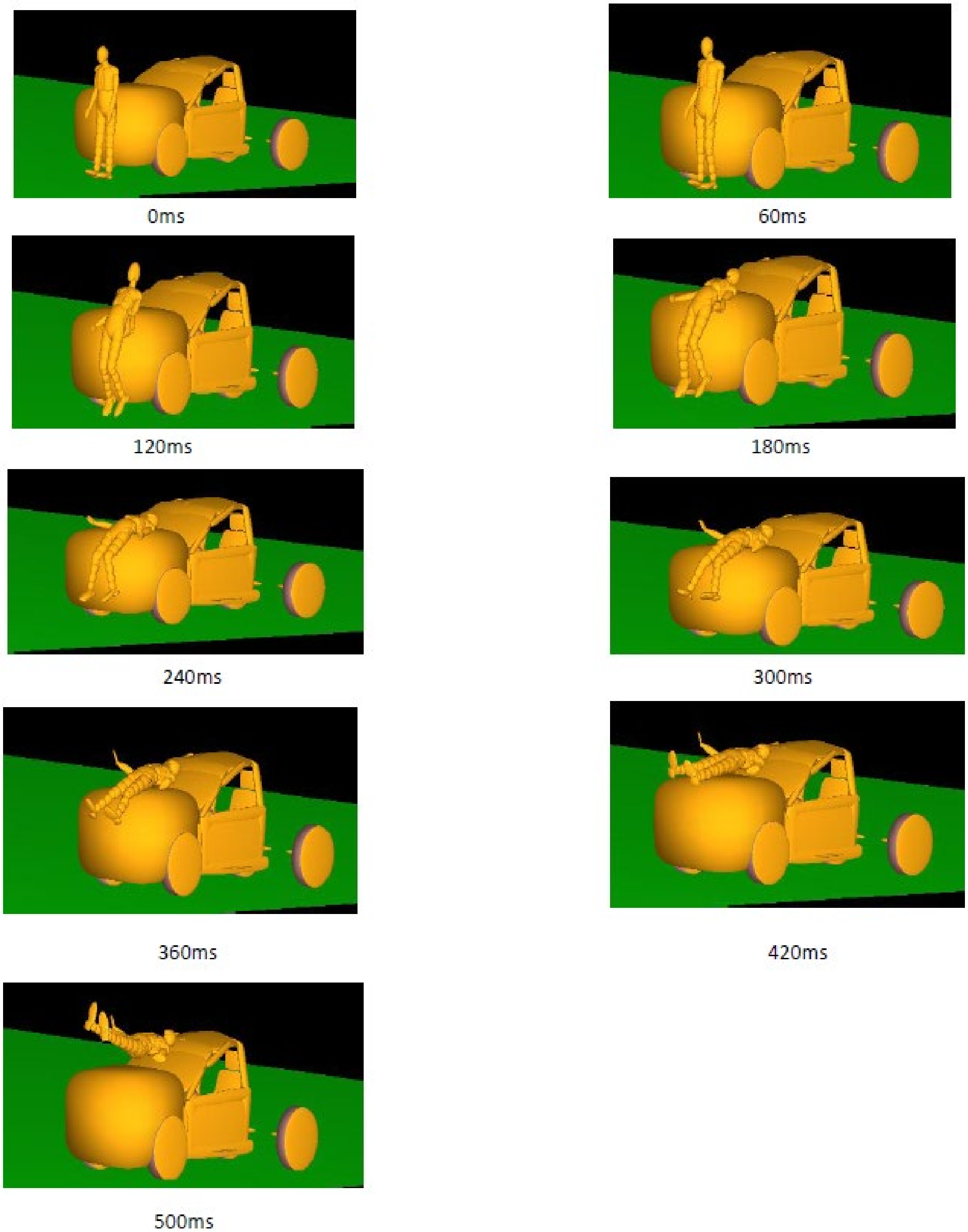


Figure 6.8. Kinematics of the 50th percentile pedestrian in pickup truck Rear impact at 18 kmph at Right Corner

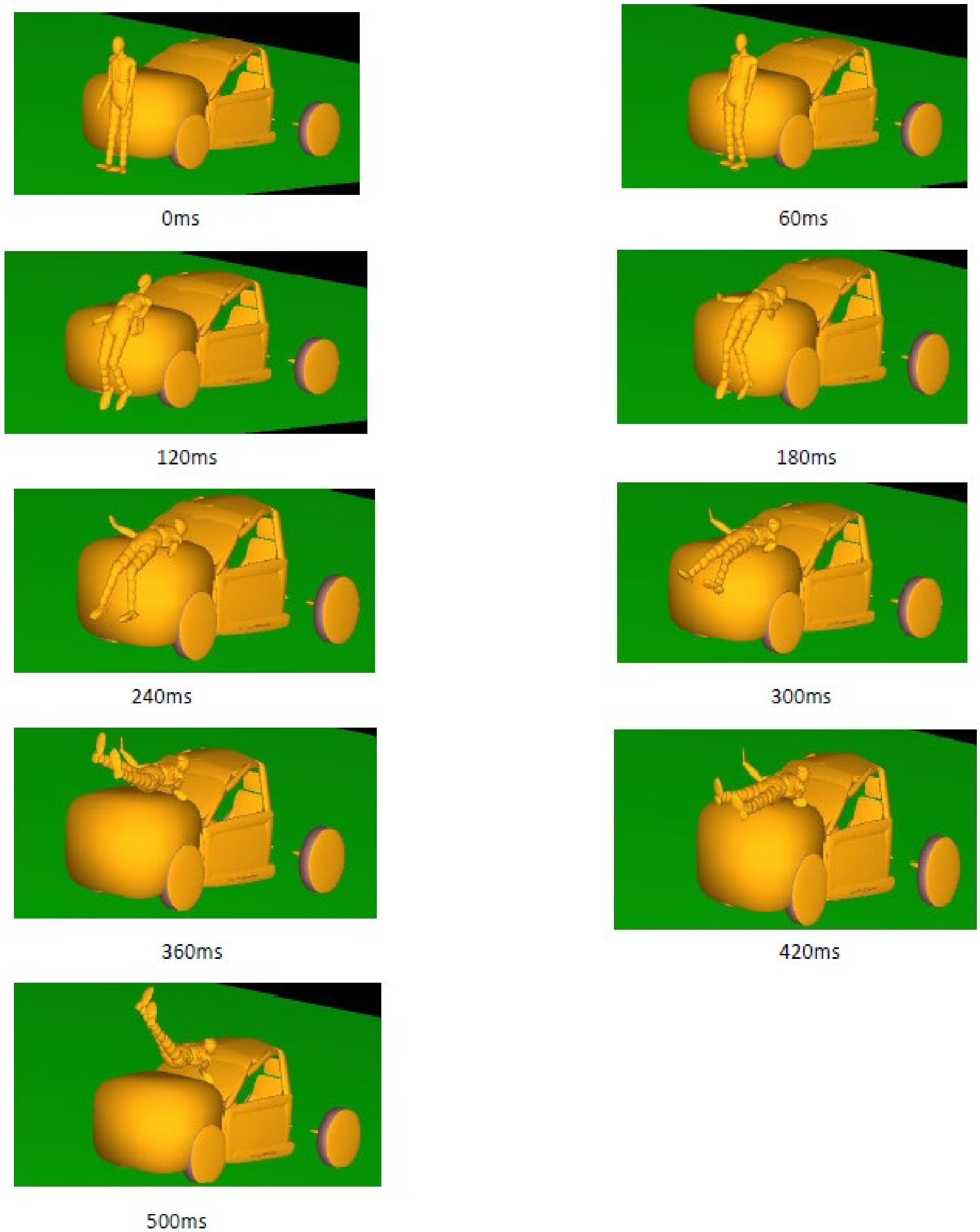


Figure 6.9. Kinematics of the 50th percentile pedestrian in pickup truck Rear impact at 21 kmph at Right Corner

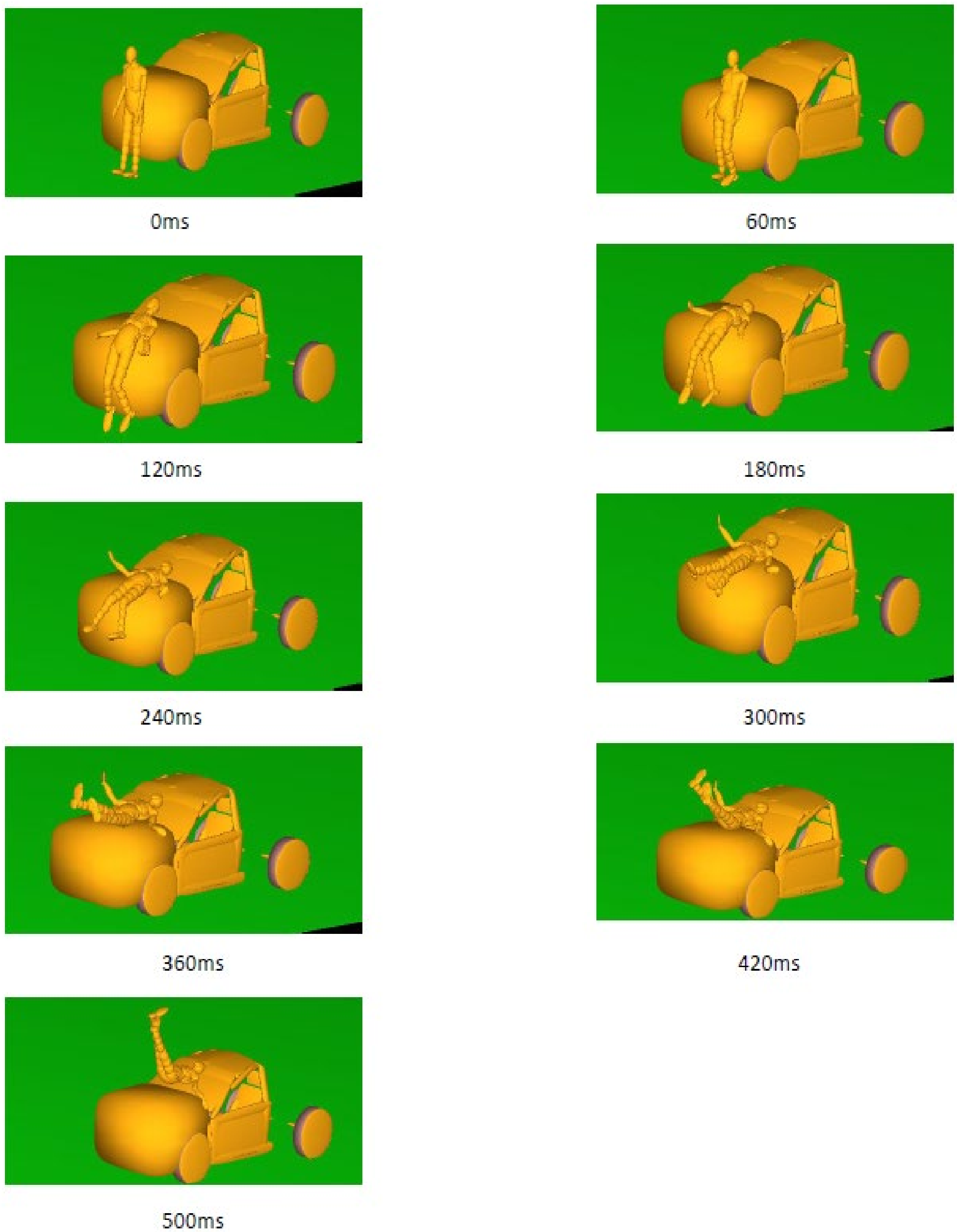


Figure 6.10. Kinematics of the 50th percentile pedestrian in pickup truck Rear impact at 24 kmph at Right Corner

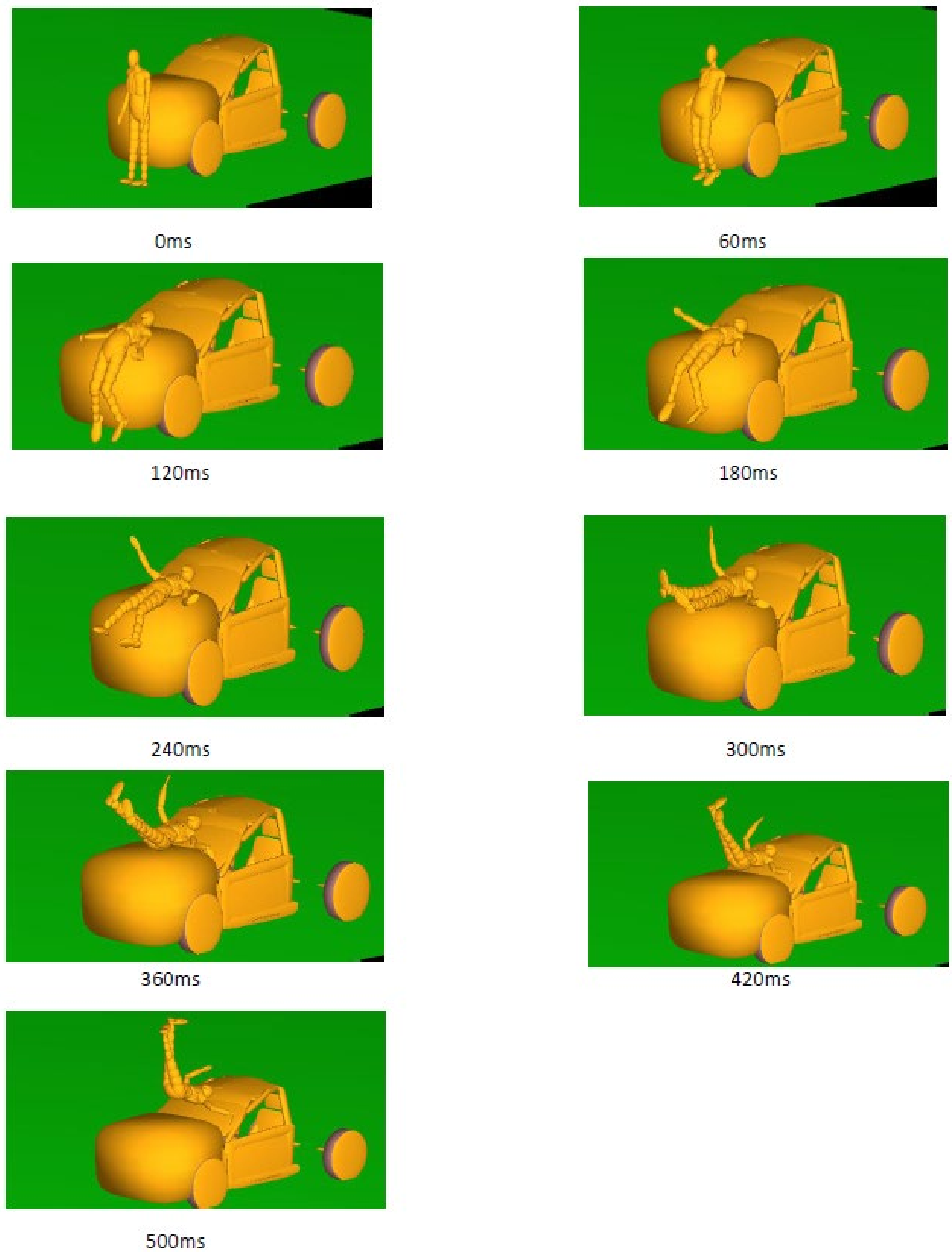


Figure 6.11. Kinematics of the 50th percentile pedestrian in pickup truck Rear impact at 27 kmph at Right Corner

6.4 Kinematics of 50^{th} Percentile Pedestrian in Pickup Truck Rear Impact at Left Corner

Adult injury risks are evaluated for low and high-speed collisions. The kinematics and tendency of pedestrian injuries are affected by the vehicle's front design, impact speed, and pedestrian height in pedestrian-vehicle collisions. When lightweight pickup trucks like the Chevrolet Silverado, which have a hood height roughly double that of a normal car, strike pedestrians, they cause more injuries, that could lead to death.

At the left corner, the kinematics of pedestrian in rear impact varies for every speed parameter. At Right Corner, the kinematics of pedestrian in front impact varies for every speed parameter. All the stiffness values of the hood used are the same applied by Yang in his simulation. The coefficient of friction applied for the pedestrian–pickup truck model is 0.5. Simulations are performed for 5 different speeds (15 kmph, 18 kmph, 21 kmph, 24 kmph, and 27 kmph) at the left corner at 500ms, and injuries are evaluated. The MADYMO 50th percentile pedestrian model is positioned to be walking towards in front end of the truck as mentioned in the NHTSA research.

The primary contact for pedestrian observed in rear impact is the truck hood. There are severe head injuries at 15 kmph. The truck directly strikes the pelvis and chest of the pedestrian in this case. At 18 kmph, head and chest injuries have occurred. At 21 kmph and above, injuries are severe at the head, pelvis, chest, and lower extremities.

Kinematics of the 50^{th} percentile pedestrian in pickup truck impact at 15 kmph, 18 kmph, 21 kmph, 24 kmph, and 27 kmph are shown in Figures 6.12 through 6.16, respectively.

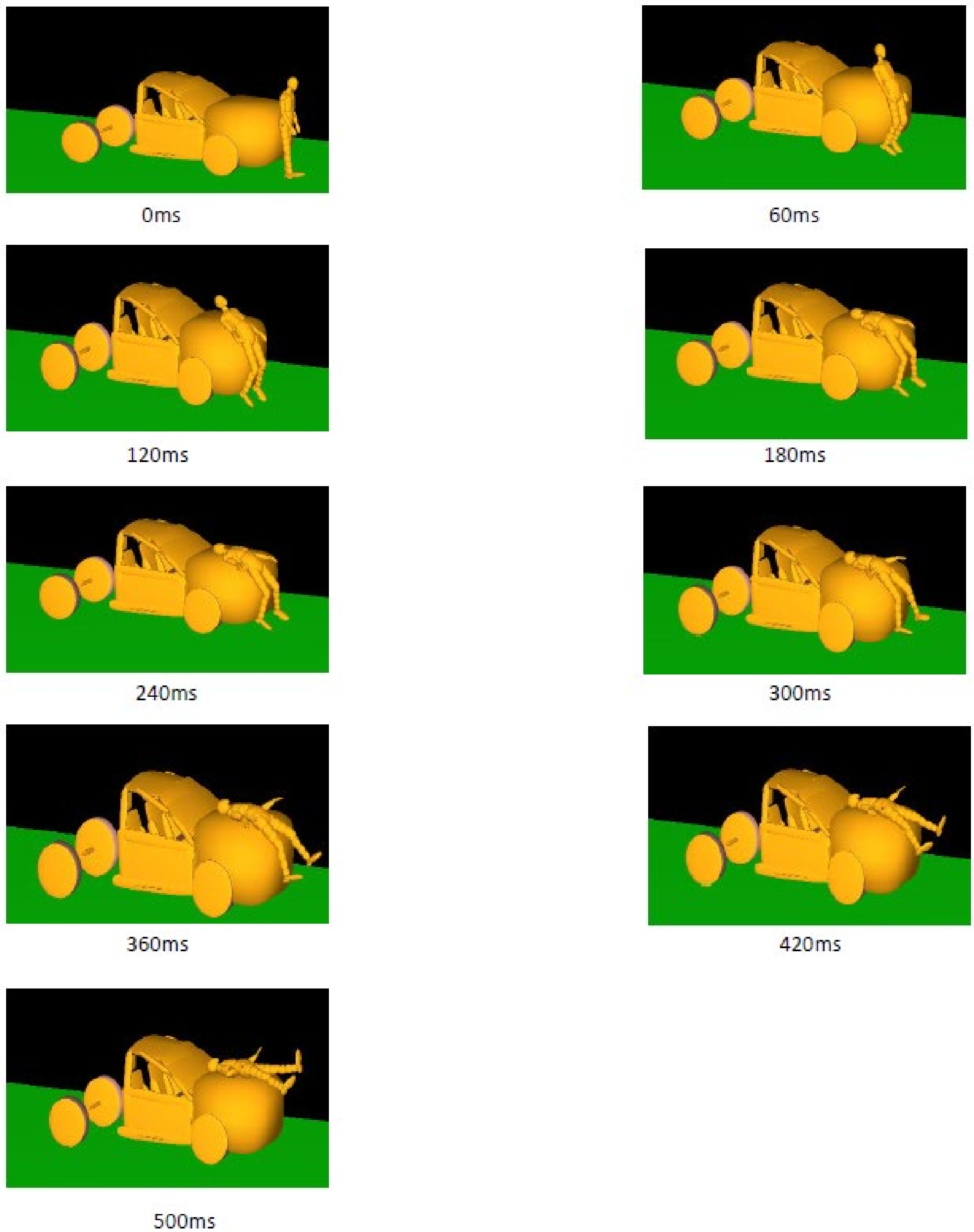


Figure 6.12. Kinematics of the 50th percentile pedestrian in pickup truck Rear impact at 15 kmph at Left Corner

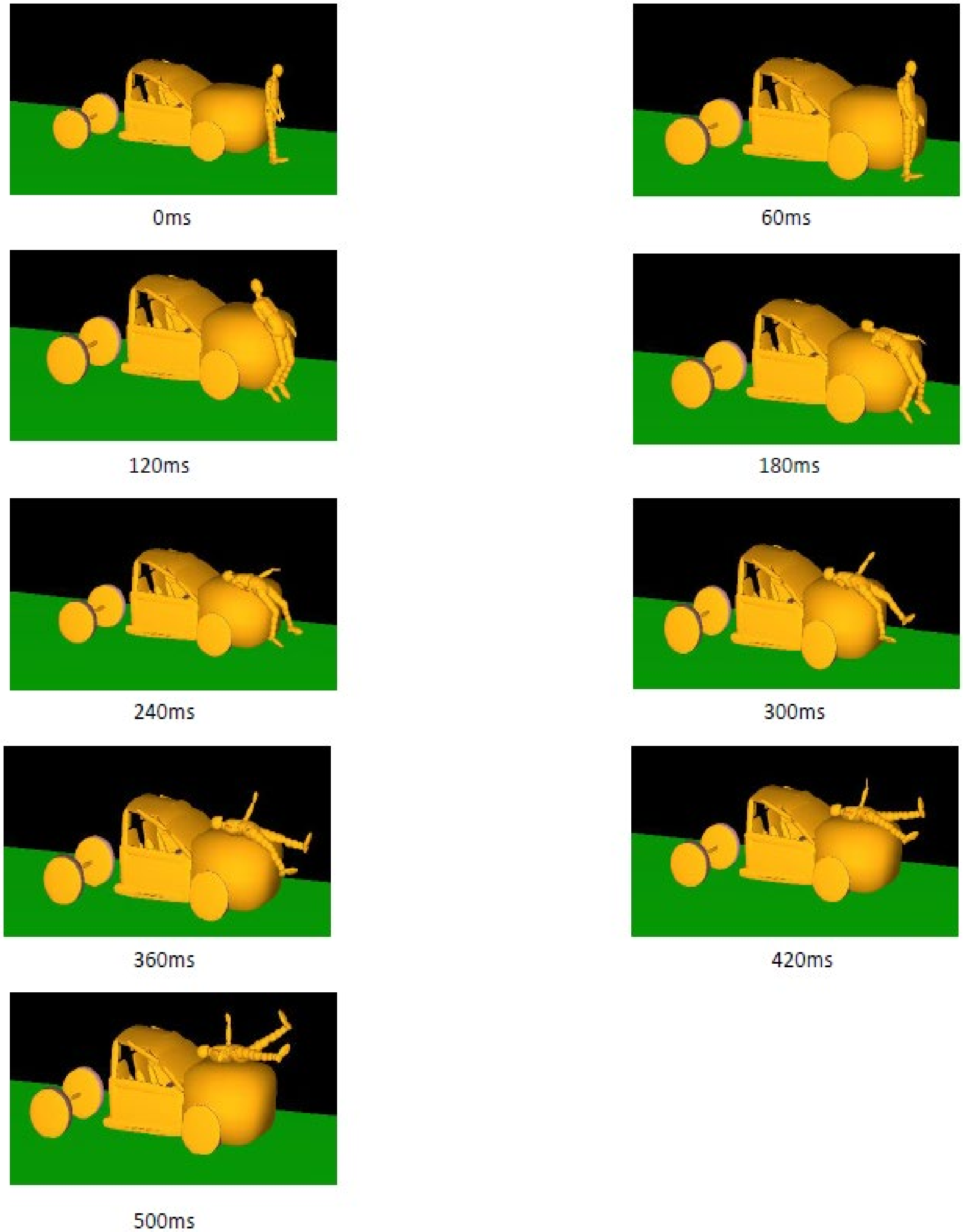


Figure 6.13. Kinematics of the 50th percentile pedestrian in pickup truck Rear impact at 18 kmph at Left Corner

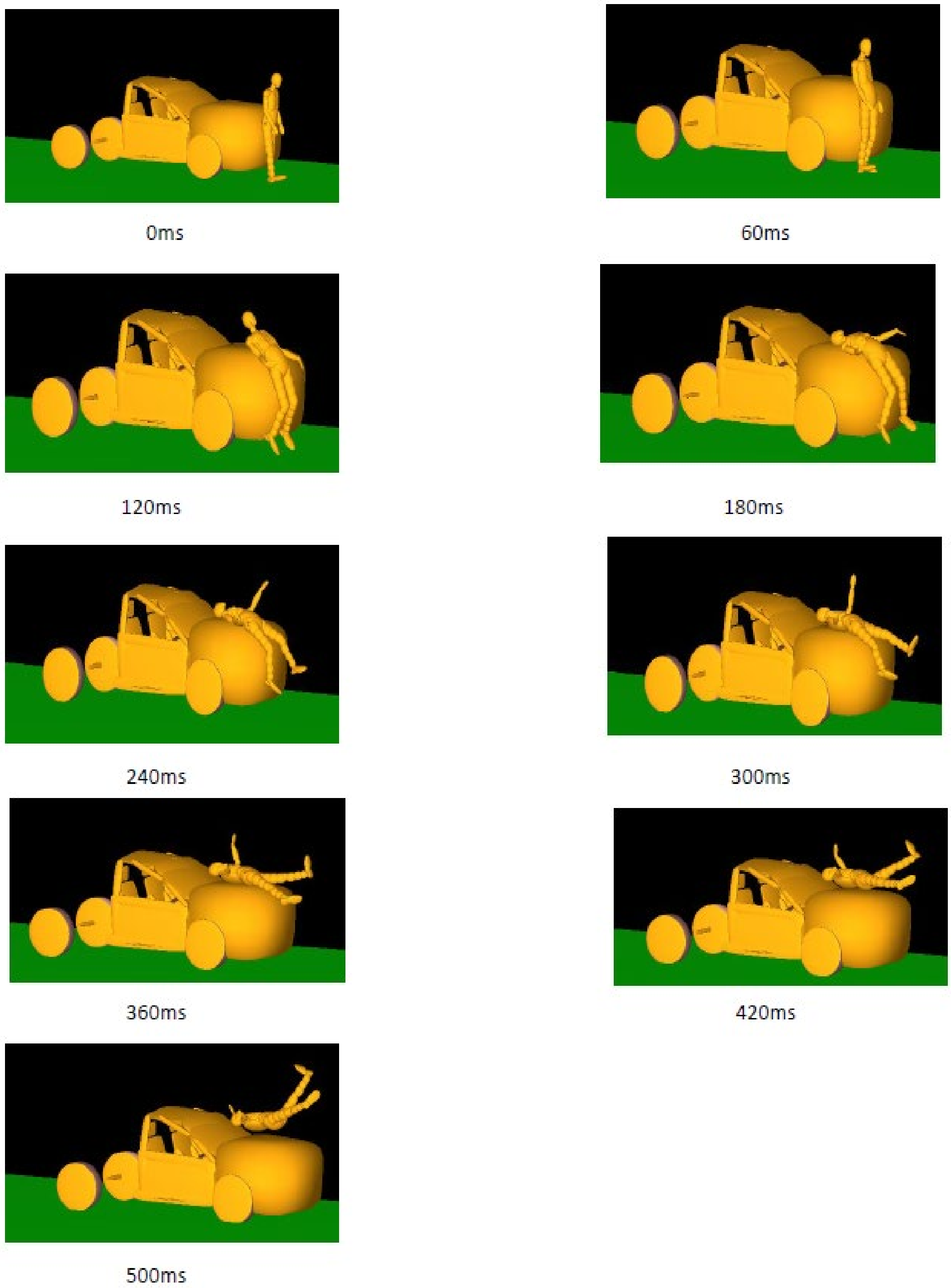


Figure 6.14. Kinematics of the 50th percentile pedestrian in pickup truck Rear impact at 21 kmph at Left Corner

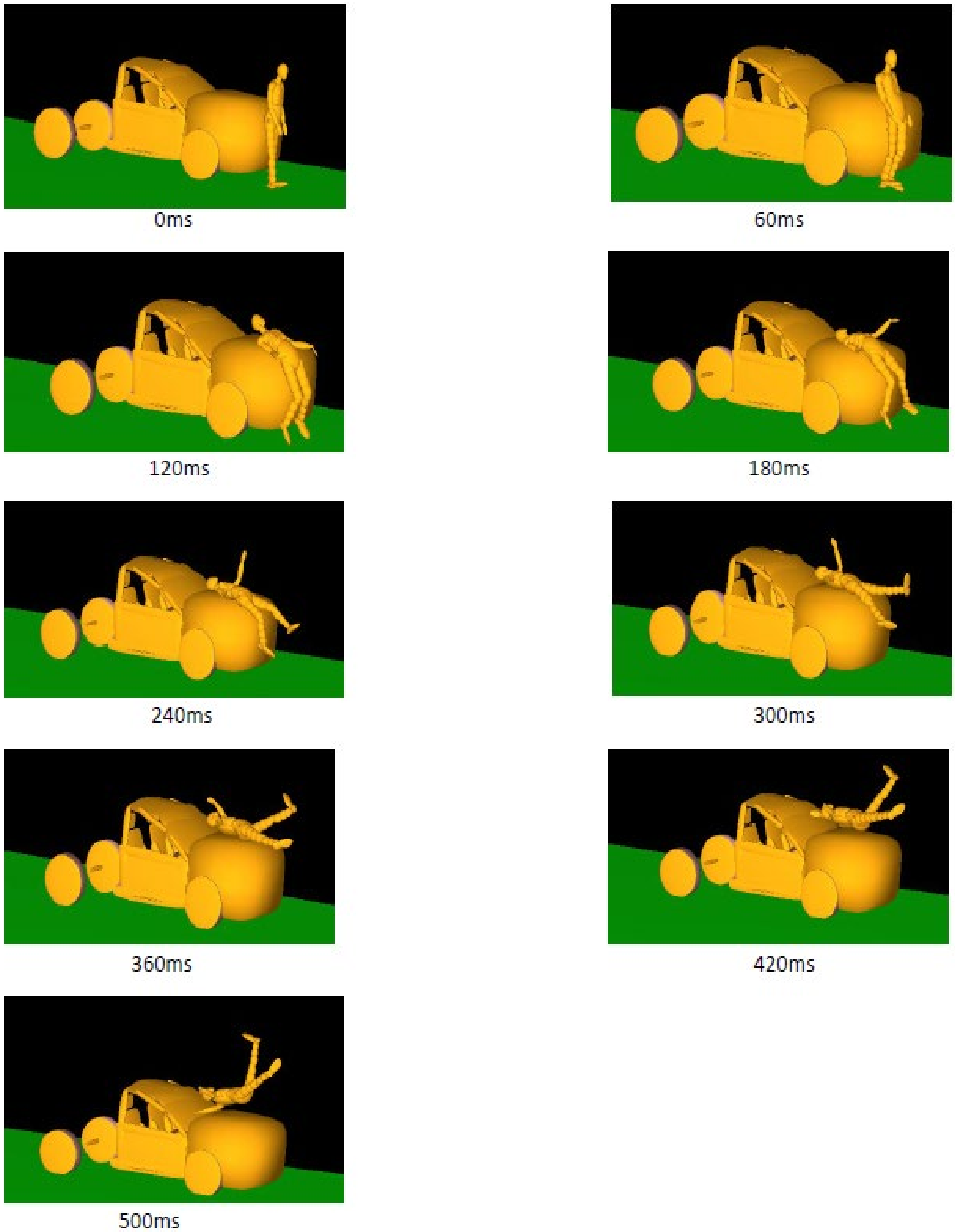


Figure 6.15. Kinematics of the 50th percentile pedestrian in pickup truck Rear impact at 24 kmph at Left Corner

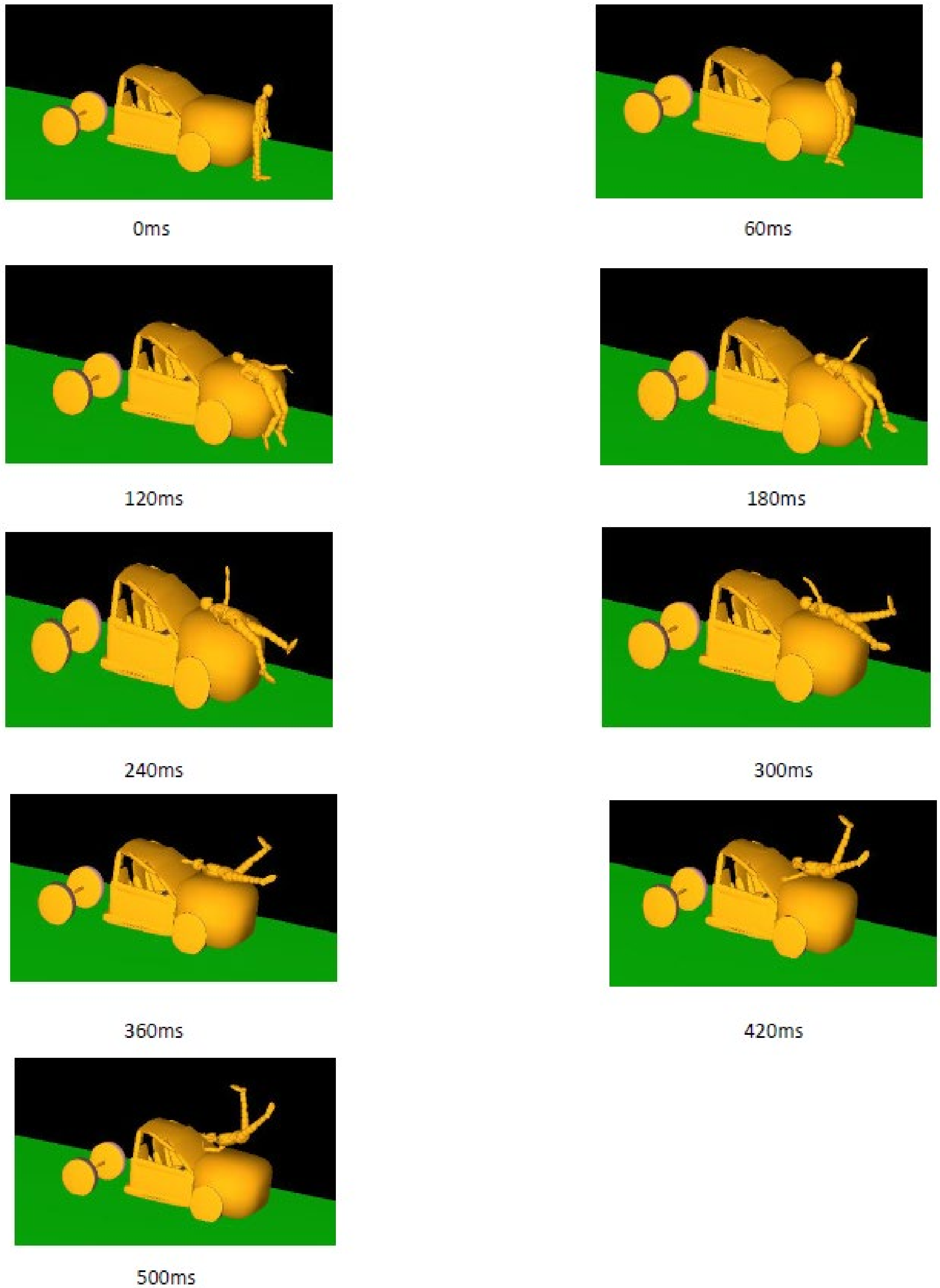


Figure 6.16. Kinematics of the 50th percentile pedestrian in pickup truck Rear impact at 27 kmph at Left Corner

6.5 Comparison of Kinematic Behavior of 50th Percentile Pedestrian in Pickup Truck Rear Impact at Three Locations

From the kinematic analysis of 50th percentile pedestrian in a rear impact, it is observed that injuries are severe at the right end when compared to the center and left end. In a rear impact, the truck hood directly strikes at the center of the pelvis, chest, and lower extremities of the pedestrian from the rear. At the Center, the pedestrian initially strikes the hood and lands on the hood of the truck at low speeds, and at higher speeds the pedestrian lands in front of the truck at some distance. At the left corner, the pedestrian initially strikes the hood and lands on the hood of the truck and with increasing speed, the pedestrian strikes the windshield and rolls over the truck. At the right corner, the pedestrian strikes the hood and lands on the windshield and at higher speeds, strikes the hood and windshield and lands beside the truck space. In this case, the secondary impact is observed at the windshield. Injury forces and accelerations are more critical and lead to fatality. In this impact, the chest, head, and lower extremity accelerations are more, and the severity of injuries is high.

6.6 Comparison of Injuries to 50th Percentile Pedestrian in Pickup Truck Rear Impact

Responses of front pedestrian – pickup truck impact are compared to understand the dynamic performance and injuries at different locations at various speeds.

Head Injury Criteria (HIC)

Table 6.1 and Figure 6.17 show the maximum values obtained for 50th percentile pedestrian at three locations for a run of 500ms. At 15 kmph, injuries have crossed the biomechanical limits (HIC_{15}<700, HIC_{36} < 1000). The highest head injury obtained is for the 50th

P pedestrian at 27 kmph. At 27 kmph, for rear impact at both ends, the biomechanical limits exceed almost 8-9 times and are fatal. The 50th P pedestrian is at higher risk after 21 kmph and above in rear impacts which might lead to death. The maximum AIS scale rating is 6, leading to mass destruction of both skull and brain as shown in Table 6.2. Injuries at the right location are severe than injuries at the left and center.

TABLE 6.1

HEAD INJURY CRITERIA OF 50TH PERCENTILE PEDESTRIAN AT LEFT, RIGHT, AND CENTER ENDS IN REAR IMPACT

Speeds (kmph)	Frontal Center Rear impact	ΔT (ms)	Frontal Left Rear impact	ΔT (ms)	Frontal Right Rear impact	ΔT (ms)
15	821	2.2	548	2.4	970	3.1
18	1268	2.5	1165	2.2	2118	2.8
21	3023	2.8	2888	2.5	4834	2.7
24	5346	3.1	5176	1.9	6705	2.5
27	8788	3.3	8154	2.1	9113	2.6

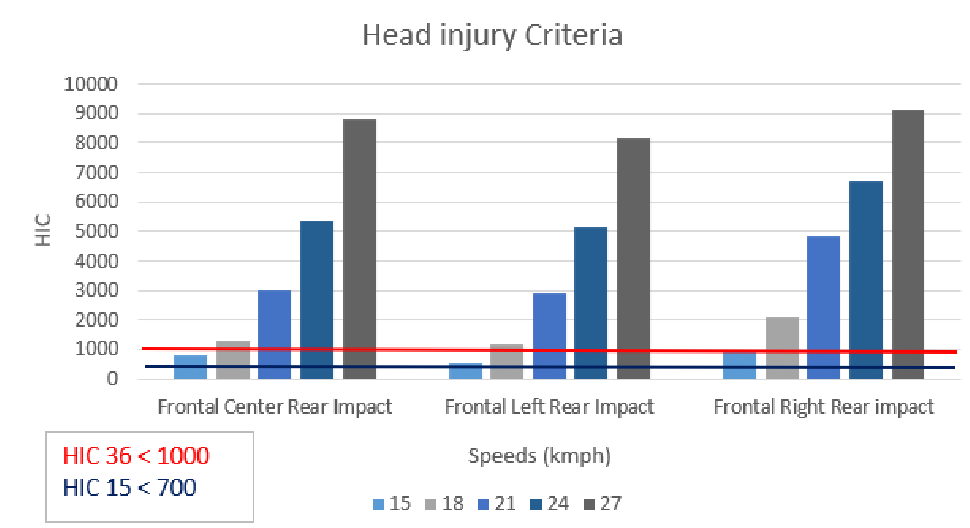


Figure 6.17. Comparison of Head Injury Criteria of 50th percentile pedestrian at Left, Right and Center ends in Rear impact

TABLE 6.2

AIS RATING FOR HEAD INJURY IN REAR IMPACT

Speeds(kmph)	Rear Impact
15	3
18	4
21	5
24	6
27	6

Head Acceleration

The maximum Head acceleration should be 80g for a pedestrian to be safe according to EEVC biomechanical criteria. The head acceleration values increase with an increase in the impact speed when the strength of the lightweight pickup truck is high. The head of the pedestrian is the initial body part that is injured in an impact and its severity is based on the impact speed and strength of the truck. Table 6.3 and Figure 6.18 show the maximum Head acceleration values obtained by 50^{th} percentile pedestrian for a run of 500ms.

At three locations, for the 50th P Hybrid pedestrian, the values are above biomechanical limits for all the velocities. At 18 Kmph and above, the head accelerations are almost 3-5 times greater than the actual value and are fatal.

At 27 kmph on the right side, the value is higher of 1124g, and the pedestrian would have an AIS 6+ injury. Injuries at the right location are severe as the pedestrian collides and lands far away from the truck when compared to other locations.

TABLE 6.3

HEAD RESULTANT ACCELERATION OF 50TH PERCENTILE PEDESTRIAN AT LEFT, RIGHT AND CENTER ENDS IN REAR IMPACT

Speeds(kmph)	Frontal Center Rear Impact	Frontal Left Rear Impact	Frontal Right Rear impact
15	181	177	198
18	315	276	354
21	492	383	573
24	753	613	813
27	984	930	1124

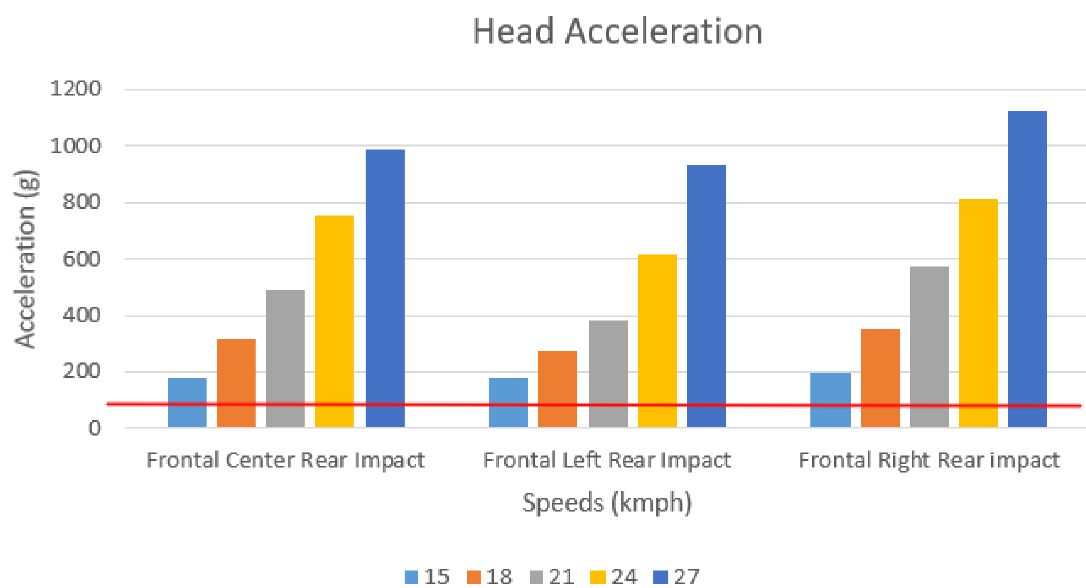


Figure 6.18. Comparison of Head resultant acceleration of 50th percentile pedestrian at Left, Right and Center ends in Rear impact

<u>Head Impact locations on Hood</u>

Figure 6.19 shows the initial head impact locations on the hood obtained in pedestrian Rear impact.

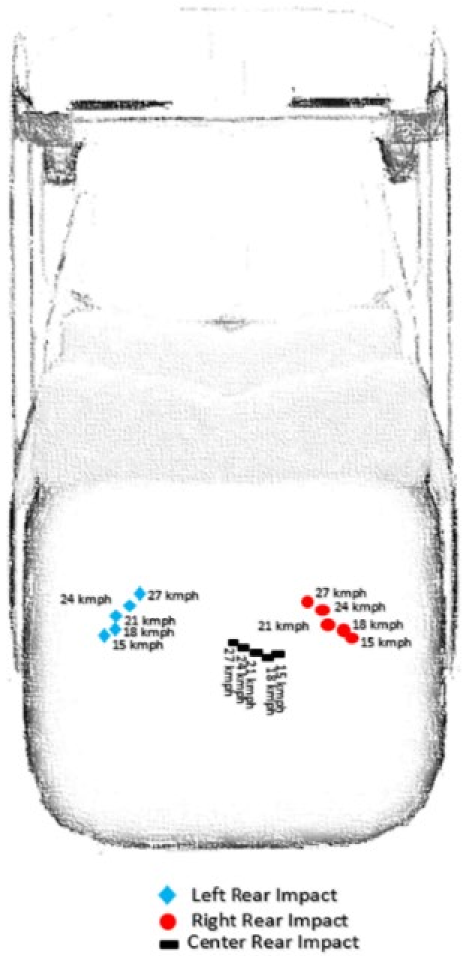


Figure 6.19. Head impact locations of 50th Percentile pedestrian on the truck hood in Rear impact

3ms Torso Up Acceleration

The maximum 3ms torso up acceleration should be 60g for a pedestrian to be safe according to EEVC biomechanical criteria. Table 6.4 and Figure 6.20 show the maximum Torso Up acceleration values obtained by 50th percentile pedestrian for a run of 500ms. At all the velocities, the torso accelerations exceeded the biomechanical limit, and fractures have occurred. At 27 kmph, the value is almost 4-5 times greater than the maximum torso threshold acceleration.

TABLE 6.4

3MS TORSO-UP ACCELERATION OF 50TH PERCENTILE PEDESTRIAN AT LEFT, RIGHT AND CENTER ENDS IN REAR IMPACT

Speeds(kmph)	Frontal Center Rear Impact	Frontal Left Rear Impact	Frontal Right Rear impact
15	87	76	98
18	138	123	165
21	196	172	218
24	234	216	296
27	290	272	352

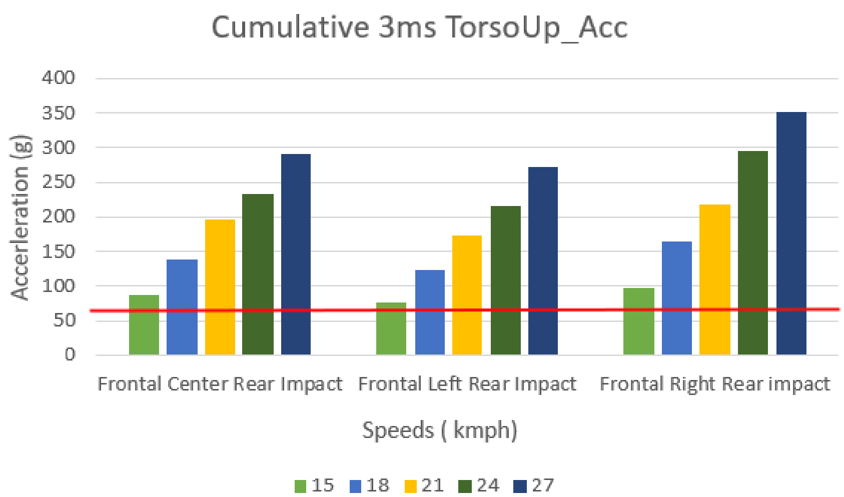


Figure 6.20. Comparison of 3ms Torso-Up acceleration of 50th percentile pedestrian at Left, Right and Center ends in Rear impact

Tibia Acceleration

Femoral and tibial injury is a common injury in pedestrian suffering impacts with vehicles. These injuries are evaluated based on femur and tibia fracture resulting from bending moment of the femur on impact with the hood and the resultant acceleration of tibia [3]. The maximum tolerance level for the tibia acceleration for a pedestrian is 150g according to EEVC biomechanical criteria. Table 6.5 and Figure 6.21 below show the maximum tibia acceleration values obtained by 50^{th} percentile pedestrian for a run of 500ms. Only at the left corner for 15 kmph, the value is below the tolerance level and the 50th percentile Pedestrian is safe. For other all velocities, the values are 1-2 times greater than the maximum value. Above 18 kmph, the values indicate that the tibia suffers fractures.

TABLE 6.5

TIBIA RESULTANT ACCELERATION OF 50TH PERCENTILE PEDESTRIAN AT LEFT, RIGHT, AND CENTER ENDS IN REAR IMPACT

Speeds(kmph)	Frontal Center Rear Impact	Frontal Left Rear Impact	Frontal Right Rear impact
15	150	147	154
18	184	183	188
21	214	210	222
24	258	256	260
27	299	294	310

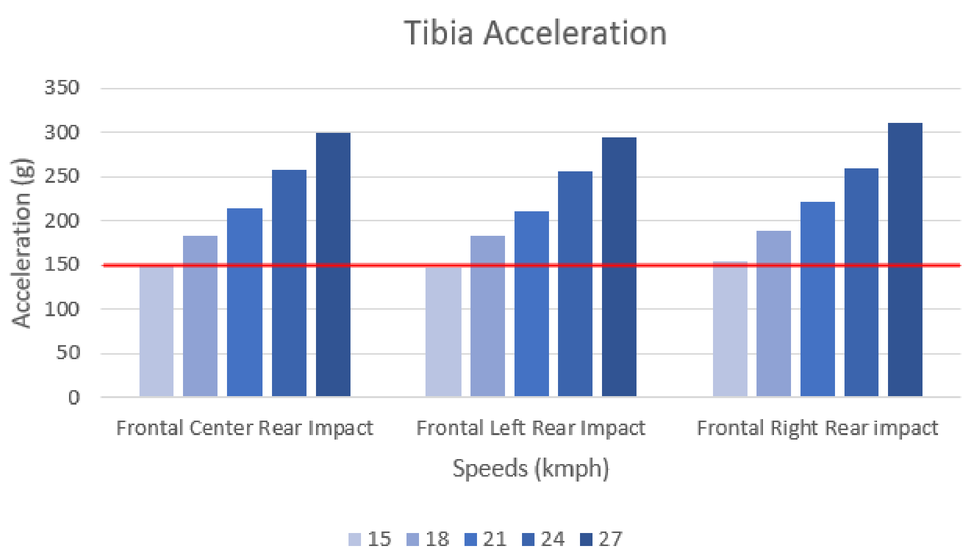


Figure 6.21. Comparison of Tibia resultant acceleration of 50th percentile pedestrian at Left, Right and Center ends in Rear impact

Femur Bending Moment

Femoral and tibial injury is a common injury in pedestrian suffering impacts with vehicles. The maximum tolerance level for the Femur bending moment for a pedestrian is 220N.m according to EEVC biomechanical criteria. Table 6.6 and Figure 6.22 indicate the maximum femur bending moments for the 50th percentile pedestrian for a run of 500ms. Until 24 kmph, the bending moments for 50th P Pedestrian are within the biomechanical limit. For velocities above 24 kmph, the values of forces are 1-2 times greater than the maximum tolerance limit. At 27 kmph, the severity level for 50th P Pedestrian is very high and leads to fractures.

TABLE 6.6

FEMUR BENDING MOMENTS OF 50TH PERCENTILE PEDESTRIAN AT LEFT, RIGHT, AND CENTER ENDS IN REAR IMPACT

Speeds(kmph)	Frontal Center Rear Impact	Frontal Left Rear Impact	Frontal Right Rear impact
15	67	61	72
18	90	85	96
21	154	151	160
24	243	236	252
27	309	298	302

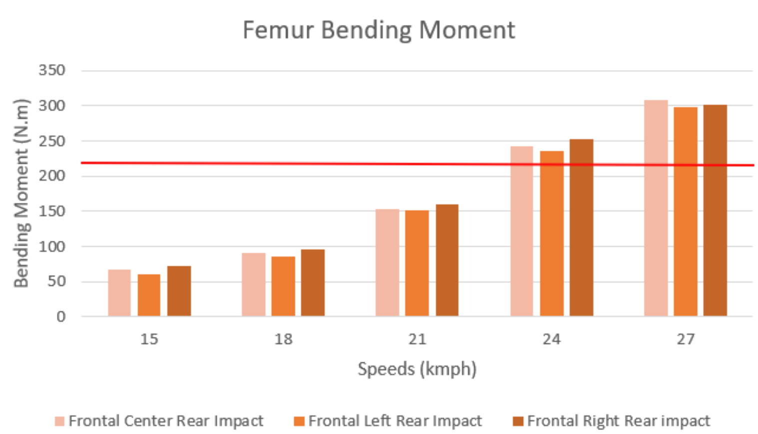


Figure 6.22. Comparison of Femur Bending moments of 50th percentile pedestrian at Left, Right and Center ends in Rear impact

Knee Force

The maximum tolerance level for the Knee force for a pedestrian is 2.5 KN according to EEVC biomechanical criteria. Table 6.7 indicates the maximum Knee forces of 50^{th} percentile pedestrian for a run of 500ms. Until 15 kmph, the knee forces for 50th P Pedestrian are within the biomechanical limit. For velocities above 21 kmph, the values of forces are 2-3 times greater than the maximum tolerance limit. At 27 kmph, the tolerance level for 50th P Pedestrian is very high and is amputated. Comparing on three locations, knee forces are more for a pedestrian at the right end than Center and Left end.

TABLE 6.7

KNEE FORCES OF 50TH PERCENTILE PEDESTRIAN AT LEFT, RIGHT AND CENTER ENDS IN REAR IMPACT

Speeds(kmph)	Frontal Center Rear Impact	Frontal Left Rear Impact	Frontal Right Rear impact
15	1.3	1.1	1.4
18	2.9	1.3	3.3
21	4.5	4.2	4.9
24	6.8	5.5	7.1
27	7.6	8.9	9.1

CHAPTER 7

SUMMARY OF ALL INJURIES AND DESIGN OF EXPERIMENTS (DOE)

In this chapter, all the injury responses that occurred to the 50th percentile pedestrian model at five different speeds for three pedestrian locations are recorded and compared. Based on the injury responses obtained, the Design of Experiments is done to understand the severity of injuries with respect to the pickup truck parameters. The parameters that are taken for evaluation are impact speed, pedestrian configuration, impact location, and vehicle hood/ bonnet stiffness.

7.1 Summary of all the Computational Results on 50th Percentile Pedestrian Study

The overall results that are in common for all the impacts at three different locations of the study are outlined in Table 7.1. A comparison is depicted in the table, where the ellipsoidal pickup truck model with 50th Percentile Pedestrian at different speeds (15 kmph, 18 kmph, 21 kmph, 24 kmph, and 27 kmph) is analyzed, respectively. The injuries such as TTI, Viscous Injury response, Pelvis resultant acceleration are only evaluated for side-impact and Torso-Up Acceleration for front and rear impacts. Hence, the following results that are outlined for comparison are Head injury Criteria (HIC-36 < 1000, HIC-15 < 700), Head resultant acceleration, Knee forces, Tibia resultant acceleration, and Femur bending moments that are obtained during the impact. Among all the responses obtained for the 50th percentile pedestrian, the severity of injury for the head is more and will be a significant factor for pedestrian death. The second severity was obtained for the tibia. This happens because the truck hits the pedestrian directly in the thorax-pelvic-tibia region.

TABLE 7.1

SUMMARY OF ALL THE INJURY VALUES FOR 50TH PERCENTILE PEDESTRIAN IN PICKUP TRUCK IMPACT

Pedestrian-Impact Positioning	Intial velocity (Kmph)	HIC (36) < 1000, HIC (15) < 700	Head_Acc (g)	Knee force (KN)	Tibia_Acc (g)	Femur Bending Moment (N.m)
Center-Side Impact	15	17	73	0.5	127	11
	18	107	134	0.8	145	35
	21	283	152	1.1	172	47
	24	713	206	1.5	186	83
	27	1411	252	1.8	209	104
Right-Side Impact	15	15	78	0.3	126	5
	18	96	155	0.4	142	22
	21	268	169	0.9	152	31
	24	673	175	1.3	163	74
	27	1210	192	1.6	189	94
Left-Side Impact	15	20	66	0.2	132	6
	18	134	103	0.6	156	27
	21	348	131	1	187	37
	24	765	230	1.2	209	78
	27	1348	235	1.7	221	99
Center-Front Impact	15	1644	216	1.4	192	104
	18	2781	379	3.5	213	161
	21	4465	624	4.4	241	218
	24	6892	802	6.2	280	271
	27	8934	1078	8.3	309	301
Right-Front Impact	15	1565	238	1.5	190	111
	18	2641	424	3.9	202	172
	21	4164	697	5.1	232	245
	24	6762	949	7.1	279	276
	27	8618	1184	8.8	304	315
Left-Front Impact	15	1280	201	1.3	186	95
	18	2164	334	3.3	206	155
	21	3476	578	3.8	224	210
	24	5538	712	5.7	266	267
	27	7095	1010	8.5	295	292
Center-Rear Impact	15	821	181	1.3	150	67
	18	1268	315	2.9	184	90
	21	3023	492	4.5	214	154
	24	5346	753	6.8	258	243
	27	8788	984	7.6	299	309
Right-Rear Impact	15	970	198	1.4	154	72
	18	2118	354	3.3	188	96
	21	4834	573	4.9	222	160
	24	6705	813	7.1	260	252
	27	9113	1124	9.1	310	302
Left-Rear Impact	15	548	177	1.1	147	61
	18	1165	276	1.3	183	85
	21	2888	383	4.2	210	151
	24	5176	613	5.5	256	236
	27	8154	930	8.9	294	298

7.2 Design of Experiments (DOE)

Design of Experiment (DOE) is a powerful statistical technique for improving product/process designs and solving process/production problems. DOE makes controlled changes to input variables to gain maximum amounts of information on cause-and-effect relationships with a minimum sample size When analyzing a process, experiments are often used to evaluate which process inputs have a significant impact on the process output and what the target level the inputs should be to achieve the desired result (output) [37].

As all the simulation studies show, the head impact protection in terms of HIC value is the most crucial parameter in injury-producing assessment to the pedestrian. Thus, the design of the experiment (DOE) is done to investigate the factors influencing the injury criteria in the impact collision:

A. Speed, Impact configuration, and Location,
B. Modification of hood stiffness to protect the pedestrian

Head Injury Criteria are observed to be the most crucial prominent injury parameter. Hence, it is considered for this analysis. Low and Medium impact speeds (15 kmph, 18 kmph, and 21 kmph) are considered as at high speeds, the injury values are very severe and pedestrian to be fatal.

7.2.1 Speed, Impact Location, and Pedestrian Configuration

The design of experiments analysis with a full-size pedestrian model is carried out with the vehicle parameters like speed, impact configuration, and location as mentioned in Table 7.2. The simulations are carried out for the full-size pedestrian model with speeds 15 kmph, 18 kmph, and 21 kmph at three locations with three pedestrian configurations. The head injury responses (Head Injury Criteria) for all the variables are obtained.

TABLE 7.2

HEAD INJURY CRITERIA BASED ON SPEED, LOCATION, AND CONFIGURATION

Impact Speeds → Frontal Impact Positioning↓	HIC 15 kmph	HIC 18 kmph	HIC 21 kmph
Center - Side Impact	17	107	283
Right - Side Impact	15	96	268
Left - Side Impact	20	134	348
Center - Front Impact	1644	2781	4465
Right - Front Impact	1565	2641	4164
Left - Front Impact	1280	2164	3476
Center - Rear Impact	821	1268	3023
Right - Rear Impact	970	2118	4834
Left - Rear Impact	548	1165	2888

7.2.2 Modification of Hood Stiffness to Protect the Pedestrian

The design of experiments analysis with a full-size pedestrian model is carried out with the vehicle parameters by reducing the stiffness of the hood to 50% and 25% as mentioned in Table 7.3 and Table 7.4 respectively. The simulations are carried out for the full-size pedestrian model with speeds 15 kmph, 18 kmph, and 21 kmph at three locations with three pedestrian configurations. The head injury responses (Head Injury Criteria) for all the variables are obtained.

TABLE 7.3

HEAD INJURY CRITERIA WHEN STIFFNESS OF HOOD IS REDUCED TO 50%

Impact Speeds → Frontal Impact Positioning↓	HIC 15 kmph	HIC 18 kmph	HIC 21 kmph
Center - Side Impact	10	78	179
Right - Side Impact	8	57	182
Left - Side Impact	13	88	227
Center - Front Impact	978	1822	2625
Right - Front Impact	986	1752	2982
Left - Front Impact	879	1384	2738
Center - Rear Impact	594	870	1921
Right - Rear Impact	668	1348	3126
Left - Rear Impact	335	692	1946

TABLE 7.4

HEAD INJURY CRITERIA WHEN STIFFNESS OF HOOD IS REDUCED TO 25%

Impact Speeds → Frontal Impact Positioning↓	HIC 15 kmph	HIC 18 kmph	HIC 21 kmph
Center - Side Impact	6	47	104
Right - Side Impact	4	31	116
Left - Side Impact	8	32	111
Center - Front Impact	426	964	1518
Right - Front Impact	572	935	1762
Left - Front Impact	389	748	1634
Center - Rear Impact	318	622	1129
Right - Rear Impact	293	844	2018
Left - Rear Impact	118	351	946

7.3 Discussion of Design of Experiments

The design of experiments (DOE) is conducted as per the factors (A. Speed, Impact configuration and Location, and B. Modification of hood stiffness to protect the pedestrian) and obtaining Head Injury responses (HIC-36 and HIC-15). The performed simulations show the effect of impact conditions on Head Injury Criteria. The following observations made in the DOE analysis are:

- Among the impact conditions, impact speed is the initial parameter that has more influence when compared to location and configuration.
- The location of impact leads to more variation in HIC values with its impact speed.
- In primary contact conditions, stiffness is the most influential factor leading to higher injuries.
- Overall, impact speed is the largest contributing factor towards higher head injuries (HIC), followed by stiffness of the hood.
- At reducing stiffness values at various speeds, the values are within the biomechanical limit and pedestrian protection is obtained.
- At low speeds, pedestrian protection is attenable for different vehicle parameters when compared to high speed.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

This research was focused on the investigation of the kinematic behavior of adult pedestrians in a pickup truck impact at different speeds. A wayfarer – Pickup truck impact reconstruction was modeled by using MADYMO simulation software, used to run crash simulations. The validated ellipsoidal truck and pedestrian model were used to perform all 45 computational simulations. The injury responses sustained by the head, chest, pelvis, and lower extremities of the pedestrian were studied from the accelerations evaluated from MADYMO analysis and results. The complete pedestrian behavior and impact locations of the head at different speeds at three different locations (Center, Right, and Left) in the front end of the truck were also examined. The most important factors such as Head Injury Criteria, Maximum Head Resultant Acceleration, Knee forces, Maximum Tibia Resultant Acceleration, Femur Bending moments were obtained from pedestrian during the collision based on proposed EEVC injury criteria. Finally, the Design of Experiments (DOE) for truck frontal design was performed. The injury responses obtained were compared with the earlier study.

The following conclusions can be obtained from this study:

- The severity of the injury of the pedestrian is highly affected by impact velocity and location and decreased by reducing the hood stiffness.

- The impact location of the head and as well as the pedestrian impact configuration affect the resultant injury potential.
- For Head Injury Criteria, the values are higher for front impact when compared with side and rear impact at all three locations. The values have exceeded the biomechanical limits (HIC-36 < 1000, HIC-15 < 700) almost 7-9 times in front impact and rear impact leading to mass fractures.
- Expect at 15kmph for side-impact, the head resultant accelerations at all the three locations at three different pedestrian configurations exceeded the biomechanical limits (80g). Among the three impacts, head accelerations are high for front impact than side and rear impact.
- As for the chest injuries, the maximum viscous injury response with a limit of 1.0 m/s was also studied. In this study, all viscous injury responses are within the limit in all simulations.
- Thorax injuries are also one of the contributing factors towards deaths of pedestrians in side impacts. In simulations, the truck is directly hit the thorax and the TTI values for speeds above 21 kmph were higher exceeding the biomechanical limit.
- In Front and Rear impacts, the Torso Resultant accelerations at all speeds and all configurations exceeded the biomechanical limits as hood height is almost double that compact car. Comparing among them, injury is severe at front impact than rear impact.
- Knee forces are low and within the tolerance levels for side impacts and Knee force values exceeded the limits for rear and front impact and the pedestrian is amputated. The values are almost 2.3 times higher than the tolerance level in front and rear impact. This is because the hood is also striking the legs along with the thorax and pelvis.

- At low extremities, injuries such as Tibia accelerations and Femur Bending moments exceeded the biomechanical limits almost 1-2 times more for higher speeds and leading to multiple fractures. Injuries at the front impact are severe when compared with the side and left the location.
- In the case of side impact configuration, the injuries to the pelvis were within the threshold limit.
- Impact speed has a crucial effect on the severity of the pedestrian injury. The higher the impact speed, the higher the Head Injury Criteria has resulted.
- The evaluation of the Design of experiments with the pedestrian model was performed for low and medium speeds for the truck front design.
- Overall, the study provides a method to update vehicle design to reduce the injuries and fatalities to wayfarers and can also be utilized for future collision protection regulations.

8.2 Recommendations

The following are some recommendations generated from the study for additional research into this area as future work, as well as some suggestions for avoiding or minimizing pedestrian fatalities by changing the front-end design of lightweight pickup trucks.

- The analysis can be performed with other pedestrian models such as 3 – year old pedestrian, 6 – year old pedestrian, 5th percentile pedestrian, and 95th percentile pedestrian.

- The Finite Element Method analysis can be performed by coupling MADYMO and LS-DYNA, to obtain a better representation of the structure of the vehicle interacting with a pedestrian.
- The hood can be equipped with extra airbags that would act as energy-absorbing components to reduce the injuries of a pedestrian.
- Additional investigation can be done on the secondary contact of the pedestrian.
- The application of a braking system with sensors on the truck hood can be used to detect obstacles in the path and thus slowing the vehicle.
- Changing the position of the hood can be used to study the severity of injury in lower extremities more precisely.
- Change of hood material and increasing the distance between engine components and the bonnet could reduce pedestrian injuries.

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