HVE-WP-2026-3

Reconstruction of Real World Frontal Impact Vehicle Collisions Using HVE with GATB – A Case Study of Unrestrained vs. Restrained Occupant Kinematics.

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2026 HVE Forum
New Orleans, LA
March 2-6, 2026

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Abstract

Occupant kinematics in motor vehicle crashes are frequently studied to analyze what interior structures occupants interact with during a crash and the severity of these interactions. Occupant motion simulation studies can inform how occupants may have been injured in a crash. An in-depth investigation was conducted of a high-speed frontal crash involving two unrestrained front seat occupants that sustained lower extremity fractures. A reconstruction of this high-speed collision between a 2008 Chevrolet Impala and a 2019 Ford F350 was modeled via Human Vehicle Environment (HVE) incorporating the Graphical Articulated Total Body (GATB) program. This reconstruction was performed to evaluate the performance of GATB in modeling the occupants' kinematics, including body motion and predicted points of vehicle interior interaction, for the two unrestrained front seat occupants within the Chevrolet Impala. Vehicle dynamics and post-collision vehicle damage were reconstructed using the HVE program and validated using the subject vehicles' EDR downloads and post-collision photos. The acceleration pulse was then utilized in GATB to predict the occupant kinematics in this crash. The occupant kinematic results and associated points of interior impact were compared and validated with the available New Car Assessment Program (NCAP) frontal crash testing data that utilized unrestrained occupants in a Chevrolet Impala. These results were also analyzed to determine the consistency of the point of interior impact as compared to the mechanisms of the diagnosed injuries from the occupants' post-collision medical records. HVE with GATB occupant kinematic reconstructions for the two front occupants demonstrated the initial impact of the knee on the dashboard and subsequent loading of the knee-femur-hip pelvis during the collision. This dashboard impact was consistent with the blunt force injuries reported. The same crash was then rerun, this time having the two front seat occupants utilizing lap/shoulder belts to compare their occupant motion and any change to points of interior interaction or impact. HVE with GATB demonstrated the influence the front two occupants' seatbelt restraints had on their interactions with the vehicle interior and the reduced likelihood of receiving blunt force injuries during the collision.

Introduction

The EDR data retrieved from a 2008 Chevrolet Impala showed that it was traveling 78 mph with an unbelted male driver and an unbelted female front seat passenger. A 2019 Ford F-350 accelerated from a near-stop across the Impala's path. The Impala decelerated to approximately 63 mph before impacting the front passenger side door and tire of the F-350. The F-350 was traveling approximately 16.7 mph at impact. This study evaluates whether GATB simulations can reproduce interior interaction patterns that are consistent with real-world injury outcomes.

Incident Vehicle Data

Impala

Figure 1 – Point Cloud of incident Impala damage.

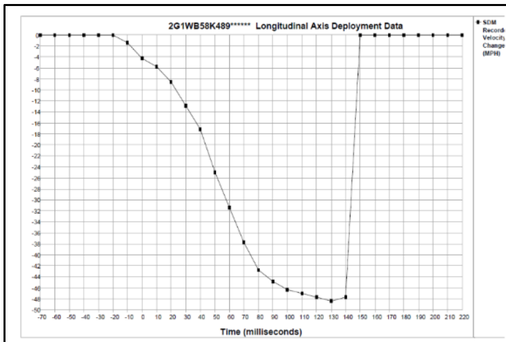
The Impala's driver and front passenger pretensioners and airbags deployed. The Impala's Airbag Control Module

(ACM) download recorded a delta-V of -47.75 mph longitudinally and 9.98 mph laterally within 130 milliseconds.

System Status At Deployment

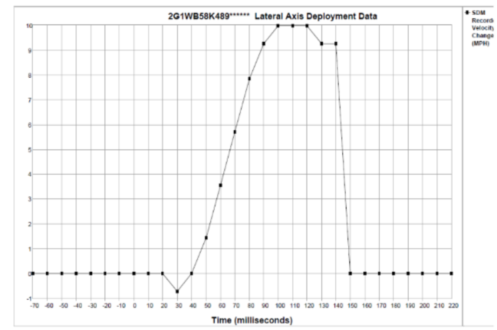
Ignition Cycles At Investigation	20176
SIR Warning Lamp Status	OFF
SIR Warning Lamp ON Time Continuously (seconds)	0
Number of Ignition Cycles SIR Warning Lamp was ON/OFF Continuously	5
Ignition Cycles At Event	20176
Ignition Cycles Since DTCs Were Last Cleared	255
Driver's Belt Switch Circuit Status	UNBUCKLED
Passenger's Belt Switch Circuit Status	UNBUCKLED
Passenger Classification Status at Event Enable	Large Occupant Classification Type #1
Passenger Air Bag Indicator Status at Event Enable	ON
Diagnostic Trouble Codes at Event, fault number: 1	N/A
Diagnostic Trouble Codes at Event, fault number: 2	N/A
Diagnostic Trouble Codes at Event, fault number: 3	N/A
Diagnostic Trouble Codes at Event, fault number: 4	N/A
Diagnostic Trouble Codes at Event, fault number: 5	N/A
Diagnostic Trouble Codes at Event, fault number: 6	N/A
Diagnostic Trouble Codes at Event, fault number: 7	N/A
Diagnostic Trouble Codes at Event, fault number: 8	N/A
Diagnostic Trouble Codes at Event, fault number: 9	N/A
Driver 1st Stage Time From Algorithm Enable to Deployment Command Criteria Met (msec)	14
Driver 2nd Stage Time From Algorithm Enable to Deployment Command Criteria Met (msec)	16
Passenger 1st Stage Time From Algorithm Enable to Deployment Command Criteria Met (msec)	14
Passenger 2nd Stage Time From Algorithm Enable to Deployment Command Criteria Met (msec)	16
Driver Side or Roof Rail/Head Curtain Time From Algorithm Enable to Deployment Command Criteria Met (msec)	N/A
Passenger Side or Roof Rail/Head Curtain Time From Algorithm Enable to Deployment Command Criteria Met (msec)	N/A
Time Between Events (sec)	N/A
Crash Record Locked	Yes
Vehicle Event Data (Pre-Crash) Associated With This Event	Yes
SDM Synchronization Counter	20175
Event Recording Complete	Yes
Driver First Stage Deployment Loop Commanded	Yes
Passenger First Stage Deployment Loop Commanded	Yes
Driver Second Stage Deployment Loop Commanded	Yes
Driver 2nd Stage Deployment Loop Commanded for Disposal	No
Passenger Second Stage Deployment Loop Commanded	Yes
Passenger 2nd Stage Deployment Loop Commanded for Disposal	No
Driver Pretensioner Deployment Loop Commanded	Yes
Passenger Pretensioner Deployment Loop Commanded	Yes
Driver Side Deployment Loop Commanded	No
Passenger Side Deployment Loop Commanded	No
Second Row Left Side Deployment Loop Commanded	No
Second Row Right Side Deployment Loop Commanded	No
Driver (Initiator 1) Roof Rail/Head Curtain Loop Commanded	No
Passenger (Initiator 1) Roof Rail/Head Curtain Loop Commanded	No
Driver (Initiator 2) Roof Rail/Head Curtain Loop Commanded	No
Passenger (Initiator 2) Roof Rail/Head Curtain Loop Commanded	No
Driver (Initiator 3) Roof Rail/Head Curtain Loop Commanded	No
Passenger (Initiator 3) Roof Rail/Head Curtain Loop Commanded	No
Driver Knee Deployment Loop Commanded	No
Passenger Knee Deployment Loop Commanded	No
Second Row Left Pretensioner Deployment Loop Commanded	No
Second Row Right Pretensioner Deployment Loop Commanded	No
Second Row Center Pretensioner Deployment Loop Commanded	No

Figure 2 – Impala ACM deployment commands.



Time (milliseconds)	-70	-60	-50	-40	-30	-20	-10	0	10	20	30	40	50	60	70
SDM Longitudinal Axis Recorded Velocity Change (MPH)	0.00	0.00	0.00	0.00	0.00	0.00	-1.43	-4.28	-5.70	-8.55	-12.83	-17.11	-24.94	-31.36	-37.77
Time (milliseconds)	80	90	100	110	120	130	140	150	160	170	180	190	200	210	220
SDM Longitudinal Axis Recorded Velocity Change (MPH)	-42.76	-44.90	-46.33	-47.04	-47.75	-48.46	-47.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Figure 3 – Impala ACM longitudinal delta-V.



Time (milliseconds)	-70	-60	-50	-40	-30	-20	-10	0	10	20	30	40	50	60	70
SDM Lateral Axis Recorded Velocity Change (MPH)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.71	0.00	1.43	3.56	5.70
Time (milliseconds)	80	90	100	110	120	130	140	150	160	170	180	190	200	210	220
SDM Lateral Axis Recorded Velocity Change (MPH)	7.84	9.27	9.98	9.98	9.98	9.27	9.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Figure 4 – Impala ACM lateral delta-V.

Scans of the incident Impala and a non-damaged exemplar were compared and showed no intrusion into the occupant compartment.

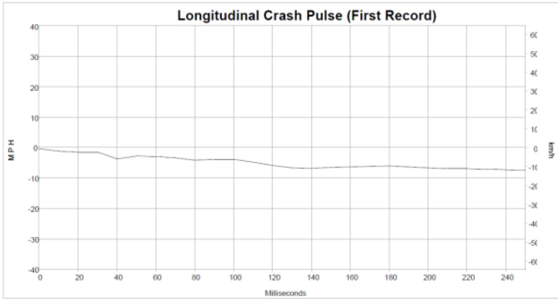
Figure 5 – Overlay of incident and exemplar Impala vehicles.

Figure 6 – Overlay of incident and exemplar Impala vehicles.

F-350

Figure 7 – Point Cloud of incident F-350 damage.

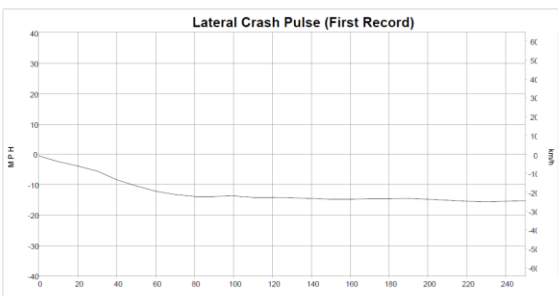
The side airbags deployed in the F-350. The F-350's ACM recorded a delta-V of -7.47 mph longitudinally and -15.25 mph laterally.



Longitudinal Crash Pulse (First Record)

Time (msec)	Delta-V, longitudinal (MPH)	Delta-V, longitudinal (km/h)
0	-0.42	-0.67
10	-1.12	-1.81
20	-1.52	-2.44
30	-1.55	-2.50
40	-3.62	-5.82
50	-2.68	-4.32
60	-2.82	-4.54
70	-3.37	-5.42
80	-4.18	-6.72
90	-3.81	-6.13
100	-3.81	-6.13
110	-4.83	-7.78
120	-5.87	-9.44
130	-6.58	-10.59
140	-6.81	-10.96
150	-6.51	-10.48
160	-6.33	-10.18
170	-6.13	-9.86
180	-6.00	-9.65
190	-6.34	-10.20
200	-6.73	-10.83
210	-6.90	-11.10
220	-6.98	-11.24
230	-7.14	-11.49
240	-7.28	-11.72
250	-7.47	-12.02

Figure 8 – F-350 ACM longitudinal delta-V.



Lateral Crash Pulse (First Record)

Time (msec)	Delta-V, Lateral (MPH)	Delta-V, Lateral (km/h)
0	-0.50	-0.81
10	-2.42	-3.90
20	-3.85	-6.20
30	-5.56	-8.94
40	-8.42	-13.55
50	-10.37	-16.69
60	-12.06	-19.41
70	-13.21	-21.26
80	-13.83	-22.25
90	-13.79	-22.19
100	-13.75	-22.13
110	-14.12	-22.73
120	-14.17	-22.81
130	-14.38	-23.15
140	-14.42	-23.21
150	-14.73	-23.70
160	-14.73	-23.70
170	-14.68	-23.62
180	-14.60	-23.50
190	-14.55	-23.42
200	-14.86	-23.91
210	-15.12	-24.33
220	-15.49	-24.93
230	-15.58	-25.08
240	-15.40	-24.78
250	-15.25	-24.55

Figure 9 – F-350 ACM lateral delta-V.

Impala Occupant Injuries

The driver of the Impala was a 22-year-old male, approximately 74 inches tall who weighed approximately 160 lbs. He sustained a right closed fibular fracture, a right open tibial fracture, a right foot Lisfranc injury, and multiple abrasions/contusions between the right knee and the right foot according to the provided medical records.

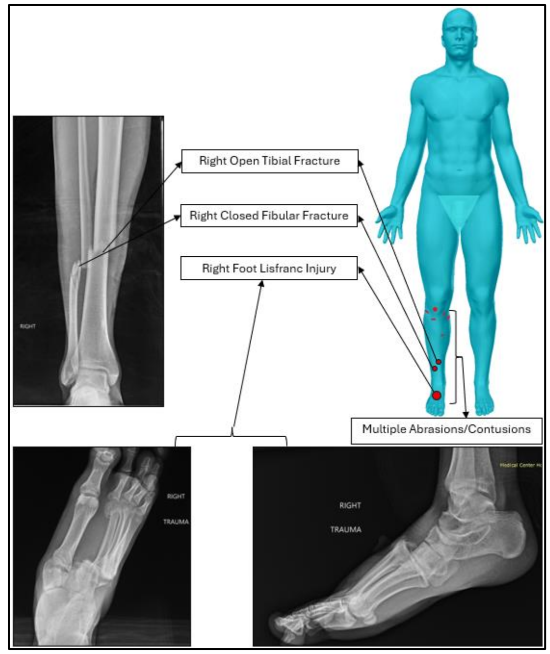


Figure 10 – Schematic diagram for Impala unrestrained male occupant injuries with corresponding radiographs.

The front passenger of the Impala was a 19-year-old female, approximately 65 inches tall who weighed approximately 225 lbs. She sustained a right posterior hip dislocation, a right transverse acetabular fracture, a right posterior acetabular wall fracture, a right femoral shaft fracture, a right distal humerus fracture, a left ulnar shaft fracture, and 3rd -5th right rib fractures according to the post-collision medical records.

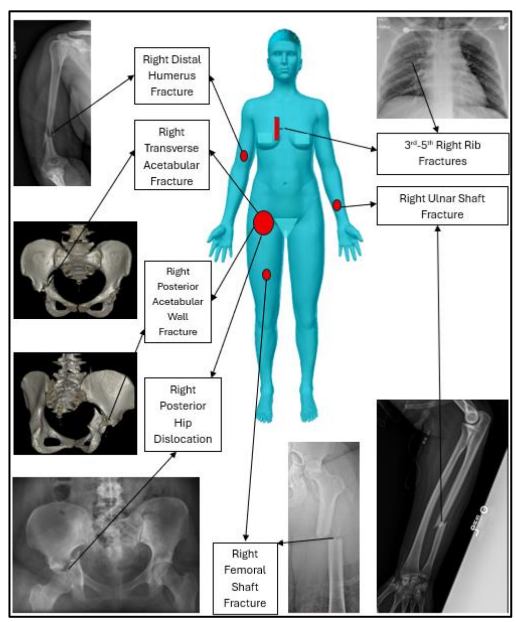


Figure 11 – Schematic diagram for Impala unrestrained female occupant injuries with corresponding radiographs.

HVE and GATB Simulation

The collision was reconstructed using the HVE-compatible EDSMAC4 simulation model and GATB. Custom 3D exemplar models were created from 3-dimensional scan data for both vehicles.

The Impala ACM data was sufficient to simulate the collision pulse directly in GATB using the longitudinal and lateral delta-V. A collision pulse including longitudinal and lateral speeds and yaw for the Impala was determined by an EDSMAC4 simulation for the purposes of this paper. The vehicles were impacted at the approximate recorded impact speeds from the ACM data. The crash was validated by comparing the resulting simulated delta-Vs to the ACM recorded delta-Vs in both vehicles.

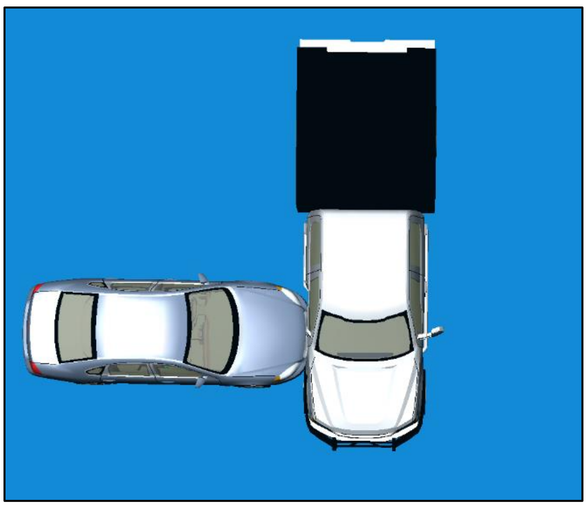


Figure 12 – Approximate alignment in EDSMAC4.

Seat, seatbelt, and steering wheel positions from the incident Impala scans were measured and replicated in an exemplar Impala. Contact surfaces required for GATB were created in the Impala model based on the interior scans of the undamaged exemplar. Contact surfaces used were the seat pan, seatback, dashboard, floorboards, brake pedal, doors, steering wheel, and airbags.

GATB surfaces for the approximate inflated airbag locations were determined by the airbag deployment zones outlined in the General Motors Police Municipal Vehicles Guide and the Chevrolet Municipal Vehicles Technical Manual for police modifications for the Chevrolet Impala.

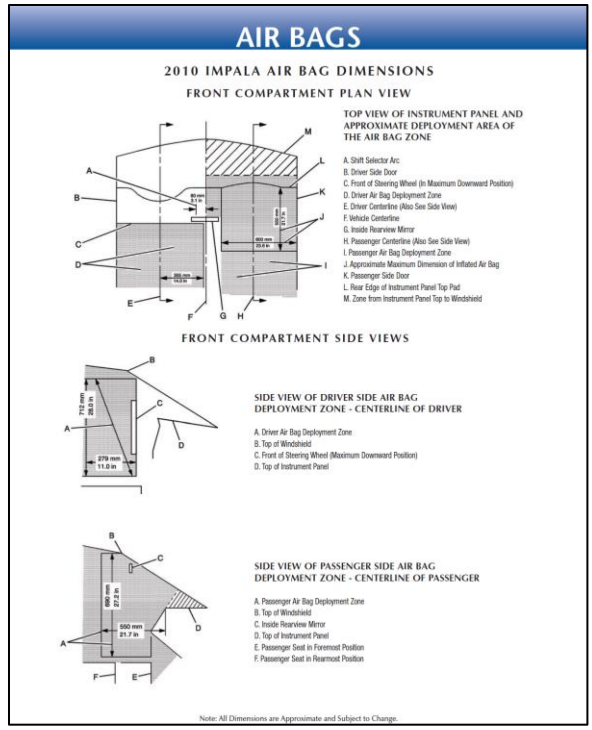


Figure 13 – 2010-GM-Police-Impala Municipal-Guide for 2010 Impala Airbag Dimensions

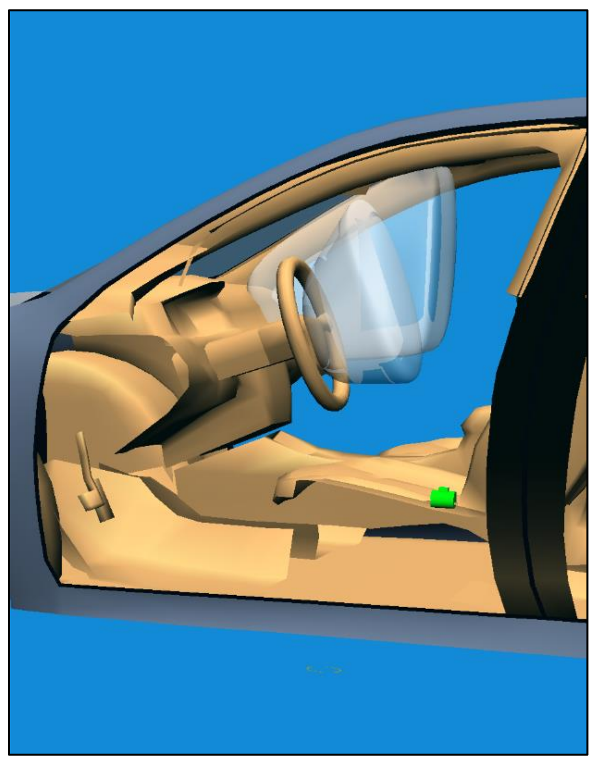


Figure 14 – Representation of the Impala airbag contact surfaces for GATB.

Review of the NCAP crash testing showed airbag inflation time for the Impala to be approximately 0.03 seconds. The Impala ACM showed the deployment command was given approximately 0.016 seconds after the trigger threshold. The trigger threshold was approximately 0.01 to 0.02 seconds after the beginning of contact. The airbag would have reached peak inflation approximately 0.046 seconds after the trigger threshold was met or 0.056 to 0.066 seconds after the beginning of the crash sequence. The GATB simulation showed the unbuckled occupants reached the airbag zone approximately 0.055 seconds into the crash sequence. The airbag was likely still inflating when the unrestrained occupants reached the airbag inflation zone.

Generator of Body Data (GEBOD) human models were created in HVE that matched the gender, weight, and height found in the medical records provided for the Impala occupants. These human models were then imported to GATB and placed in their respective seats in the Impala model. Contact interactions between the appropriate vehicle services and body segments were activated.

The GATB simulation was executed using the crash pulse calculated by EDSMAC4. In one simulation, the modeled seatbelt positions were activated to engage with the occupant chest and pelvis using both the torso belt and lap belts respectively. Pre-tensioners were not used in this simulation (the default of 0 inches of slack was used) in order to perform as conservative analysis. This was compared to another GATB simulation with the same crash pulse and starting body positions without the use of belt restraints.

Results

In the unbuckled simulation, both the driver and passenger interact with the airbag, likely before it was fully inflated. In the buckled simulation, both occupants remain coupled to the seats and no interaction with the airbag occurs.

Driver

Simulation of the unrestrained driver shows his right knee interacted with the dashboard and then his right foot slipped over the brake pedal and interacted with the floorboard. This is consistent with the driver's injuries described in the medical records. The restrained model's right knee does not interact with the dashboard, and the right foot does not impact on floorboard beyond the pedal.

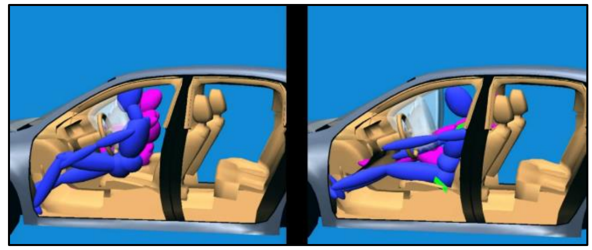


Figure 15 – Driver's furthest forward position during the crash sequence both unbuckled (left) and buckled (right).

Passenger

The passenger in the unrestrained simulation impacts the dashboard with both knees. This is consistent with the injuries described in the medical records. In the restrained simulation, the passenger's knees do not reach the dashboard and the reported injuries would likely been prevented.

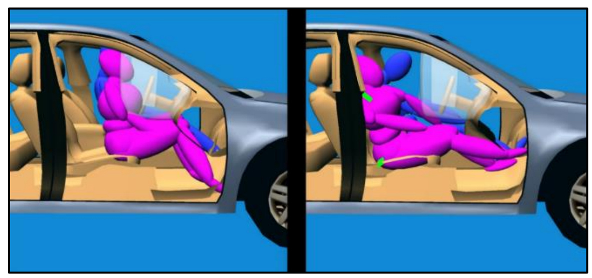


Figure 16 – Passenger's furthest forward position during the crash sequence both unbuckled (left) and buckled (right).

Validation

1. Crash Testing

The National Highway Traffic Safety Administration (NHTSA) Report No. 208-MGA-2007-004 includes test results for a 2007 Chevrolet Impala following a frontal barrier collision at 40 kph (25 mph) utilizing unbelted driver and passenger Anthropometric Test Devices (ATDs). The tested Impala experienced a 28.3 mph delta-V. The crash test resulted in frontal airbag deployments. The following photographs show the pre- and post-test images of the vehicle and passenger ATDs for a qualitative comparison of the points of contact with the interior structures. The dummies were painted to show head, face, and knee contact with the vehicle interior during the crash sequence. Video of the crash test sequence shows the airbags were fully inflated prior to the unrestrained occupants reaching the airbag.

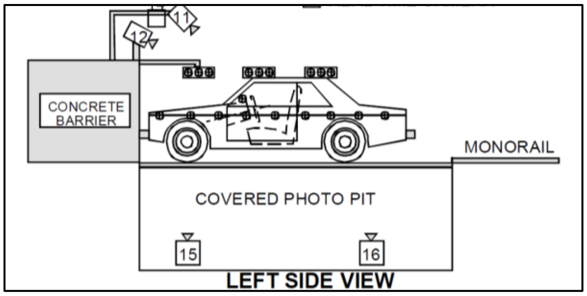


Figure 17 – Crash test setup [NHTSA Report No. 208-MGA-2007-004].

Figure 18 – Unrestrained Driver pre-test [NHTSA Report No. 208-MGA-2007-004].

Figure 19 – Unrestrained Driver post-test [NHTSA Report No. 208-MGA-2007-004].

Figure 20 – Unrestrained Driver post-test airbag contact [NHTSA Report No. 208-MGA-2007-004].

Figure 21 – Unrestrained Driver post-test showing locations of knee contact [NHTSA Report No. 208-MGA-2007-004].

Figure 22 – Unrestrained passenger pre-test [NHTSA Report No. 208-MGA-2007-004].

Figure 23 – Unrestrained passenger post-test [NHTSA Report No. 208-MGA-2007-004].

Figure 24 – Unrestrained passenger post-test airbag contact [NHTSA Report No. 208-MGA-2007-004].

Figure 25 – Unrestrained passenger post-test showing locations of knee contact [NHTSA Report No. 208-MGA-2007-004].

2. Biomechanical Relevance and Literature Review

The injuries that both occupants sustained are considered blunt force injuries. The occupants' treating physician's records reinforced that these injuries were classified as blunt force in nature. The injury patterns are consistent with interactions with vehicle interior structures during unrestrained forward motion.

As the Impala impacted the Ford in the incident collision, the driver's unrestrained body moved forward relative to the vehicle, towards the point of impact. This forward motion resulted in contact between the upper half of his body and the steering wheel, or his respective front airbag as it inflated and the lower half of his body interacted with the rigid interior components such as the lower dashboard/floor pan. Published literature has shown that forward excursions due to lack of seatbelt use during frontal collisions usually cause a driver to impact the airbag prior to or during the inflation phase of airbag deployment (instead of the deflation phase). This exposes the driver to contact with rigid structures (e.g., steering wheels, dashboard, windshield, inflating airbags, etc.) [Horsch 1990, Yoganandan 1993, Crandall 1994, Crandall 1997, Berg 1998, Yoganandan 2015, Schmitt 2019]. Literature discussing frontal collision testing with restrained and unrestrained occupants also shows that a lack of seatbelt usage increases the loading of the lower extremities during the forward excursion phase of the collision [Rudd 1998]. McGwin, et. al, concluded that airbag deployment among unbelted occupants increases the risk of lower extremity injuries [McGwin 2003].

As the Impala impacted the Ford in the subject collision, the unrestrained passenger's body moved forward relative to the vehicle, towards the point of impact. This forward motion results in contact between the upper half of her body and the upper dashboard or the passenger airbag as it inflated and the lower half of her body interacted with the rigid interior components such as the glovebox door/handle. Published literature has shown that forward excursions during frontal collisions due to lack of seatbelt use cause a front passenger to impact the airbag prior to or during the inflation phase of airbag deployment (instead of the deflation phase). This exposes a passenger to contact with rigid structures (e.g., dashboards, windshield, inflating airbags, etc.). This contact can induce injuries to the head, thorax, upper extremities, and lower extremities [Horsch 1990, Yoganandan 1993, Crandall 1994, Crandall 1997, Berg 1998, Yoganandan 2015, Schmitt 2019].

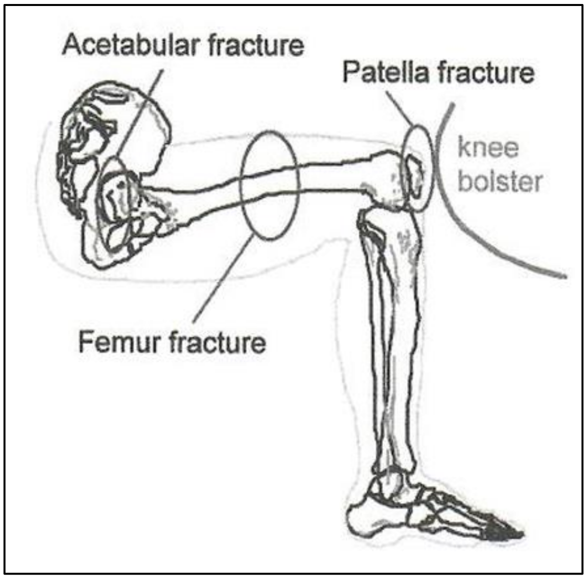


Figure 26 – Dashboard impact injury mechanism showing possible fracture locations for unrestrained/improperly restrained occupants that impact their knee(s) on the dashboard during frontal collisions [Schmitt 2019].

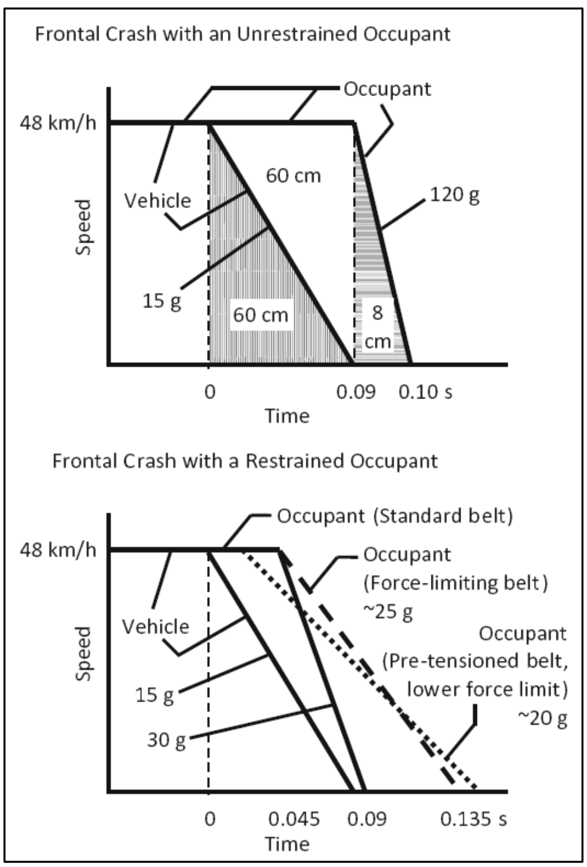


Figure 27 – Comparison of unrestrained and restrained occupants in frontal crashes of 48 km/h (30 mph) [Yoganandan 2015].

Study Limitations

This case study represents the reconstruction of single frontal impact scenario. Occupant position, restraint use, airbag modeling assumptions, and variations in crash configuration or accident type may influence kinematic outcomes.

Summary

The simulation effort described was used to determine the extent to which the Impala's unrestrained occupants interacted with the Impala's vehicle interior. The simulation effort described was also used to determine the likelihood that the unrestrained Impala occupants' blunt force injuries as diagnosed by their treating physicians would have been prevented had they utilized their seatbelt restraints.

This study demonstrated that HVE EDSMAC4 utilizing GATB can be used to evaluate unrestrained occupant movement and potential interior contact locations during a frontal collision. The simulation model was validated by comparing the interior surfaces the model predicted the occupants would interact with and the observed interior components that the ATDs interacted with during unrestrained NCAP frontal crash testing.

A literature review of injuries sustained during unrestrained frontal crash occupant motion sequences further validated the study. The papers and studies reviewed connected the mechanism of inducing the occupant's diagnosed injuries to the points of contact that had been predicted by the GATB model. The correlation between the points of contact inside the vehicle and injury causation was also observed during the unrestrained NCAP frontal crash testing

The GATB model incorporating seatbelt restraints also reiterated how the use of seatbelts reduces or prevents such interactions between the body and vehicle interior, decreasing the likelihood of blunt force "dashboard injuries" in frontal collisions.

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