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**Case Study: Forensic Simulation of Passenger Dynamics in
Airborne Turbulence and Crash Events Using HVE, GATB, and
FDR Data**

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Forensic Simulation of Passenger Dynamics in Airborne Turbulence and Crash Events Using HVE, GATB, and FDR Data

Thomas Jenkyn, PhD, PEng

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ABSTRACT

Instances of severe turbulence appear to have increased in recent years, leading to a rise in litigation involving passenger injuries sustained during such events. Also, several high-profile air crashes involving commercial aircraft, such as the 2018 and 2019 Boeing 737 Max 8 crashes, and the collision between a US Army helicopter and a commercial jet landing at Reagan National Airport in Washington, DC, have also been the subject of injury-related litigation.

The Human Vehicle Environment (HVE) and Graphical Articulated Total Body (GATB) software packages are built upon the underlying Articulated Total Body (ATB) formulation originally developed in the late 1960s for simulating air crashes. ATB was initially applied to improve aircrew survivability, optimize cabin layouts, and enhance restraint systems—capabilities that continue within the modern HVE-GATB environment. Flight data recorder (FDR) outputs, including three-dimensional linear accelerations and roll, pitch, and yaw rates from which angular accelerations can be derived, provide a rich source of mechanical and flight dynamics data for these simulations. HVE enables detailed modeling of aircraft interiors, contact surfaces, and

restraint systems to simulate occupant motion under dynamic conditions.

This paper presents simulations of passenger kinematics and kinetics during an actual severe turbulence event and a crash scenario in a commercial airliner and private business jet, that have been used in litigation of passenger injury and death to date.

THE LITIGANTS

For several cases of this type, the author has been retained by the lawyers for the plaintiff passengers and air crew, and their surviving family to investigate these incidents from a biomechanical perspective. In particular, the author was asked to determine effects of the acceleration magnitude, direction and frequency acting on the occupant's body during the incidents based on the flight data recorder (FDR) data. In particular, the author was asked to determine the motion of the head, neck, arms and legs and their interaction with their surroundings, and whether any biomechanical loading was sufficient to cause injury. The author was also asked to determine whether the seat and seatbelt restraints would have caused injury.

THE INCIDENTS

The incidents under study occur within the passenger cabin of a commercial or business jet aircraft such as the narrow-body Boeing 737 Max 8 or the business jet Gulfstream G280. The cabin layout comprised economy or first-class seating sections, with passengers oriented in forward-facing, rearward-facing, and limited side-facing configurations depending on seat position and cabin arrangement. A representative cabin section is shown in Figure 1.

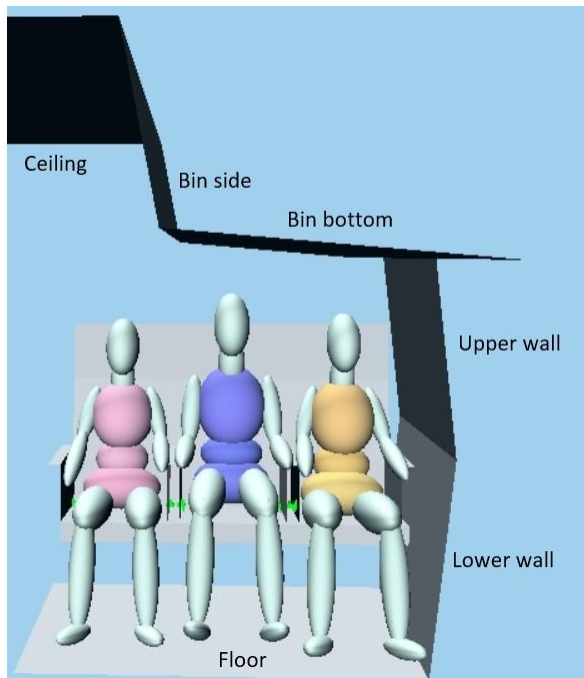


Figure 1: Frontal view of three passenger body models in economy class seats with lap belts secured. Contact surfaces of the aircraft cabin are labeled. The seat and armrest were also contact surfaces.

The analyses focus on occupant kinematics, kinetics, and injury mechanisms arising from aircraft accelerations recorded during in-flight upset conditions. The dynamic environment within the cabin is defined using flight data

recorder (FDR) data, including linear accelerations in the longitudinal, lateral, and vertical axes of the aircraft reference frame. In addition, time histories of pitch, roll, and yaw rates are incorporated to capture the rotational components of motion (Figure 2). The spatial position of each passenger within the aircraft fuselage is explicitly modeled, recognizing that translational and rotational accelerations vary as a function of distance from the aircraft center of gravity.



Figure 2: Examples of the two aircraft involved and the non-inertial reference frames attached to each.

Occupants are represented using Graphical Articulated Total Body (GATB) models, scaled to match each occupant's anthropometry, specifically height and inertia. The human body model consists of 15 linked segments that are connected at 14 discrete joints. The biomechanical loading and kinematics of each segment were calculated

throughout each simulation. Passengers were restrained by lap seatbelts attached to the seat structure. Aircrew members seated in the cockpit or jump seats were restrained using four- or five-point harness systems consistent with aviation standards. The cabin geometry was represented using contact surfaces. These include the seat bottom, seat back, armrests, floor, walls and windows, and overhead stowage bins (Figure 1).

Two example in-flight incidents are examined in this whitepaper. The first involves an extreme turbulence event in a narrow-body commercial jet characterized by large-amplitude vertical accelerations, both positive and negative, producing transient upward ejection and subsequent re-contact with the seat structure.

The second scenario involves a fatal air crash of a business jet during a landing approach conducted at a high rate of bank and descent. While maneuvering in cold weather, the aircraft entered an aerodynamic wing stall during the turning approach. The loss of lift at low altitude resulted in a rapid departure from controlled flight and subsequent ground impact. In this event, the aircraft did not remain structurally intact, and the abrupt deceleration and rotational dynamics generated severe cabin accelerations that produced complex and highly injurious occupant kinematics.

SEVERE TURBULENCE SIMULATION

The clear-air turbulence event in this study was associated with a mountain wave

encounter while the narrow-body commercial aircraft was in straight and level cruise flight. There were no evasive maneuvers or significant control inputs preceding the onset of the disturbance. The severity of the event was sufficient to warrant a formal investigation by the National Transportation Safety Board (NTSB), reflecting the magnitude of the aircraft response and the potential for occupant injury.

Flight Data Recorder (FDR) information was available at a sampling rate of four samples per second, providing adequate temporal resolution to characterize the primary acceleration transients. The turbulence episode persisted for approximately 31 seconds, during which the aircraft experienced substantial fluctuations in vertical acceleration.

The most severe sequence began with a rapid reduction in normal $+1.0\text{ g}$ vertical acceleration down to approximately $+0.22\text{ g}$ within one second, followed by a sharp increase to $+1.78\text{ g}$ over the next two seconds. This was followed by another drop to -0.48 g over 1 second, indicating a period of true negative g , and then a rebound to approximately $+1.72\text{ g}$ within one second. Passengers therefore experienced sustained negative vertical acceleration for slightly more than one second, a condition associated with loss of seat contact for unrestrained occupants and significant belt loading for restrained occupants.

The complete time histories of the three orthogonal aircraft accelerations—longitudinal, lateral, and vertical—are presented in Figure 3. These acceleration

inputs form the basis of the simulation crash pulse.

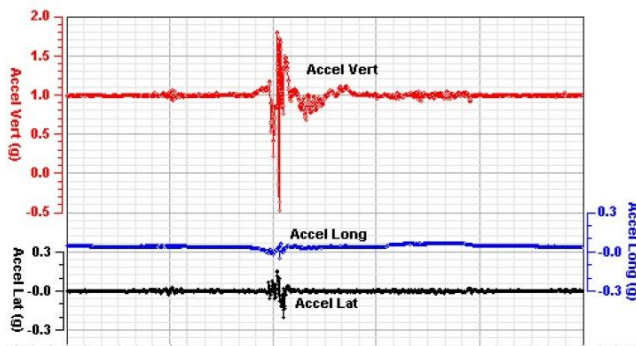


Figure 3: Three accelerations from the clear air turbulence FDR in the vertical (red), longitudinal (blue) and lateral (black) directions as a multiple of g.

INJURIES TO THE PASSENGERS AND FLIGHT CREW

During the actual flight, several unrestrained passengers were reported to have been ejected upward from their seats. This behavior is consistent with the period of true negative vertical acceleration recorded in the FDR data, during which the aircraft experienced negative g conditions sufficient to overcome restraint-free body weight.

To examine this mechanism in detail, three passengers seated in an economy row were modeled (Figure 1). The three orthogonal acceleration components obtained from the FDR were applied in HVE as an acceleration-based collision pulse. A 10-second segment of data was selected for simulation, encompassing the most severe vertical acceleration peaks observed during the turbulence event. The simulations were conducted using scaled GATB articulated human body models.

Simulation outputs included, but were not limited to, joint angles between body model segments in all three directions with respect to time, seatbelt tensions, the contact forces between each body segment and any contact surface struck, and the linear and angular velocities and accelerations of each of the body model segments with respect to time. The simulations were run with a time-step of 0.001 s. Contacts with body segments were run with a shorter time-step of 0.0002 s for the duration of contact.

In the initial simulations of groups of generic passengers in economy and first class seats, occupant scaling was performed by adjusting each GATB human body model for sex, height, and weight across a 5th to 95th percentile range. Male models ranged from 5'-7" to 6'-6" (172–198 cm) in height and 134 to 214 lbs (61–97 kg) in mass, while female models ranged from 4'-11" to 5'-9" (150–177 cm) and 99 to 152 lbs (45–69 kg). The lower bounds captured smaller adults and older children. Given the large number of possible combinations across three economy and two first-class seats, a structured sampling approach was used to run a feasible number of simulations while representing the range of body sizes, sexes, and seating positions and identifying factors most correlated with seatbelt tension. Later, once the litigants were separated into tranches of plaintiffs for individual trials, the passengers in the simulations were scaled to the actual height, weight and sex of each plaintiff. It was found that biomechanical loading was most strongly correlated with passenger weight. It was insensitive to sex and height.

Seatbelt tensile stiffness and strength were modeled in accordance with SAE Aerospace Standard AS8043, "Restraint Systems for Civil Aircraft," for a Type 1 lap belt restraint system. The ultimate tensile strength was set at 5,000 lb (22.2 kN). Belt elongation was defined as 15% at 11.1 kN, representing a stiffness greater than the minimum requirement of 20% elongation at the same load, thereby providing a conservative representation of belt stretch characteristics. Contact surfaces representing the floor, sidewalls, and bulkheads were assigned default material properties within the simulation environment. In contrast, seating surfaces and armrests were modeled with reduced stiffness characteristics consistent with the European Union Aviation Safety Agency (EASA) CS-25 certification standards for commercial-category aircraft seating. Peak biomechanical loading was found to be insensitive to material stiffness of the seatbelt and contacts surfaces. However, time to peak was shorter the stiffer the material properties.

In the modeled seating configuration shown here, the aisle passenger (pink) was unrestrained, while the two adjacent passengers (blue and yellow) were restrained with properly positioned lap seatbelts. Figure 4 illustrates the critical transition in vertical acceleration from +1.78 g to -0.48 g over approximately one second. As the vertical acceleration rapidly crossed through zero and became negative, the unrestrained aisle passenger was ejected upward from her seat. She forcefully impacted the cabin ceiling with her head and remained in contact with the ceiling panel while negative g conditions persisted. She

did not return toward her seat until the vertical acceleration once again became positive. The peak head impact force during ceiling contact was simulated as 876 N (197 lb-f).

In contrast, the restrained passengers remained in their seats due to tensile loading in the lap belts. At the peak negative acceleration of -0.48 g, belt tension reached approximately 68% of body weight. This level of restraint loading is considered highly likely to produce localized bruising or contusion over the anterior superior iliac spines (ASIS) of the pelvis, assuming proper belt positioning across the bony pelvis. If the lap belt is worn improperly over the abdomen rather than low across the iliac crests, the same restraint forces would be transmitted into the abdominal musculature and underlying organs, increasing the potential for soft tissue and visceral injury.

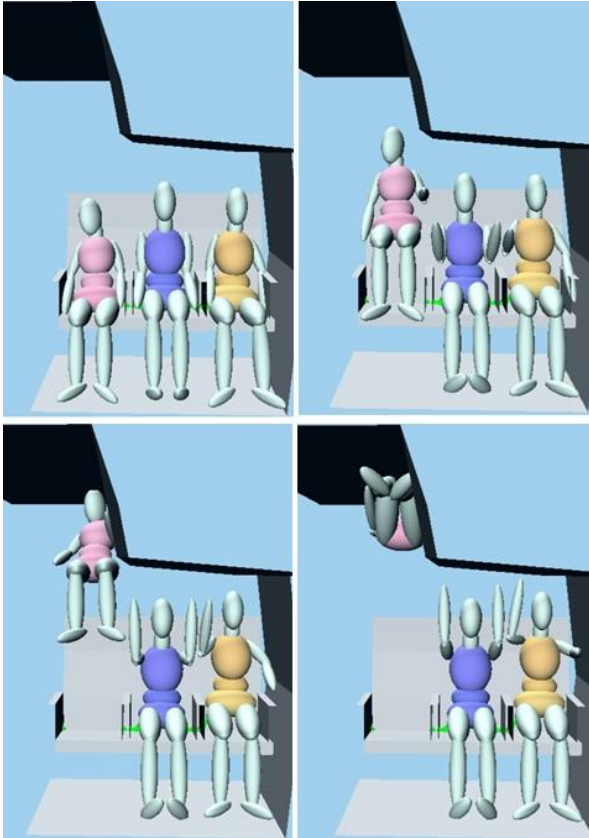


Figure 4: The aisle seat passenger (pink) is unrestrained. The vertical acceleration transitions over 1 second from +1.78 $g's$ (top left) down to -0.48 $g's$ (bottom right). The unrestrained passenger is ejected from her seat and forcefully strikes the ceiling.

HIGH BANK AND DESCENT RATE LANDING

In the second analysis, a business jet was conducting a landing approach into a mountain airport that required a descending left turn with a relatively high rate of descent. The event occurred in December in the northern hemisphere, and ambient air temperatures from the ground up to approximately 10,000 feet were below freezing. Although there was no active

precipitation—no rain, sleet, or snow—the environmental conditions were conducive to wing icing. Evidence suggests that ice accumulated on the left wing during the descent.

Due to the supercritical wing design, which is sensitive to contamination along the leading edge and upper surface, the accumulated ice altered the aerodynamic characteristics of the left wing. The left wing subsequently experienced an aerodynamic stall while the right wing continued to generate lift. This asymmetric lift condition produced a rapid increase in left roll rate and a progressively steepening bank angle that peaked at more than 60 degrees. The aircraft departed controlled flight and impacted terrain short of the runway. All occupants sustained fatal injuries. At issue in this analysis was the nature and severity of occupant loading and injury potential in the seconds immediately preceding ground impact.

The flight data recorder (FDR) was recovered from the accident site, and usable data were successfully extracted. The relevant parameters were sampled at eight samples per second, providing sufficient temporal resolution to characterize the rapid changes in aircraft motion during the final sequence. The aerodynamic stall and resulting high bank rate persisted for approximately eight seconds prior to impact, during which the aircraft reached an extreme left bank angle and exhibited complex translational and rotational accelerations.

At the onset of the wing stall, vertical acceleration was approximately +1.0 g, consistent with steady flight. The aircraft was

decelerating in the longitudinal axis and experiencing a lateral acceleration toward the left. Within one second, vertical acceleration increased to +1.51 g, then decreased to +0.59 g over the following two seconds, before rising again to +1.65 g shortly before impact. Longitudinal acceleration initially increased to +0.21 g after one second, transitioned to a deceleration of -0.19 g at approximately two seconds, and then reversed again to a forward acceleration of +0.43 g prior to ground contact. Lateral acceleration peaked at approximately 0.27 g to the right about 1.5 seconds before impact.

Occupants within the cabin were therefore subjected to a complex three-dimensional acceleration environment, with significant components in the vertical, longitudinal, and lateral directions. These combined accelerations, coupled with the extreme bank angle and rotational motion, would have produced substantial occupant displacement forces. Any unrestrained passenger would likely have been thrown violently about the cabin during this departure from controlled flight.

The complete time histories of the three orthogonal aircraft accelerations—longitudinal, lateral, and vertical—are presented in Figure 5. These acceleration inputs form the basis of the simulation crash pulse.

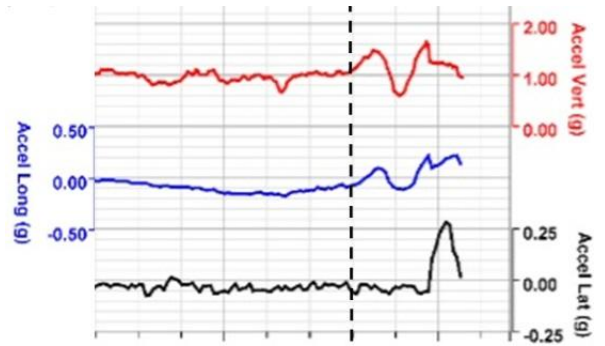


Figure 5: Three accelerations from the high bank turn and crash FDR in the vertical (red), longitudinal (blue) and lateral (black) directions as a multiple of g. The start of wing stall is indicated with the vertical broken line.

INJURIES TO THE PASSENGERS PRIOR TO IMPACT

In the subject flight, there were five persons on board: two adult male passengers, two male pilots, and one female cabin crew member. The precise seating locations of the two passengers and the cabin crew member at the time of the wing stall could not be definitively established from the available evidence. It was presumed that both pilots were seated in the left and right cockpit seats during the landing phase of flight and restrained with a multi-point harness system.

The interior seating configuration of the business jet is illustrated in Figure 6. The cabin layout included seats oriented in multiple directions, with some seats facing forward, others aftward, and at least one oriented laterally toward the left side of the aircraft. Seating positions were distributed along both the left and right sides of the cabin, resulting in differing occupant orientations relative to the aircraft

longitudinal axis and the direction of the developing bank and descent.

Given the uncertainty regarding the seating positions of the passengers and cabin crew member and recognizing that occupant kinematics are strongly influenced by seat orientation and restraint use, all five seating orientations present in the aircraft were evaluated. Each configuration was simulated for both restrained and unrestrained conditions to assess the range of possible occupant motions and loading environments during the eight-second departure from controlled flight.



Figure 6: Business jet seating layout included both forward and aft facing seats on the left and right side of the aircraft as well as a leftward facing couch on the right side of the aircraft. All orientations were simulated.

The simulations were run over the 10 second period starting 2 seconds before the aerodynamic stall until ultimate impact. Simulation outputs included joint angles between body segments in all three planes over time, seatbelt tensions, contact forces between body segments and impacted cabin surfaces, and the linear and angular velocities and accelerations of each body

segment as functions of time. The simulations were executed with a primary time step of 0.001 s, with a refined time step of 0.0002 s applied during body-to-surface contact intervals to improve resolution of impact dynamics.

Figure 7 shows the simulation with a male passenger seated on the left side of the aircraft facing aft. Near the end of the 10 second simulation, the rightward lateral acceleration of the aircraft causes his torso, neck and head to be pushed to the left side of the aircraft. The seatbelt keeps him in his seat, but the tension in the seatbelt peaked at 91.7 N while aft facing and 115.1 N while forward facing. The seatbelt tension peaked at 164.5 N while sitting on the couch.

For the unrestrained simulations, the peak torque on the neck ranged from 1.61 Nm to 4.21 Nm in the flexion direction and 2.9 Nm to 17.1 Nm in the extension direction. The loading on the lower back at the T12-L1 joint ranged from 153.2 N to 215.7 N and at the L5-S1 joint from 148.8 N to 215.7 N. When sitting on the left side of the aircraft and aft-facing, the simulation showed the passenger would have struck his head on the interior wall or window. In this simulation, the contact force on the head was 485 N (109 lb-f).

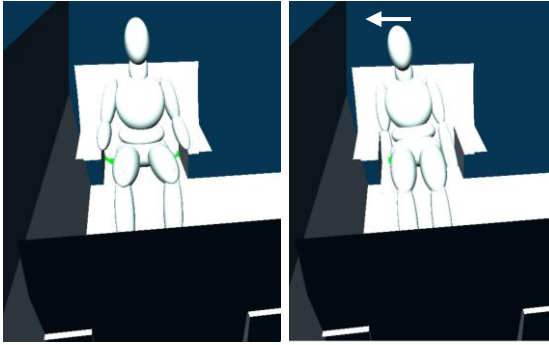


Figure 7: The simulation restrained passenger on left side of the aircraft facing aft. Near the end of the 10 second simulation, the rightward lateral acceleration of the aircraft causes the torso, neck and head to be pushing to the left side of the aircraft (white arrow).

CONCLUSIONS

These two aircraft incident simulations—an extreme clear-air turbulence event and a wing stall-induced loss of control during landing—demonstrate the capability of HVE with GATB human body models to reconstruct complex, three-dimensional occupant dynamics under realistic flight conditions. By directly applying FDR-derived accelerations and rotational data, the analyses quantified restraint loads, contact forces, and occupant kinematics for varied seating orientations and restraint conditions. The results illustrate how negative g events and asymmetric aerodynamic departures generate distinct injury mechanisms. HVE-GATB provides a rigorous, physics-based framework for evaluating occupant motion, restraint effectiveness, and injury potential in aviation environments.

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ABOUT THE AUTHOR

Thomas Jenkyn is the Senior Engineer at TLS Forensic Biomechanics and Engineering Ltd, specializing in forensic biomechanics with emphasis on automotive and aviation injury analysis and occupant dynamics. He has led and contributed to investigations involving commercial and private aircraft, including the Boeing 737 MAX 8 and the US Army helicopter and American Airlines flight 5342 midair collision at Reagan National Airport.

Dr. Jenkyn has been a licensed Professional Engineer since 2004 and serves the Association of Professional Engineers of Ontario by setting and grading the technical examination required to obtain accredited expertise in biomechanics.

Dr. Jenkyn is a Professor of Biomechanics at the University of Western Ontario, holding a joint appointment in the Mechanical and Materials Engineering and the School of Kinesiology, where he conducts research in injury biomechanics and medical imaging that directly informs his aviation and impact simulation work. He holds undergraduate and master degrees in Aerospace Engineering from the University of Toronto, a PhD in Biomedical Engineering from Strathclyde University in Glasgow, Scotland and a Post-doctoral Research Fellowship in Orthopaedic Biomechanics and Diagnostic Radiology from the Mayo Clinic in Rochester, Minnesota.