RESEARCH STUDY #C-02-13
ANALYSIS OF BUS CRASH DATA

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1. INTRODUCTION

When two unequal-weight motor vehicles collide, the lighter one's speed changes more than that of its heavier counterpart. As a result, the lighter vehicle (1) incurs a disproportionately greater amount of the ensuing structural crush/collapse, and (2) exposes its occupants to a higher risk of severe injury. The ramifications of this fundamental principle of physics become especially significant as the weight disparity increases—e.g., a tenfold weight difference between a passenger car and a large transit bus. Consider such a collision where one or both vehicles are moving at high speed at the moment of impact. Crash investigations have shown that for the most part, bus passengers incur less serious injuries than persons in riding in the car. In some of these crashes, the bus undergoes a comparatively small velocity change and its passengers walk away from the incident with very minor injuries or no injuries whatsoever.

Paradoxically, transit bus passengers make injury claims when the vehicle they're riding in experiences an even smaller velocity change following such a collision. Such allegations usually involve occult (not visually apparent) trauma such as minor neck, shoulder, or back pain. In many cases the claimant's initial, nagging pain intensifies dramatically after visiting a medical practitioner, providing the impetus to seek the advice of a personal-injury attorney. More often than not, a formal medical claim is filed. Many such allegations appear to be specious relative to crash reconstruction findings and/or common sense, raising the ugly specter of blatant insurance fraud.

The New York State Department of Transportation's Passenger Transportation Safety Bureau (NYSDOT/PTSB) and the New York Statewide Traffic Accident Reconstruction Society (NYSTARS) have collaborated to address this pervasive problem in a logical and systematic manner. To this end they conducted several full-scale bus crash tests indicative of typical roadway incidents that have engendered fraudulent injury claims. The two agencies subsequently issued a request for proposal to have the empirical data collected from these experiments examined by a credible, independent source with the requisite expertise to ascertain what type(s) of injuries, if any, would have been sustained by an adult occupant on that bus.

CUBRC via its designated subcontractor, Calspan Corporation, was selected for this purpose. Under this agreement and consistent with the NYSDOT Statement of work, Calspan has:

- Reviewed, analyzed, and interpreted, to the extent feasible, the crash test data provided by NYSDOT.
- Searched and summarized the open literature dealing with previously conducted (up to 20 years back) research dealing with the type of bus crashes of interest to this project.
- Prepared a topic report written in layman's terms detailing the results of the above two tasks.

It is anticipated that this report will be disseminated to persons whose knowledge of the subject matter varies widely. Consequently the author, with the concurrence of the NYSDOT Program Manager, has incorporated in it a brief overview on the origin and nature of injuries incurred by transit bus passengers in low-speed crash exposures.

2. BUS OCCUPANT INJURIES IN A LOW-ΔV CRASH ENVIRONMENT

The probability, number, type, and severity of injury suffered by occupants of passenger transport vehicles involved in a crash incident depends on the nature and severity of the crash itself and the vehicle's overall *structural* and *interior* crashworthiness.[1] Structural crashworthiness denotes the ability of the vehicle's primary load-carrying elements to distribute those loadings and allow them to collapse in a controlled, orderly, and timely manner while maintaining a sufficient amount of survival space in the cabin for the vehicle's occupants. The latter function endeavors to prevent occupants from being crushed or ejected from the vehicle[2] while the former attempts to control the magnitude, shape, and duration of the acceleration profile (the so-called vehicle crash pulse)[3] this protective envelope experiences during the crash. Structural crashworthiness per se is not a major concern in bus collisions if that type of vehicle is subjected to a relatively low velocity (speed) change[4]—less than or equal to 6.2 mph. (Note: For the sake of word economy this parameter will from now on be referred to as "low-ΔV.") This limit is consistent with one of the proposed guidelines prescribed in whiplash-related research currently in progress [1].[5]

A vehicle with such a protective "cocoon" may still not be able to prevent its occupants from dying or suffering serious harm as a result of the crash. The cabin interior—*everything* inside, including seats, padded or unpadded surfaces, and restraint systems (if any)—must modulate the crash pulse sufficiently to mitigate its effects on them. How well all of these subsystems work together to limit the severity of potentially injury-causing accelerations, forces, displacements, and moments[6] persons in the cabin may be exposed to constitutes a relative measure of vehicle interior crashworthiness. The nature of these injuries is discussed next.

Blunt force occupant injury

All crashes—even low-ΔV bus collisions—can cause one or more regions of an occupant's body to suffer relatively blunt impacts with cabin interior surfaces and/or other occupants. These *secondary collisions* (designated as such because they occur *after* the first or primary impact involving the vehicle structure) impart impulsive loadings[7] to the impacted area. Such blows can produce physiological changes on and/or deep below the surface of the affected body region as well as inside adjacent regions. Bodily injury occurs if this response is so severe that the

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[1] The term "crashworthiness" refers to the ability of a passenger-carrying vehicle of any kind to protect its occupants during potentially survivable crashes.

[2] Occupant casualties also result from post-crash events such as exposure to fires, toxic gases, or explosions. These hazards are not addressed in this report.

[3] Strictly speaking, the crash pulse varies from point to point in the cabin. A pulse considered representative of the conditions felt by the occupant(s)—e.g., the average over at least several points—is often specified.

[4] Speed is equal to distance traveled divided by the time of travel. When the *direction* of speed is important, it is referred to as velocity. Otherwise the two terms may be used interchangeably.

[5] Numbers in brackets denote references listed in Section 7.

[6] A moment is a physical quantity whose magnitude is equal to the product of a force and the perpendicular distance between its line of action and a specified point.

[7] In simple terms an impulsive-type loading can be regarded as the product of a force and a very short duration of time that (usually) varies in a complex manner.

biological system deforms beyond its inherent recoverable limit, damaging its anatomical structure and altering its normal function.

Body region secondary impact speed has a significant affect on this type of injury. This parameter, which indicates how fast that part of the body is moving relative to the struck surface at the moment of impact, is a function of the vehicle crash pulse and the distance the occupant moves before contact. The location and orientation of the affected body region(s) and the physical characteristics of the impacted surface(s) also have a major effect in this type of trauma.[8]

Blunt force injuries affect both the external and internal regions of the body. The former appear as contusions (bruises), lacerations (cuts), fractures, and dislocations, while the latter produce a variety of trauma to organs, soft tissue, and the nervous system.

Inertially generated occupant injury

Low-ΔV collisions that do *not* produce direct body region-cabin interior contact can still cause inertially generated trauma. This type of injury (e.g., whiplash) occurs as a result of body region exposure to certain levels of linear and/or angular accelerations associated with dynamic actions such as rapid rotational motion. It occurs when the magnitude, direction, onset rate (how fast a quantity's magnitude increases), and/or duration of these accelerations combine in a manner that exceeds the appropriate biomechanical tolerance level (see later discussion). Most inertially generated injuries cannot be correlated with identifiable structural damage to bones or ligaments. They also exacerbate the effects of internal body trauma arising from blunt force impact.

Experimental simulation of crash-induced injury

The U.S. Department of Transportation (DOT) mandates that most passenger-carrying vehicles demonstrate at least minimum levels of crash (and other) safety performance in order to be sold and allowed to operate on U.S. roadways. These requirements are embodied in Federal Motor Vehicle Safety Standards (FMVSS) developed by the National Highway Traffic Safety Administration (NHTSA). Vehicle crash safety certification requires compliance with full-scale crash, sled, and component-level tests delineated in related test procedures.

A large quantity of electronic data measured by various kinds of instrumentation mounted at selected locations in the vehicle and inside one or more anthropomorphic test devices (ATDs)—crash test dummies—is typically collected in most crash tests. They include the aforementioned accelerations, forces, displacements, and moments—all *critical quantitative measures* of vehicle and occupant response to the crash. At Calspan, this data is recorded by a high-speed digital data acquisition system and converted into a usable, computer-based binary format. In addition, slow-motion imagery from numerous high-speed video cameras strategically placed on the ground and (when permitted) onboard the vehicle record multiple views of the crash itself and the occupant response to that event (i.e., whole-body trajectory, individual body region motion, and cabin interior contacts, if any). Pre-and post-test still photos and post-test observations made by the test crew also

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[8] Other time-related factors also are important, notably the loading duration relative to body region response time and the ratio of load duration to that time. The latter parameter governs the magnitude of the loading that actually affects the occupant.

are included in a typical crash test data package.

Post-test analysis of this information is a two-step process. The first involves a routine checkout of all instrumentation employed in the test followed by a comprehensive review of the processed electronic data. The latter procedure involves closely examining each transducer output for potential anomalies such as data shifts, noise spikes, data loss, and acceleration traces that don't return to zero. Where possible, questionable electronic data is correlated relative to events captured on videotape to ascertain its authenticity. In the second step, all data are studied and synthesized to ensure, whenever possible, that the findings indicated by one source are compatible with those drawn from all other sources. This careful scrutiny is done with the realization that the high stakes typically involved (e.g., whether a vehicle can be offered for sale to the public) mandate that the results and conclusions presented in the test report reflect, to the extent feasible, a bona fide account of vehicle and dummy crash performance.

Vehicle occupant injury criteria

Biomechanically based indices have been developed which attempt to quantify the onset of probable occupant harm arising from blunt-force impact and inertial effects on specific human body regions. Formulated using data developed in experiments involving animal and cadaver test subjects, a relatively small number of these indicators are currently specified by the U.S. Department of Transportation for use in the experimental evaluation of crash survivability for occupants of certain passenger-carrying motor vehicles and commercial aircraft. They comprise maximum allowable values of acceleration, force, moment, displacement, and other parameters incorporating these measures using *certified test dummies*. Currently these indicators are prescribed for a very limited number of dummy sizes/weights, with emphasis on the 50th-percentile (mid-size) male.

Common injury indicators and their accepted limits associated with a Hybrid III mid-size dummy are listed in Table 1.[9] Shown therein are (1) an acceleration-based algorithm called the Head Injury Criterion (HIC), (2) the resultant linear acceleration of the upper torso center of gravity, (3) fore-aft compressive displacement of that same body region, and (4) compressive axial force acting on the upper leg. These thresholds are currently prescribed by NHTSA as part of FMVSS 208 [2]. The Federal Aviation Administration (FAA) also utilizes the HIC and upper leg force as part of its own injury criteria defined in applicable Federal Air Regulations [3]. It is of interest to note that no such criteria have yet been adopted by NHTSA for transit buses.

Members of the vehicle crash safety research community frequently debate the real-world significance of these and other indicators of crash-related inertial and blunt-force injuries [4, 5, 6]. The criteria are problematic and inherently flawed, for they fail to account for factors such as gender, weight, size, and overall physical condition—all of which affect the onset and maximum severity of virtually all physical trauma.

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[9] This listing is not intended to be totally inclusive. Other indices have been adopted or are currently being evaluated by NHTSA. Most injury criteria thresholds eventually will be scaled commensurate with test dummy size/weight.

Considerable research has been conducted in an effort to classify vehicle crash-related injuries to real people. The most well known and widely accepted of these indices is the Abbreviated Injury Scale (AIS). Associated with the AIS is a manual that provides detailed descriptions of the trauma that commonly occur to various parts of the body as a result of a crash incident. Each region is assigned a "threat-to-life" ranking: 0, none; 1, minor; 2, moderate; 3, serious; 4, severe; 5, critical; and 6, unsurvivable (a fatality).

One final note on this topic. Injury indices such as those cited in Table 1 are currently applied to humans by means of injury risk curves. These plots indicate the probability of suffering a specific AIS-level injury under the same crash conditions imparted to an appropriate size test dummy. A typical injury risk curve is shown in Figure 1. Here, a HIC of 1,000 corresponds to an 18% chance of sustaining a head injury equal to or greater than AIS4. That level of injury to a real person would likely produce an open head fracture and between six to twenty-four hours of unconsciousness.

Table 1
Typical biomechanical indicators of vehicle crash survivability: Hybrid III test dummy

| Body Region	Requirement
head	The resultant acceleration at the center of gravity of the head shall be such that the expression, defined as the Head Injury Criterion (HIC) $$\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a\,dt\right]^{2.5} (t_2 - t_1)$$ shall not exceed 1,000, where "a" is the resultant translational (linear) acceleration expressed as a multiple of G (the acceleration of gravity). Times t_1 and t_2 are separated by not more than 36 milliseconds and maximize the integral
chest (upper torso region)	The resultant acceleration at the center of gravity of the upper thorax shall not exceed 60 Gs, except for intervals whose cumulative duration is not more than three milliseconds The compressive displacement of the sternum relative to the spine shall not exceed three inches
upper leg (femur)	The compressive force transmitted axially through each upper leg shall not exceed 2,250 pounds
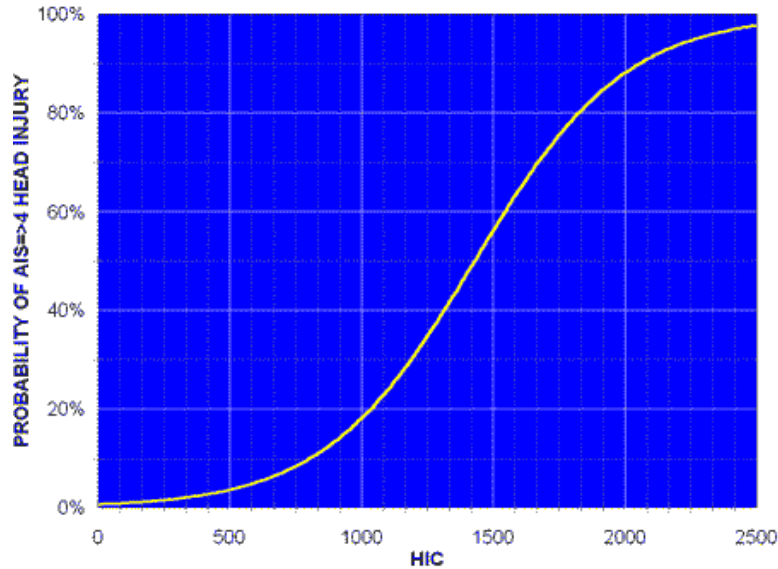
Figure 1.   Example HIC-based head injury risk curve for a real person.

In-cabin occupant protection schemes

Earlier we alluded that limiting an occupant's secondary impact speed can decrease the severity of blunt force and inertially induced injuries. This objective is accomplished worldwide in most motor vehicles by installing occupant restraint mechanisms such as safety belts and air bag/curtain systems in the cabin. Occupants that fail to use or disable these devices metaphorically disconnect themselves from the vehicle, significantly increasing the possibility that they will become seriously injured or die as the result of a vehicle crash—even moderate-ΔV-level collisions (between 6.2 and 9.9 mph per [1]). Unfortunately, certain types of motor vehicles are still not required to be equipped with any such proven safety features. Transit buses fall into this category, rendering moot any further discussion of this topic.

For the sake of completeness it should be noted that vehicles lacking restraint systems can be designed to provide at least some degree of occupant crash protection by utilizing a concept called "compartmentalization." In this approach occupants are *passively contained* within a relatively small zone inside the cabin instead of being actively or potentially restrained by a mechanical system per se (safety belts and automatically triggered inflatable bags and curtains, respectively). The rationale here reflects the reasoning presented above: The occupant is accorded less space to move relative to the cabin, which in turn limits secondary impact speed and thus mitigates the effects of the (often inevitable) interior contact. Compartmentalization is currently utilized in U.S. school buses as part of FMVSS 222 [7]. The regulation prescribes stringent force-deflection and crash energy-absorption specifications for cushioned seat backs and strategically located barriers. These features are effective for the case of collinear or slightly angled frontal or rear collisions. But they fall far short in other common school bus crash incidents such as side impact and rollover.

Effective compartmentalization requires the use of properly designed collapsible, force-limited, and cushioned contact surfaces to keep accelerations, forces, displacements, and moments sustained by the occupant below the aforementioned acceptable injury tolerance levels. The interior structure or

feature entrusted with this function must therefore be "occupant-friendly"—i.e., possess (1) force-deflection characteristics that enable it to absorb a substantial amount of the occupant's kinetic energy; (2) limited elastic recovery potential (too much of which would cause undesirable occupant rebound action); and (3) smooth contours free of small-radius edges, allowing impact forces to be distributed over a relatively large area of the occupant's body. This study does not address the topic of compartmentalization.

The next section summarizes the results obtained from the four crash tests mentioned in the Introduction.

3. BUS CRASH TESTING

NYSDOT contractors not affiliated with CUBRC/Calspan performed four full-scale bus-car crash tests on October 4, 2001. Table 2 briefly describes these experiments and adds some pertinent, explanatory commentary where deemed necessary. This summary was derived from hard copy test documentation provided by NYSDOT [8, 9].

Table 2
Crash test summary

Test no.	Bullet (moving) vehicle		Target (stationary) vehicle	Bus crash pulse components measured[2]		Actual impact configuration	Dummy response observed via onboard video camera	
	Type	V_i^1 (mph)		Horiz plane	Vert plane		Impacts with bus interior	Comments[3]
2	bus[4]	33	Chrysler New Yorker	x	z	front-to-rear, slightly off center	knees/lower legs with fwd seat back (uncertain)	
3	bus[4]	35	Plymouth Sundance	x		front-to-side perpendicular (t-bone)	none	
4	Chevrolet Celebrity	34	bus[4]	none	none	front-to-rear, far off center[5]	unknown	videotape coverage not available
5	Plymouth Reliant	38	bus[4]	y		front-to-side perpendicular (t-bone)	none	

[1] Speed at moment of bus-car impact.
[2] Accelerometers were mounted on the floor at CG location, with x and y parallel to the bus longitudinal and transverse axes, respectively; z denotes the accelerometer perpendicular to that plane.
[3] Test 2, 3, and 5 dummy kinematics are described in Section 5.
[4] One bus was used both as a bullet and a target vehicle.
[5] Intended as an inline front-to-rear impact; the bullet vehicle nearly missed its target, resulting in minimal engagement between the left-front corner of the car and the right-rear corner of the bus.

Test setup and recorded data

All tests were conducted using the same 1986 GMC transit-style bus—40 feet long, test weight equal to 27,560 pounds—shown in Figure 2. It was employed as the bullet (striking) vehicle in the first two tests as well as the target (struck, stationary) vehicle in the remaining two crashes. Four apparent "junker" automobiles identified in Table 2 were utilized as bullet or target vehicles.

Two different subcontractors collected bus acceleration data. One was involved in tests 3 and 4 only and mounted his accelerometers at several different locations in the cabin. The other was involved in all four tests and mounted his on the floor at the bus center of gravity (CG).[10]   As noted in Table 2, this study utilized the latter data exclusively. No acceleration data was obtained from invalid test 4.

All acceleration data was provided in hard copy form only (no electronic files) without any indication of the filter channel class applied during data processing [8]. Most data appear to have been filtered at a channel class somewhat higher than the 60 Hz frequency commonly employed.[11]

Figure 2. Crash-tested bus.

Figure 3. Bus interior and test dummy passenger.

What is purported to be a Hybrid II 50th-percentile (mid-size) male test dummy[12] was placed in a seat adjacent to the aisle. Veteran Calspan and NHTSA researchers, however, question that identification, for photos of this *uninstrumented* test device (e.g., Figure 3) provide compelling evidence to the contrary. The disputed dummy doesn't resemble any bona fide extant (or extinct, for that matter) test dummy utilized over the past 50 years; it has detailed facial features, individual toes, "hair," and an unconventional shoulder joint assembly to boot. (This might explain why crucial dummy-related electronic data—of vital importance in virtually any test data analysis—was not collected.) Calspan was especially concerned about the kinematics-related biofidelity[13] of this dummy. The implications of this potential problem on this study are discussed in Sections 5 and 6.

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[10] The traffic cone shown in Figure 3 is directly over the bus CG (horizontal plane) location.
[11] As specified by SAE Recommended Practice J211, "Instrumentation for Impact Test."
[12] According to information provided by one of the test subcontractors to the NYSDOT Program Manager, John Fabian.
[13] Kinematics biofidelity is a subjective assessment of how well a test dummy mimics the overall trajectory and individual body region movements of a real person in a dynamic environment.

Several video cameras were stationed on the ground to record the intervehicular collision and its aftermath. Dummy in-cabin motion was recorded by two onboard video cameras—one real-time, the other high-speed—seemingly at the same (or close to the same) location.

Figure 3 is the lone dummy pre-test setup photo provided. It shows the dummy's hand resting on a tubular assembly located above the seat back in test 2—perhaps to simulate a "braced" configuration to resist an impending collision. Video imagery revealed that the dummy was somewhat reclined in its seat, with perhaps only a few inches or so of clearance between its knees/lower legs and the seat back surface directly ahead of it.[14] No explanation was available [8, 9] as to why the dummy could not be adjusted to assume a more upright (and realistic) sitting posture. Video imagery indicated that its posture pre-test was essentially the same in tests 3 and 5; the latter two experiments, however, dropped the arm-bracing feature.

Test results

Tests 2 and 3 consisted of front-to-rear and front-to-side impacts by the 27,560-pound bus into nominal 2,600- and 2,500-pound automobiles at 33 and 35 mph, respectively (see Table 1[15]). In each case the bus experienced a very low-magnitude crash pulse, registering global peaks of 1.5 and 3 Gs and corresponding calculated average accelerations of –0.9 and –0.7 G, respectively. Pulse durations differed substantially; in test 2 this waveform extended over a roughly two-second period of time while in the latter impact, it occupied only 150 milliseconds (0.15 seconds).[16] [This disparity turned out to have a plausible explanation (from Mr. Fabian); the person driving the bus in that test applied the brakes as the vehicle approached its target.[17]] Test 2's ΔV in the x direction (the bus' pre-test heading) was given as –4.17 mph; the same parameter in test 3 was –2.59 mph.

Test 4 was a planned impact of the bus rear structure by an automobile moving at 34 mph. A towing malfunction allowed the car to veer off to its right, resulting in minimal engagement between the two vehicles. No data was obtained in this experiment.

In test 5, a 2,300-pound car clocked at 38 mph struck the left side of the bus broadside, with the impact on the side opposite the one containing the row of seats where the dummy was positioned. Several distinct acceleration peaks ranging between –4.1 and +12.7 Gs over a roughly 150-millisecond-long duration were measured at the bus floor CG location. Because of the pulse's oscillatory nature, however, the net effect (average acceleration) on the bus in its y direction (perpendicular to the bus longitudinal axis) during the crash event was only 0.3 G. The calculated ΔV in the same direction was 1.06 mph.

Figure 4 presents an unspecified post-crash photo from what most likely is test 2.

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[14] Pre-test linear and angular measurements documenting dummy body segment clearances and inclinations relative to its seat and immediate surroundings were not available.

[15] Test numbers employed here are consistent with those used in the previously cited test reports (test 1 was a collision between a moving switcher engine and a stationary car).

[16] A millisecond is equal to one-thousandth of a second.

[17] In test 2 the brakes were applied *at the moment of impact*, producing a combined collision/braking acceleration pulse. In test 3 the brakes were not applied until *after the collision*, generating separate impact and braking pulses.

Figure 4. Dummy position following test 2.

4. LITERATURE REVIEW

Likely sources were searched in an effort to find full-scale crash and sled test reports in which a test dummy was placed onboard an actual transit bus (or sled buck) and that vehicle (or buck) subjected to a low-ΔV crash pulse.[18]   None were found, even in Calspan's own extensive records. Several national crash data collection systems such as the Fatality Analysis Reporting System (FARS), the Crash Injury Research and Engineering Network (CIREN), and the Crashworthiness Data System (CDS) also were searched—without success—for real-world crashes satisfying the desired test conditions.[19]   Indeed, the paltry number of bus-related cases per se listed in these sources dealt only with (as expected) high-ΔV crashes similar to those discussed in [10].

5. DATA REVIEW, ANALYSIS, AND INTERPRETATION

The crash test data package supplied by NYSDOT to Calspan contained less than the amount of information typically obtained from a crash test. Moreover, that which was provided often fell short in other respects such as clarity and compliance with accepted practice. Uncertainties stemming from the use of an unconventional test dummy, coupled with the total absence of electronic dummy data, seemed certain to doom any meaningful analysis of the data. But the benign nature of the crash pulses imparted to the bus offset enough of these deficiencies and enabled Calspan to salvage this effort.

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[18] Sled testing is an experimental technique employed to simulate a crash test without damaging an actual vehicle. A buck is a stiffened framework or shell containing one or more test dummies and all pertinent cabin-interior systems installed in their respective normal location. (Two rows of bus seats mounted on a suitable platform would have sufficed for the crash tests discussed in this report.) The buck is bolted to a carriage that is constrained to travel along a straight and level track. The assembly is (usually) propelled by a high-pressure gas mixture which flows over a custom-designed metering pin configured to produce a specified crash pulse.

[19] CDS, the most comprehensive of these collections, cannot accommodate crashes involving transit buses because these vehicles don't fit the CDS coding process.

Table 3 presents a capsule summary of the dummy's kinematics gleaned from the available test video coverage. In a nutshell, not much happened. With the exception of test 2, dummy movement was minimal. Mr. Fabian, who was situated in front of the dummy in each test, corroborated this statement.

Table 3
Dummy kinematics observed in test video imagery

Test no.	Test configuration[1]	Observations[2]
2	bus into car: rear end	Dummy slid (translated) forward, simultaneously rising above the seat cushion surface with little, if any, accompanying upper torso rotation (pitching). Overall forward translation terminated with apparent impact between knees/lower legs and aft surface of the seat back directly in front. Virtually no head rotation relative to upper torso until dummy stopped moving forward; head then pitched fore-aft about 45 degrees
3	bus into car: broadside	Negligible overall dummy forward translation or upper torso pitch. Head pitched fore-aft slightly[3]
5	car into bus: broadside	Entire dummy leaned slightly toward the bus aisle (yaw motion only; no apparent lateral translation along the seat), then slid forward a bit. Minimal head yaw relative to the upper torso

[1] Details provided in Section 3.
[2] Initial response only cited in all cases; rebound motion was less uneventful.
[3] Narrative reflects best possible account gleaned from real-time video imagery only (no high-speed video coverage).

The relatively small dummy excursions described in Table 3 are a manifestation of the low-ΔVs sustained by the bus cabin in the principal direction of impact. It's not too much of a stretch to surmise that a properly instrumented Hybrid II or Hybrid III dummy would most likely have experienced extremely low levels of head and upper torso acceleration as well as zero chest deflection. Upper leg compressive forces (also low magnitude) would have been recorded in just one of these crashes: test 2—assuming of course that the hypothetical substitute Hybrid II or Hybrid III dummy would have translated at least as far forward as the actual dummy did. Calculated values of the injury-indicating indices listed in Table 1 would therefore have been far below their respective allowable limits in all three tests. John Fabian concurred.

Computer modeling prelude

The behavior of extremely complex systems or phenomena typically cannot be explained using analysis and logical reasoning. However, it's often possible to single out one or more significant factors so that the actual system can be described by a simplified *model*—one that can provide valuable insights into a selected aspect of its nature. Mathematical models use equations for this

purpose.[20] All models neglect certain factors that characterize the actual system, thus they are at best an approximation of the real-world situation being examined. This limitation is acceptable so long as the error involved is small enough to render its predictions meaningful.

Simulating vehicle occupant crash response via mathematical modeling is an inherently complex task. The results are dependent not only on the many inputs and assumptions utilized in the occupant- and cabin-related portions of the model, but also upon the accuracy and validity of the necessary inputs that attempt to quantify the dynamics of the vehicle crash itself. Such predictions should therefore always be viewed from the standpoint of being at best *a relative measure* of what *could* happen in an actual crash—regardless of the sales hype espousing the accuracy of even the most sophisticated state-of-the-art computer codes commonly utilized for this purpose (e.g., MADYMO).

ATB bus occupant/cabin model construction

Several steps are involved in developing a rigid body type computational model to simulate test dummy in-cabin reaction to a given vehicle crash scenario. They include (1) prescribing geometric inputs for specific portions of the cabin interior and all predetermined and potential occupant contact surfaces; (2) orienting the rigid bodies (and their encapsulating ellipsoid surfaces) comprising the simulated occupant to provide a reasonable "fit" to the vehicle seat while satisfying pre-crash force and acceleration equilibrium considerations—all while attempting to maintain known clearances between the various body regions and surrounding surfaces; (3) specifying material property inputs for cabin interior surfaces, controls, and other things that could come in contact with the occupant; (4) specifying geometric and material property inputs for any restraint systems that may be present; and (5) prescribing estimated or previously calculated values of instantaneous cabin wall or other interior system intrusion-related motion that may be required in some simulations. Items 4 and 5 obviously weren't applicable to this study.

The desired low-ΔV bus occupant/cabin model was created using the ATB (Articulated Total Body) computer code [11]. ATB is a versatile and affordably priced rigid body occupant dynamics analysis used for motor vehicle crash and aircraft flight safety modeling applications. While it lacks many of the features offered by its more expensive cousins, it can serve as an adequate alternative for various types of systems. ATB can provide, from any perspective inside or outside the vehicle cabin, 3D animations showing occupant motion, occupant interaction with restraint system components, and any impacts that may occur between an occupant and cabin interior surfaces or other occupants. As part of its quantitative output, ATB also generates time histories of the accelerations and forces sustained by all occupant body regions during the crash.

Pertinent bus material-related parameters were unknown (attempting to locate or experimentally develop them was beyond the scope of the project), thus best estimate or "proven" values used before in other, roughly similar crash modeling applications were invoked. Figure 5 illustrates the model employed in this project—a simple, bare-bones configuration that contains just enough

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[20] Mathematical models are also referred to as computational or computer models (the latter term a "given" in today's PC age).

detail to simulate the salient features of in-cabin dummy reaction to the three different crash pulse inputs.

Computer codes such as ATB and MADYMO offer users the choice of the many different crash test dummies commonly employed to simulate vehicle occupant response in crash and other dynamics-type scenarios. Each dummy type is represented by a unique dataset that embodies the physical characteristics of its actual "nuts and bolts" counterpart—e.g., mass distribution and inertial properties; force-deflection and energy-absorbing properties; and joint type and physical characteristics. Many of these inputs reflect the end product of laboratory-based experimentation and measurement. Modeling the low-ΔV bus crashes was complicated by the need to select an available ATB-defined dummy "package" to adequately simulate an unconventional test dummy whose provenance and size class/weight was a mystery. This left no alternative but to assume, despite all evidence to the contrary, that the test device was a "novel" Hybrid II male dummy made for use in crash safety applications.
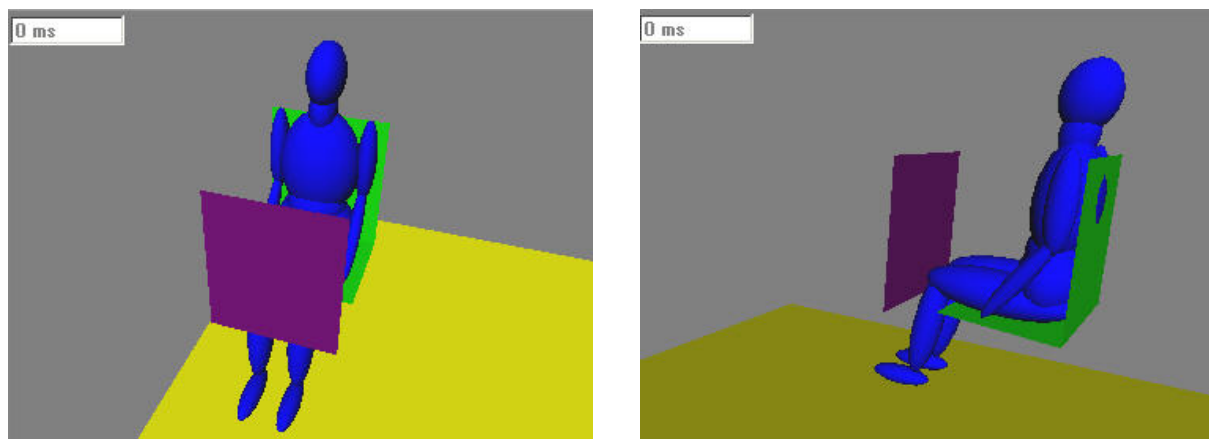

Figure 5. Two views of the ATB low-ΔV bus occupant/cabin model.

Electronic files containing bus acceleration-time response data required for input to the computer model were unavailable, necessitating their re-creation from hard copy plots of these curves published in [9]. These irregularly shaped waveforms were first approximated as a series of best-fit straight-line segments selected to include the greatest number of peak acceleration values. The end points of these lines were then adjusted slightly so that their coordinates could be calculated at equal intervals of time—consistent with ATB's input requirements. Figure 6 illustrates the crash pulse approximation utilized for test 3.[21]   Typically several trial approximations were necessary before the test-generated ΔV and its derived counterpart obtained from the estimated pulse converged satisfactorily.[22] Each new comparison required constructing a slightly different pulse shape by selectively adjusting peak acceleration magnitudes on the latter curve.

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[21] The curve has been reflected about the time axis per ATB input requirements.

[22] The plot-based estimated velocity change was obtained via numerical integration—i.e., calculating the net area by algebraically adding the positive and (for the example shown, just one) negative areas contained in simple geometric shapes superimposed on the estimated crash pulse plot. Text boxes in Figure 6 illustrate how the net area was calculated.
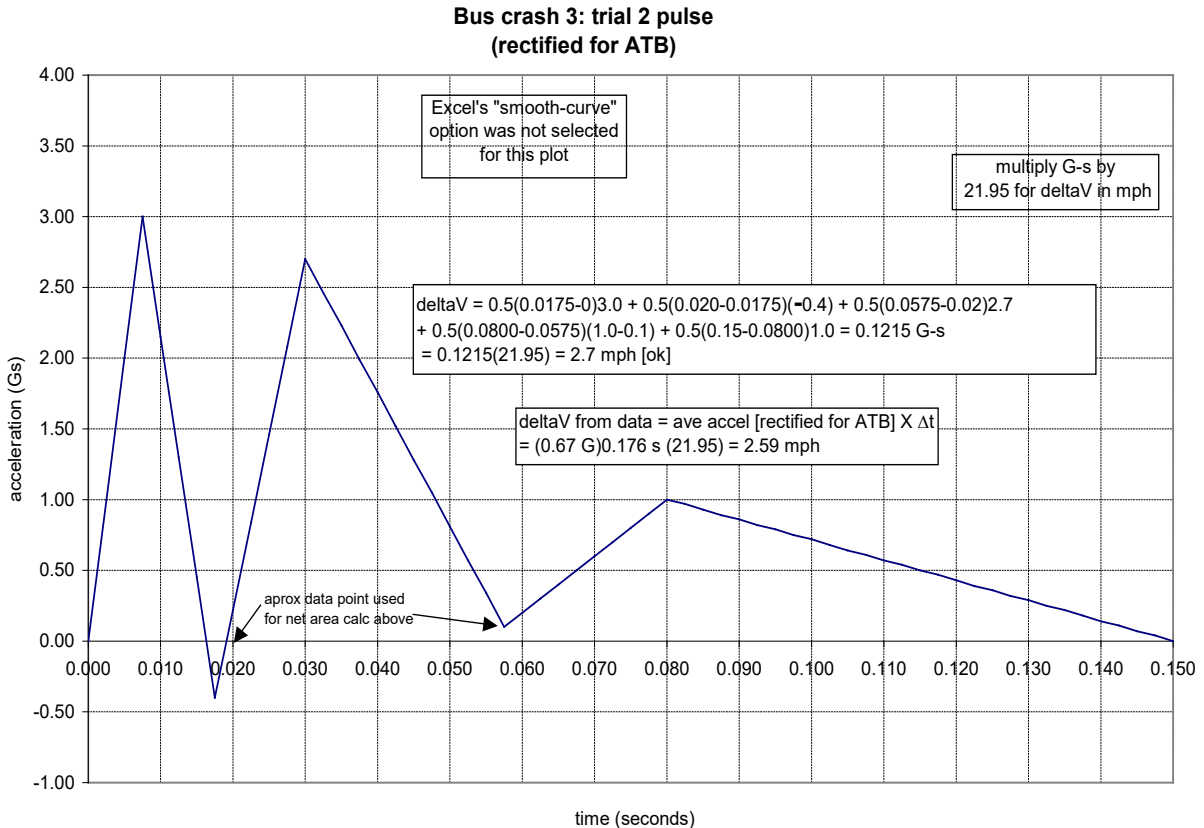
Bus crash 3: trial 2 pulse
(rectified for ATB)

Excel's "smooth-curve" option was not selected for this plot

multiply G-s by 21.95 for deltaV in mph

deltaV = 0.5(0.0175-0)3.0 + 0.5(0.020-0.0175)(-0.4) + 0.5(0.0575-0.02)2.7 + 0.5(0.0800-0.0575)(1.0-0.1) + 0.5(0.15-0.0800)1.0 = 0.1215 G-s = 0.1215(21.95) = 2.7 mph [ok]

deltaV from data = ave accel [rectified for ATB] X Δt = (0.67 G)0.176 s (21.95) = 2.59 mph

aprox data point used for net area calc above

Figure 6. Approximate test 3 crash pulse used in the ATB computer model.

Model validation

A mathematical model must be properly validated before its predictions can be regarded with any degree of confidence. The question of what constitutes "proper validation" is a complex and contentious issue. Indeed, Committee No. 60 of the American Society of Mechanical Engineers is currently working toward developing international standards governing the correctness and credibility of all modeling and simulation activities [12]. When completed, the validation process will at last be subject to strict protocols (see, e.g., [13] and [14]).

The procedure employed to validate the low-ΔV bus occupant/cabin model was necessarily informal and subjective: (1) select the crash that produced the most complex dummy kinematics, and (2) formulate a model that best simulates its overall trajectory displayed in the video imagery. Test 2 was the obvious choice (see Table 3). Making this happen required some trade-offs—notably, adjusting the known bus seat height and seat row spacing to accommodate the ATB-generated occupant, thus allowing it to assume a seating posture and knee-seat back clearance roughly similar to that of its physical counterpart. A number of adjustments, including occupant body segment orientation relative to the seat and floor; lower and upper torso, femur, and arm penetration into the applicable seating planes; and foot penetration into the floor plane were made to satisfy ATB's stringent time-zero (equivalent pre-test) dummy acceleration and force equilibrium requirements in all three coordinate directions. Once those balances were achieved, the test 2 impact speed and the data points defining its approximate crash pulse were input

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to the model. The model was exercised repeatedly to create computer animations of the occupant trajectory as a function of the friction coefficient inputs governing sliding contact between a body region and the appropriate plane. Each animation was compared with the video imagery and the best models identified. Models also were formulated using combinations of friction coefficient inputs, and the above comparison process repeated. The model whose animation compared the most favorably with the video imagery was regarded as having been "validated."

The kinematics displayed by ATB's relatively heavy body region representations—i.e., its three contiguous torso and two upper leg segments—correlated fairly well with those exhibited by the corresponding parts of the test dummy. ATB's relatively light body regions (e.g., the head and arms) did not. These observations are consistent with the inertial properties of mass. Namely, an acceleration input imparted to a heavy body will cause it to undergo a slow and steady change in its motion compared to the more rapid change in the motion of a lighter-weight body produced by the same acceleration. It's also possible that ATB's joint properties lack sufficient damping, thus magnifying the small-mass response.

As alluded to earlier in this section, the huge datasets used by even the most sophisticated occupant dynamics analyses can at best only approximate the physical properties and dynamic behavior of a *known* test dummy. Such disparities are the norm and can often be compensated for by adjusting other parameters. Here this situation was compounded because of the *unidentifiable* physical dummy used (which may not have been designed for crash-related applications) in the crash tests. Under the circumstances the final version of the ATB model employed to simulate the test 2 dummy's trajectory turned out just about as well as can be expected.

Model-generated findings

In test 2, ATB's simulated occupant kinematics (overall trajectory *and* individual body region movements) during the forward phase of the motion agreed fairly well with that shown on videotape. Figure 7 presents "stills" extracted from the ATB animation at time zero and at the time of maximum occupant forward motion. As noted above, the model failed to correctly simulate the motion
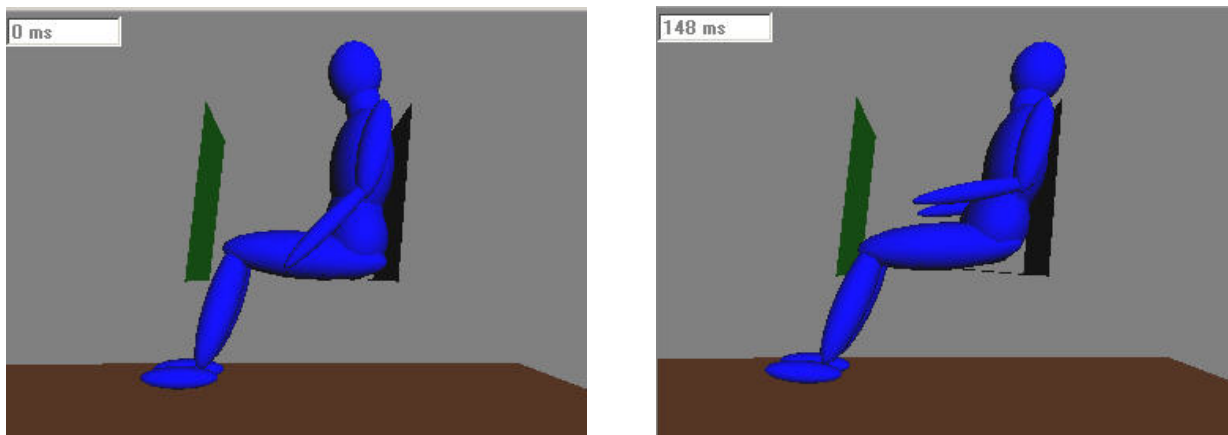

Figure 7. ATB model-forecasted dummy configurations: pre-test and initial lower leg-seat back contact.

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of the test dummy's head. For example, at the time when the video imagery indicates apparent dummy lower extremity contact with the seat back, its head had already moved forward and pitched downward, in sharp contrast to the computer-predicted head orientation shown in Figure 7.

Model-forecasted values of the HIC, maximum resultant chest (upper torso body segment) acceleration, and maximum femur (upper leg) axial force were all extremely low (HIC less than 1, both acceleration measures under 10 Gs, femur forces about 400 pounds). But as stated earlier in this section, computer models cannot be expected to generate *absolute predictions* for the real system being simulated. Their principal function is to provide *relative comparisons* for trend analyses and "what-if" studies (discussed in Section 6). In this particular case, suffice it to say that the *order of magnitude* of the above injury-indicator predictions appears to be on target; after all, nothing of much consequence happened to the test 2 dummy.

One version of the test 2 model featured the dummy's left arm raised and extended to just contact the top of the seat back ahead of it—an attempt to crudely mimic the braced-position setup employed in the experiment (as shown in Figure 3, where the dummy's hand is "grasping" a tubular component extending above the seat back). Braced- and unbraced-simulation results were virtually identical—most likely a manifestation of ATB's inability to simulate the hand-tube interface by some mechanism other than the frictional "connection" employed in the model. As a sidebar, dummy kinematics (and accelerations, had they been measured) in a hypothetical repeat of test 2 for an unbraced dummy setup would probably be very similar to that in the original test. This speculation is based on the typically low rotational resistances that characterize test dummy elbow and shoulder joints.

Test 3 and test 5 simulations with the validated model provided roughly the same level of agreement with respect to occupant kinematics as did the test 2 run. Again the principal differences between the two sources involved head motions. ATB-predicted HICs and peak body segment accelerations were of the same order of magnitude as those forecasted by the test 2 simulation.

6. CONCLUSIONS AND RECOMMENDATIONS

This study examined the dynamic response of an unrestrained test dummy of unknown biofidelity seated in a large transit bus during a staged collision in which the bus incurred only a small change to its initial velocity. Empirical data collected from three such tests were analyzed in an attempt to ascertain what type(s) of injuries, if any, would have been sustained by a human sitting in the same location. The data consisted of video imagery showing the dummy's overall trajectory and the movement of its individual body regions, hard copy plots of the cabin acceleration profile at a point on the floor, still photos, and Project Manager John Fabian's documented firsthand impressions as he "rode down" each crash onboard the bus.

Analysis of that data strongly suggests that a mid-size male human would probably *not* have suffered blunt force or inertially generated injury in tests 3 and 5, both of which were characterized by extremely small dummy excursions in the cabin. The risk of injury to a person in the remaining test (no. 2) was problematic because of the substantially larger torso displacement and head rotation exhibited by the dummy, coupled with its suspect biofidelity (which may have been responsible for the upper torso reclining instead of pitching forward as

expected as the dummy slid forward along its seat). Bottom line: A more biofidelic 50th-percentile dummy such as a Hybrid II or Hybrid III might have struck its head on the seat back in front of it.

Although computer modeling was not utilized as extensively as originally hoped, the simulations that were performed hinted at its potential value as part of a possible follow-on research effort. To wit: One especially notable advantage of having a validated computer model is the ability to use it to conduct so-called perturbation or "what-if" studies of the actual system being simulated. Such analyses involve making systematic and relatively small changes to various model inputs in order to explore the possible ramifications of those modifications on that system. The work can be carried out inexpensively and conveniently at a PC.

A brief exploratory "what-if" study with bus velocity change (ΔV) as the perturbed parameter was contemplated for incorporation in this study but subsequently dropped due to time and funding constraints. The plan envisioned was to increase the test-generated ΔV incrementally and develop a new, more severe crash pulse for each of the three crash scenarios. Acceleration-time data from each modified curve would be input to the model, which would be exercised to provide the corresponding occupant kinematics animation and injury-indicator output. Repeating this process for increasingly higher ΔVs might have uncovered a trend indicative of incipient trauma and the bus velocity change at which it occurred. The most likely candidate for such a study would have been test 2. By progressively increasing its ΔV above the 4.17 mph registered during the test, the model might have indicated the possibility of head and/or upper torso contact with the seat back in front of the occupant, perhaps accompanied by significantly higher femur forces as well.

The test 3 incident also would seemingly subject its occupant to the same mechanism(s) of injury as test 2 for a sufficiently high bus ΔV. Injury to a bus occupant in a more severe test 5-type crash environment would most likely occur as a result of tipping over laterally and rolling out of the seat into the aisle, landing on the floor. This action could cause trauma to more than one region of the body, including the head, chest, pelvis, and upper extremities.

If this research is to continue it is imperative that the data collected be as accurate and extensive as possible—and include *quantitative* (electronic) dummy data. A good start along this path would be to conduct all future full-scale crash and sled testing in accordance with the strict protocols stipulated by NHTSA. Implicit in this recommendation is the use of properly certified test dummies sanctioned for vehicle crash safety usage by the U.S. Department of Transportation. Additional thought also should be given to test planning per se to help ensure that the tests actually performed are as meaningful as possible and provide a sufficient amount and variety of data—electronic, visual, and narrative—to justify the expense.

Finally, it is hoped that this report will help define a viable framework for the conduct of future research that may lead to the development of an effective technique to combat fraudulent injury claims arising from low-ΔV transit bus crashes.

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