Rollover Collisions

Injuries related to automotive side glass

By Stephen A. Batzer

AUTOMOBILE SIDE GLAZING is generally composed of ~4 mm thick sheets of either tempered safety glass (TSG) or laminated safety glass (LSG), and also demonstrates simple or complex curvature. TSG indicates a single piece of thermally treated glass possessing substantially higher mechanical strength than annealed (stress-free) glass. When broken at any point, the entire piece spontaneously breaks into small blocky particles. LSG indicates two pieces of glass bonded by an intervening layer of specially formulated plastic. It will break under sufficient loading, but the shards tend to adhere to the polymer interlayer, which also provides a barrier to penetration.

Most of today's passenger vehicles come equipped with TSG, but LSG is increasingly being used for its safety and convenience benefits. The base material used for both types of glazing is annealed soda-lime glass with various additives (e.g., calcium, iron, copper), and it is generally tinted either green for solar load reduction, or gray for lites behind the B-pillar for privacy. (Pillars are bars that are located at the upper side of the vehicle separating the front and rear window, windshield, at the rear glass of the vehicle. The B-pillar is located between the side of the driver and the rear passenger.)

This glass is made by the float process that was developed by Sir Alastair Pilkington in 1959 (Pilkington PLC, 2000). The process consists of drawing molten glass in a continuous ribbon across a vat of molten tin to produce a more uniform, flaw-free product than the plate glass process that it replaced. Upon exiting the tin bath, the glass goes through an annealing lehr. Automatic cutters remove the edges and cut the product to length for further processing. Annealed glass can be drilled, given edge preparations, heated and bent, tempered, laminated or given coatings. Monolithic annealed glass is rarely used in modern vehicles because of its low strength and undesirable fracture characteristics.

The U.S. regulation governing the design of automobile glazing is found in the Federal Motor Vehicle Safety standards at 49 CFR 571.205, Glazing Materials (2001), which indicates that one purpose of the standard is to "minimize the possibility of occupants being thrown through the vehicle windows in collisions." This safety consideration is particularly important since, although a consistent majority of rollover fatalities were determined or believed to have not been wearing their seatbelts, a substantial 28% were, in fact, restrained but died anyway (Deutermann, 2002).

The standard that governs material selection for automotive glazing is ANSI/SAE Z26.1-1996. This is a material standard, and does not govern the safety performance of the glazing system made from the material that is specified. The automotive glazing system comprises the transparent window proper, a regulator system including mounting brackets if it is moveable, plus any edge fixation and/or framing.

Tempered Glazing

Tempered glazing is the dominant glazing for sidelights—as it has been since the early 1960s when it largely displaced laminated glass in these positions. Although chemically strengthened glazing has been used on a limited scale, thermal tempering is the preferred process. This is done after any necessary drilling, shaping or edge preparations. The glass is heated in a furnace to approximately 620 ºC (1150 ºF), then blasted with air on both sides.

The quenching action immediately hardens the exterior surfaces, leaving the interior relatively hot but stress-free as the furnace heating was done to a level above the stress-relief temperature. As the interior cools, it attempts to contract more than the relatively cool exterior. This results in an interior in tension with an exterior in compression.

In Europe, tempered glass is often referred to as "toughened" glass. Each designation is a bit of a misnomer, however, since tempered glass does not undergo a conventional tempering process (i.e., heating to transform microconstituents) and toughened glass has no ductility and, thus, its energy absorption (toughness) is poor. A nearly insignificant energy

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Abstract: *The injury mechanisms associated with tempered and laminated side glazing in automobile rollover collisions are enumerated and analyzed. The effects of impact, containment loss, entrapment, laceration and eye injury are discussed. It is shown that the greatest statistical threat to an occupant is not from the glazing directly, but from partial or full ejection coupled with exposure to the exterior. The history and relative merits of tempered and laminated side glazing are discussed, and examples from accident statistics, actual rollovers and the results of current research are reviewed.*

input from a prick-punch or awl will cause complete disintegration of a tempered sidelight.

ASTM International (2005) specifies two basic levels of glass thermal treatment. Type HS (heat-strengthened) has a surface compression of 24 to 52 MPa (3,500 to 7,500 psi). Heat-strengthened glass is generally twice as strong as annealed glass, but has similar fracture characteristics. Type FT (fully tempered) generally has a minimum surface compression of at least 69 MPa (10,000 psi) or an edge compression of at least 67 MPa (9,700 psi). Automotive glass is considered tempered for U.S. automobile use when the exterior compressive stress meets or exceeds 69 MPa (10,000 psi). Fully tempered glass is generally considered to be four times as strong as annealed glass. Remarkably, tempered glass does not measure any harder than annealed glass when subjected to a microhardness test (Guardian Industries, 2006).

The strength of tempered glass is proportional to the square of its thickness for a given temper level. The tempered glass of today (~4 mm thick), therefore, is substantially weaker than previous versions at ~6 mm (¼-in.) thick. In the 1950s, this thicker glass was strong enough to produce concussions in side collisions. Bending strength diminishes with surface scratches. This is why tempered glazing made by the float process with the associated high-quality surface is stronger at the time of manufacture than tempered plate glass, which has a ground and polished surface. Yudenfriend (1961) found that glazing in service had a significantly diminished strength due to abradement.

If properly manufactured, tempered fragments formed during breakage are relatively small and blocky. Standard 205 requires that, post-fracture, no piece away from the periphery or crack initiation side remains uncracked or has a weight exceeding 4.25 g (0.15 oz). However, uneven tempering or twisting of the sidelight prior to fracture can produce splines, which are fragments with large aspect ratios. Furthermore, a single sheet can have areas of successful and unsuccessful tempering (Photo 1).

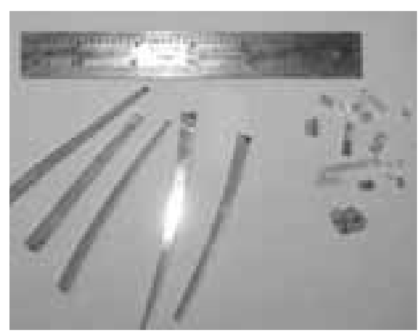

Photo 1 (left): Temper variations in a single sheet of automotive side glass shown by an impact test.

The fragments (as shown in Photo 1) include desirable blocky fragments, splines and incompletely disintegrated fragments that, if not cracked, would exceed the allowable ANSI/SAE Z26.1 particle size limit. Tempered glazing is not used in windshields due to its fracture characteristics. As the fragments loosely adhere and are separated by newly formed surfaces, light transmission is disrupted, particularly in low light conditions, severely limiting transparency.

Laminated Glazing

Use of laminated glazing actually predates that of

tempered glazing in automobiles (1910 vs. 1935). Laminated glass is almost universally of trilaminate construction, with two plies of glass sandwiching a polymer interior sheet. The polymer interlayer is usually made from polyvinyl butyral (PVB) that provides significant energy-absorbing capability. This design requires approximately three times the kinetic energy for a blunt impactor to penetrate compared to a tempered sidelight (Clark, Yudenfriend & Redner, 2000). Other materials used as the energy-absorbing layer include polyester, polyethylene terephthalate (PET), nylon, urethane and polycarbonate.

In the early 1960s, the formulation of laminated automotive glazing was fundamentally changed for the U.S. market to improve its safety properties. The PVB interlayer was doubled in thickness from 0.015 in. to 0.030 in. (0.76 mm), and controlled adhesion of the plies replaced maximum adhesion (Rodloff & Breitenbürger, 1967). Drop testing with this new high-penetration-resistant (HPR) laminated glazing showed that fracture would occur at impact velocities of 16 to 24 kph (10 to 15 mph) with a 6.8 kg (15 lb) headform (Alexander, Mattimoe & Hofmann, 1970).

The velocities measured for full penetration with a 10 kg (22 lb) headform are uniformly high [e.g., 44 kph (28 mph) (Rieser & Michaels, 1965), and 48 kph (30 mph) (Patrick & Daniel, 1964)].

Development of HPR glazing has been one of the most significant advances in automotive safety. Before HPR was developed, it was common for the occupant's head to penetrate the windshield through an aperture approximately equal to the size of the head. This formed a "glass necklace" or "horse collar," which often produced severe or lethal effects. Multiple, deep lacerations would form from forehead to throat as the head moved through the fractured windshield (Kahane, 1985).

Regarding HPR glazing technology, Kahane (1985) observed:

> HPR windshields have already been informally evaluated. The dramatic reduction in the demand for facial plastic surgery following introduction of HPR made it clear to the safety community that [the requirement for] HPR has been, perhaps, more successful than any other standard.

The slicing and soft-tissue laceration commonly seen in pre-HPR glazing was replaced by "relatively minor scrape-like abrasions," some pitting injuries and fewer concussive brain injuries (Huelke & Chewning, 1968; Widman, 1965).

Significantly, the "P" in HPR refers specifically to occupant ejection mitigation rather than impact protection from outside objects (Patrick & Daniel, 1964). The change to the HPR windshield in the mid-1960s occurred after the domestic auto industry exchanged laminated side glazing for tempered in the early 1960s and, therefore, the entire vehicle did not take advantage of this new technology.

In September 1999, Enhanced Protective Glass Automotive Association (EPGAA, 2006) was formed. EPG glass refers to thin, heat-strengthened trilaminate designed as a drop in replacement for tempered glazing, and may or may not have the same 0.76 mm-thick PVB interlayer as does HPR glazing. Claimed advantages for this glazing over tempered glazing include safety (occupant ejection mitigation), security (deterring "smash and grab" robberies), noise attenuation, UV protection and thermal load reduction.

Since EPG glazing is not used in the windshield, it

Automotive Glazing Terminology

Advanced glazing: terminology used by NHTSA to indicate automotive side glazing with occupant retention capabilities superior to conventional tempered glass.

Anneal: to prevent or remove stresses in glass by controlled cooling from an elevated temperature.

ANSI/SAE Z26.1: American National Standard for Safety Glazing Materials for Glazing Motor Vehicles and Motor Vehicle Equipment Operating on Land Highways. This national voluntary consensus standard by reference regulates the materials used to glaze passenger vehicles.

Belt line: the bottom edge of a moveable side window portal; the top of the major portion of an automobile door.

Cullet: waste or broken glass that is usually recycled into the melt during primary glass manufacture.

Dicing: the breakage of thermally tempered glass into small, cube-like fragments.

EPGAA: Enhanced Protective Glass Automotive Association, a trade group of glass manufacturers that promotes the use of heat strengthened laminated side glass for safety and superior performance.

FMVSS 205: the Federal Motor Vehicle Safety Standard regulating passenger vehicle glazing within the U.S.

Glass: a hard, transparent, brittle material with a relatively high softening point, substantially insoluble in water and organic solvents, and nonflammable in the usual sense. An inorganic product of fusion that has been cooled to a rigid condition without crystallization.

Glaze: to fit with a transparent material such as glass.

Glazing: the material used to give a smooth transparent surface to an object.

Heat-strengthened glazing: single or multiple plies of glass which are given a light temper such that the fracture strength is between that of annealed glass and fully tempered glass. Heat-strengthened glazing does not dice and has the fracture characteristics of annealed glass.

HIC: head injury criterion; an estimator of potential head impact injury as measured by an anthropomorphic test device.

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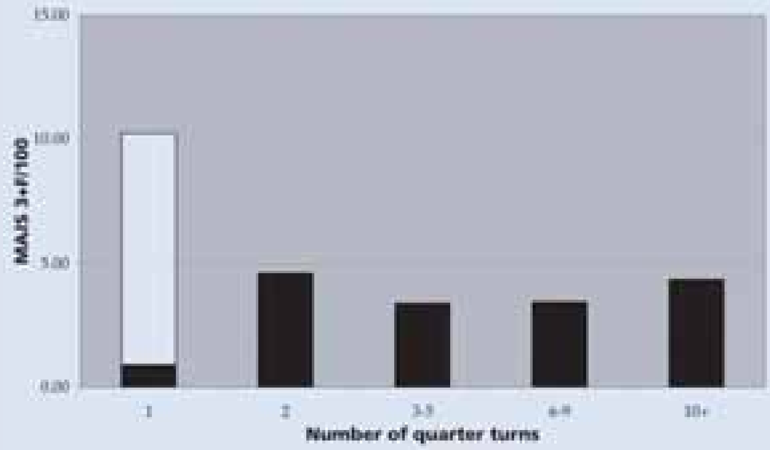
Figure 1

Injury Rate: Front Seat Occupants



Note. *Injury rate of unbelted nonejected front seat age 12+ occupants with MAIS 3+F injuries in single vehicle rollovers by number of quarter-turns. Dark = pure roll-related injury; light = injury due to impact with fixed objects or vehicles. From "Crash Attributes that Influence the Severity of Rollover Crashes," by K. Digges and A.M. Eigen, 2003,* Proceedings of the ESV Conference, *paper 231.*

is not required to pass the same impact testing as is HPR windshield glass and may use a thinner layer of PVB. LSG in moveable sidelights is usually heat-strengthened glass to provide fracture resistance to door slams. Prior to the development of EPG, laminated glass was thicker and heavier than tempered glass. This new glazing, being the same thickness as the tempered glazing it replaces, is actually lighter, as the PVB interlayer is lighter than glass.

One last laminated glazing design is "glass-plastic," which generally refers to tempered glass with a polymer sheet applied to the interior surface for its energy-absorption or antilacerative properties. This technology is essentially identical to the user applying an antishatter film to the inboard surface. Laminated glazing was studied as an occupant-retention replacement for conventional tempered glass (Clark & Sursi, 1989; NHTSA, 1995, 1999, 2001), but its use was never mandated by NHTSA (2001).

Vehicle & Occupant Kinematics in Rollover Collisions

The mechanism of rollover initiation has been well documented in the literature. It can be caused either by impact with another vehicle, tire-to-ground furrowing, impact with a fixed obstruction such as a curb, or poor design leading to rollover because of steering inputs alone on an unobstructed highway surface. Rollover initiates when the vehicle's dynamic center of gravity exceeds the support point of the tire on the initially leading side of the roll, and the vehicle overturns. Initial velocities are generally higher for rollovers than purely planar collisions (Digges, 2002). Approximately two-thirds of rollover vehicles have not suffered a major impact upon rollover (Mackay, Parkin, Morris et al., 1991). Eighty-five percent of rollovers are single-vehicle events (Cohen, Digges & Nichols, 1989).

The kinetic crash energy of rollover is dissipated over several seconds, rather than in ~0.1 s as is characteristic of planar collisions. It typically takes approximately twice as long for a vehicle to roll to a halt in an uncontrolled manner as it would for panic braking from the same velocity. This points to the inherent survivability of these accidents. If a rolling vehicle slides on its side or top, well-established metal-to-surface friction coefficients apply. These are relatively low—on the order of 0.2 to 0.3. For continuous rolling to rest, Bratten (1989) developed an empirical "tumble number" to bracket the overall

Automotive Glazing Terminology (continued)

HPR: high-penetration-resistant glazing; the type of laminated glass used in all windshields within the U.S. market. Composed of two exterior sheets of glass sandwiching a 0.030 in. (0.76 mm) PVB interlayer using controlled adhesion.

Light (lite): a medium (such as a window) through which light is admitted.

PVB: polyvinyl butyral ($C_{12}H_{10}ClN_5$), the polymer interlayer of most laminated glass.

Safety glazing material: A product consisting of organic and/or inorganic materials so constructed or treated to reduce, in comparison with annealed glass, the likelihood of injury to persons as a result of contact with these safety glazing materials when used in a vehicle.

Soda-lime glass: the predominant glass formulation for automobiles and consumer products. Made from approximately 60% sand (SiO_2), 20% soda ash (Na_2CO_3), 15% dolomite ($CaCO_3$ + Mg_2CO_3) and 5% limestone ($CaCO_3$).

Spline: an undesirable, generally straight, long shard of fractured glass. For tempered glass, splines arise from either a complex stress state (e.g., torsion) during fracture or an improper tempering.

Tempered glass: glass that has been rapidly and carefully cooled from near its softening point in order to induce permanent compressive surface stress. Exhibits superior strength and fracture characteristics when compared to annealed glass.

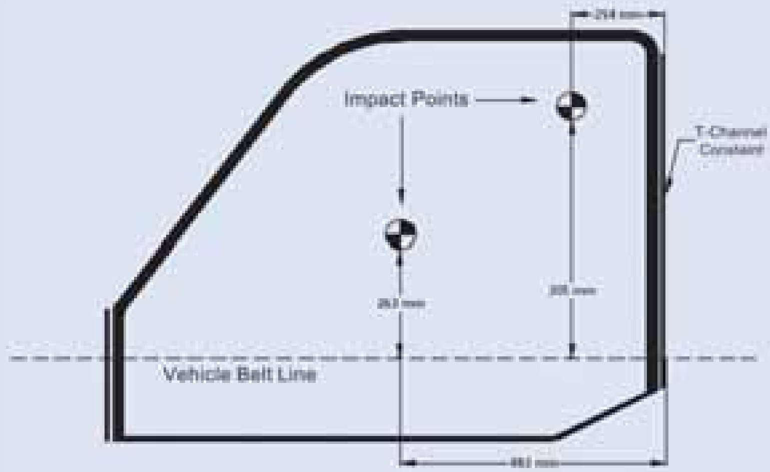
Weathering: glass surface attack by atmospheric elements.

deceleration rate. The average deceleration rate was estimated to be 0.486 *g* from analyzing numerous studies. Robinette & Fay (1993) determined a similar number, stating the typical horizontal deceleration, averaged over the entire rollover, to be 0.43 *g*.

During rollover, the occupant's motion generally follows that of the vehicle in a largely straight, ballistic, bouncing motion to rest. Both belted and unbelted occupants are jostled about in the vehicle in a complex, up-and-down, back-and-forth, chaotic motion, with modest impact velocities into the vehicle interior surfaces. Horizontal, vertical and rotational accelerations are in play. Because of this, unbelted occupants are often thrown through windows, and belted occupants partially excurse, with arms, heads, necks and shoulders going through newly opened portals including sunroofs.

Figure 2

Glazing Impact Locations



Note. *From* Ejection Mitigation Using Advanced Glazing: Status Report II, *by NHTSA Advanced Glazing Research Team, Figure 4.1, 1999.*

As the corners of the vehicle impact the ground, the occupant moves toward the impact and may strike the glazing, pillars or other vehicle components. Examination of accidents, reconstructions and dolly rollover tests indicate that the changes in velocity per corner strike are typically on the order of 5 mph or less (Altman, Santistevan, Hitchings et al., 2002; Orlowski, Bundorf & Moffatt, 1985). Changes in vertical velocity caused by roof impact are on the order of 5 mph or less (Friedman & Nash, 2001). The in-plane and out-of-plane velocity changes must be added vectorially, and momentum moves the occupant, relative to the vehicle, opposite to that of the impact vector.

Seven rollover tests conducted by NHTSA (1995) had an average head-to-glazing contact velocity of 11.2 kph (7.0 mph) (Knapton, 1983), and a maximum of 21.9 kph (13.6 mph). The analysis indicated that lack of restraint tended to bring about higher head-to-glazing impact velocities. NHTSA (1995) researchers later modeled three actual rollovers (using VDANL and MADYMO) under varied occupant conditions, resulting in seven total "virtual" rollovers. The maximum head impact velocity into the glazing was determined to be 13, 14, 14, 15, 20, 20 and 22 kph. This represented an average within-test maximum of 17 kph (10 mph), and an absolute between-test maximum of 22 kph (13.7 mph).

Takahashi & Iyoda (2003) reported the results of 12 rollover tests with an average belted-dummy impact velocity of approximately 2.1 m/s (4.8 mph), with a maximum of approximately 5.5 m/s (12.3 mph). These results were given in the context of side curtain airbag development for injury reduction in rollovers. These results suggest that designing for a maximum occupant impact velocity of 5.5 m/s (12 mph) will provide sufficient protection for most occupants. This number was confirmed as a design goal of a major automotive component supplier (Viano & Parenteau, 2005). Significantly, the effective weight of the occupant that is actually resisting containment is a fraction of the total body weight, and has been estimated to be 18 kg (40 lb) (NHTSA, 1999) for 50th percentile males.

Glazing Failure Mechanisms in Rollover Collisions

During rollover, if the roof structure is quite strong, the glass performs well and generally will not fracture. This is particularly true behind the B-pillar, as vehicles tend to roll "nose down" because of engine weight. The converse—that weak roofs produce glazing fracture—also is true.

The so-called "Malibu I" rollover tests (Orlowski, Bundorf & Moffatt, 1985) indicate this. Four production and four roll-caged vehicles were subjected to Federal Motor Vehicle Safety Standard (FMVSS) 208 dolly rollover tests, each with two unbelted front seat dummies. For the roll-caged vehicles, 16 of 20 (80%) tempered side and rear glazing panels survived body flexure, while for the production vehicles only 2 of 20 survived unbroken. Malliaris, DeBlois and Digges (1996) indicated that more than 80% of ejections through glazing areas involved the shattering of the glazing by crash forces prior to the occupants reaching the precrash surface. The mechanisms of glazing failure in rollover collisions for all types of glazing materials have been cataloged by Batzer (2005, 2006). In rollovers, glazing commonly fails via:

1) intact detachment and loss due to failure of the mounting hardware;

2) fracture and complete loss of tempered glass due to body/framing deformation, crash pulses or impact with objects on the vehicle's exterior or interior.

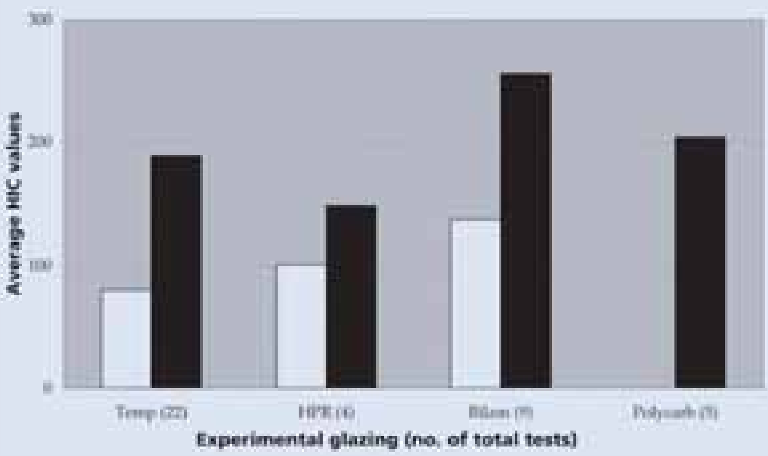
3) loss of above-beltline fixation of moveable laminated side glazing via pullout from the seal and loss of shape integrity (the "wet washcloth");

4) gross door-mounted window frame deformation due to interaction with the roadway.

For these failures, only laminated glazing can maintain its occupant retention function in rollovers once fractured. Even then, it requires sufficient peripheral fixation in order to maintain its geometric integrity. In fact, the strength of the door-mounted window frame is sometimes insufficient to resist loading by the occupant, and the occupant is injured or killed by partial or full ejection over the frame during side collisions and/or rollovers.

Figure 3

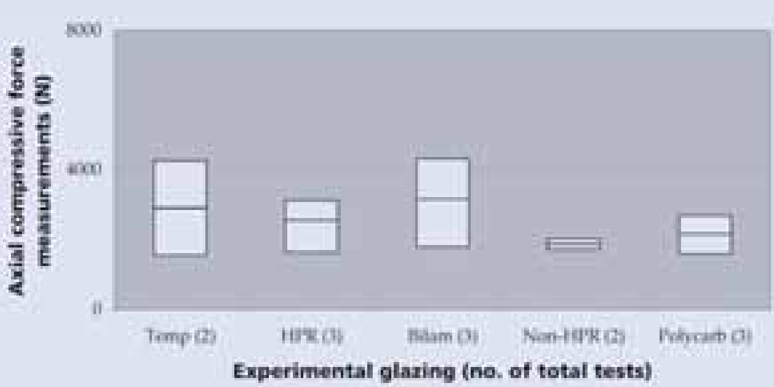
Average Center & Corner Impact HIC Values



Note. *Average of center and corner impact HIC values for 23.6 kph (15 mph) strikes. Light = broken; dark = unbroken. From* Ejection Mitigation Using Advanced Glazing: Status Report II, *by NHTSA Advanced Glazing Research Team, 1999.*

Figure 4

Axial Compressive Force Measurements



Note. *Axial compressive force measurements for 23.6 kph (15 mph) impacts minimum/average/maximum values. From* Ejection Mitigation Using Advanced Glazing: Status Report II, *by NHTSA Advanced Glazing Research Team, 1999.*

Glazing-Related Injury Mechanisms in Rollover Collisions

Injury from glazing contact has long been of concern, and both tempered and laminated glazing designs of today produce fewer injuries than did previous formulations. Because so few current vehicles contain LSG, it is not possible to conduct a robust statistical analysis of injuries in rollover collisions comparing the two. However, previous and current research is sufficient to evaluate both forms of glazing and to draw meaningful comparisons.

Digges and Eigen (2003) showed that even in multiple-roll rollovers, the rate of injury, even for unrestrained occupants is low (Figure 1, p. 36). Within the population of one-quarter-roll collisions (vehicle rotates a net 90º about its roll axis), a substantial 94% of the severely injured occupants received their injuries either from impact with another vehicle initiating the rollover or from impacts with fixed objects (e.g., trees, poles) either before or during the rollover. By removing these two conditions, the injury rate for quarter-turn collisions is less than 1 per 100 exposed (Figure 1). Most vehicles that roll do so about the principle travel axis of the vehicle. These are called barrel rolls. A small number of occupants involved in rollovers—3.6%—are in "end-over" rolls about the pitch axis and generally suffer a greater level of injury.

Occupant-to-Glazing Impact

An analysis of neck injuries in auto crashes (Ommaya, Backaitis, Fan et al., 1983) indicated that most injuries resulted from contacts involving relatively rigid, nonglazing structures such as the pillars and rails. To address this, FMVSS 201, Occupant Protection in Interior Impact, has been updated to require energy-absorbing materials.

Occupant-to-occupant impacts are also experienced in collisions, sometimes with serious injury effects. As part of its occupant retention glazing project, NHTSA (1995, 1999, 2001) conducted a comprehensive study including existing injury scope, feasibility, cost, tradeoffs, and potential benefits and drawbacks, particularly for ejection injuries prevented and possible increased occupant-to-glazing contact injuries. Various glazing materials were studied, including monolithic tempered as the baseline, HPR trilaminate, a non-HPR trilaminate, polycarbonate (monolithic rigid plastic), and bilaminate (a glass-plastic formulation consisting of tempered glass with inboard layers of PVB, PET and an abrasion-resistant silicon coating for scratch resistance).

They conducted free-motion headform tests to measure head injury criterion (HIC) indicating potential brain injuries and side impact sled tests to measure potential neck injuries. For a frontal barrier crash of 48 kph (30 mph), FMVSS 208 (2001) sets the maximum permissible HIC level at 1,000 for 36 ms (HIC 36) as defined by:

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

where: a is the resultant head acceleration; t_2-t_1 = 36 ms; and t_2 and t_1 are selected to maximize HIC.

It should be noted that then as now, no injury criteria are generally agreed upon with respect to side impacts to the head for either HIC or other injury mechanisms. During side impacts and rollover collisions, the head and shoulders can hit virtually any portion of the glazing. Two points, the upper rear corner of the glazing and the approximate geometric center were chosen by NHTSA for study (Figure 2, p. 37).

The results of the free motion headform tests indicated that head or brain injury is unlikely with any side glazing formulation considered. A combination of hits to the geometric center of the glazing and the upper rear corner were used; their averages are shown in Figure 3. (*Note:* For this and other NHTSA graphs, the number of individual tests per glazing type is included in parentheses.)

As expected, unbroken sidelights produce more of a direct injury mechanism than do broken sidelights that fail to completely retain the headform. Notice that the polycarbonate glazing (currently not allowed within the U.S. as a material for windows requisite for driver visibility) never failed to retain the headform.

Sled tests allowed the relative motion of the dummy into the framed experimental sidelights at speeds of up to 24 kph (15 mph). To determine the maximum neck injury potential of such impacts, the dummy was tilted to about 26° toward the glazing to help ensure that initial contact was by the head, rather than the shoulders, maximizing neck loading. Figures 4, 5 and 6 present the values determined for the tests using the experimental glazing panels. Note that there were not and are not well-accepted injury criteria for neck injuries for side impacts. The criteria given by NHTSA in two different publications differed significantly (NHTSA, 1999; Eppinger, Sun & Kuppa, 1999).

Significant variability was measured in lateral neck shear loads, axial compression and moments about the occipital condyles. It was observed that occupant-to-glazing impacts were in general more severe with HPR laminated than tempered. However, the occupant generally does not strike tempered glass in rollover collisions since the glazing is already broken out.

The tempered and bilaminate glazings gave the highest axial compression forces, followed by HPR, polycarbonate and non-HPR. The moments about the occipital condyles were highest for HPR, followed by the bilaminate, polycarbonate, non-HPR and tempered glazing. The neck values were highest when the head strike preceded that of the shoulder. The highest lateral neck shear force was incurred with bilaminate and polycarbonate glazing. Several research and companion studies have shown that the potential for neck injury due to impact into laminated side glazing is low in rollovers (Sances, Carlin & Kumaresan, 2002; Sances, Kumaresan, Carlin et al., 2003).

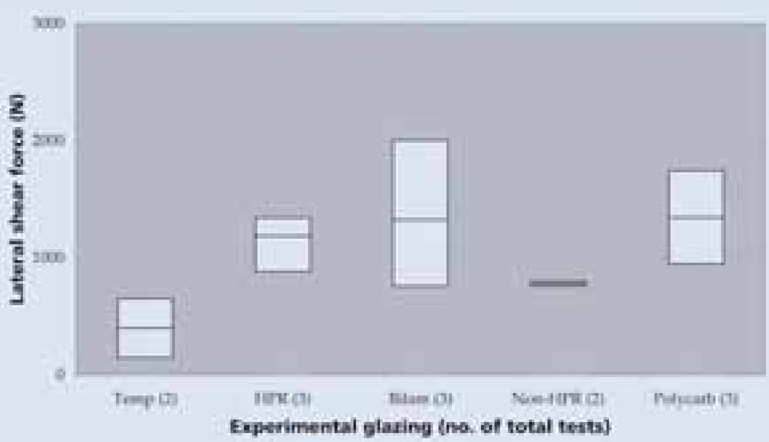
Figure 5

Moment about Occipital Condyle

Note. *Moment about occipital condyle for 23.6 kph (15mph) impacts minimum/average/ maximum values. From* Ejection Mitigation Using Advanced Glazing: Status Report II, *by NHTSA Advanced Glazing Research Team, 1999.*

Figure 6

Measured Lateral Shear Force



Note. *Measured lateral shear force for 23.6 kph (15 mph) impacts minimum/average/maximum values. From* Ejection Mitigation Using Advanced Glazing: Status Report II, *by NHTSA Advanced Glazing Research Team, 1999.*

In summary, NHTSA's experimental work demonstrates that currently available glazing is capable of retention, has low HIC values and probably does not exhibit a potential for head or neck injury for healthy occupants at likely rollover impact velocities. NHTSA (1999) declares that "even if there can be small increases in low-level neck injury, it is anticipated that the fatality prevention benefit of advanced glazing would likely greatly outweigh any such disbenefits."

As far back as the early 1960s, when tempered glazing was being compared to the old style, non-HPR laminated glazing for side windows, the similarity in impact trauma was recognized.

Table 1

Percentage of Serious Injuries/Fatalities Sustained During Rollover

Occupant restraint	No ejection	Complete ejection
Unbelted	4.2	34.9
Belted	2.5	40.8

Note. *Percentage of serious injuries (MAIS 3-5) and fatalities sustained by occupant in light vehicles during rollover. From* Injuring Contacts in Light Vehicle Rollovers, *by Data Link Inc., 1993.*

> Research on injury potential of automotive glazing was initiated at Wayne State University in 1958. . . . The results of the program showed that tempered glass is not likely to cause more head injuries than laminated glass. . . . These investigators can find no significant difference in the injury production from the two types of side windows (Widman, 1965).

Patrick (1995) also reported that "laminated side glass would not be hazardous from an impact standpoint (except for laceration) when struck with the glass in its normal position."

A further comparison can be made with non-HPR to HPR-type windscreens. The resistance to penetration dramatically increased with this newer technology, and could presumably have caused more blunt impact trauma. According to Kahane (1985), "With pre-HPR glazing, there was a 50% probability that an unbelted occupant would penetrate the windshield in a frontal crash with a Delta V of 14 mph. With HPR glazing, the likelihood of penetration does not reach 50% until the Delta V is 31 mph." The difference between these two velocities for a fixed occupant mass is 120% greater momentum and 390% greater kinetic energy. Kahane (1985) continues, "HPR windshields had little or no observed effect on injuries characteristic of blunt impact trauma: concussions, contusions and complaints of pain."

Photo 2: Laminated side glazing pictograms signifying "occupant containment" and "exterior impact resistance."

Noncontainment

During rollover, occupants can be fully contained or ejected, either partially or fully. If ejected, the chance of serious injury increases significantly. National Crash Severity Study (NCSS) analysis indicated that there is a 40-fold increase in severe to fatal injury probability when ejection occurs. Other investigations have qualitatively agreed with this ratio (NHTSA, 1995; Malliaris, DeBlois & Digges, 1996). Studies of both tempered and HPR glazing indicate that the greatest risk of serious injury for the occupant is associated with ejection. An occupant is more than 10 times more likely to go through a glazing portal than through a door in a rollover crash, and glazing size is important. Ejection through glazing from two-door cars is twice as likely as it is with four-door vehicles (Digges, 2002).

The 1993 study presented in Table 1 indicates the percentage of serious injuries and fatalities to occupants who remained in their vehicles during rollovers of light vehicles. The Data Link findings show that approximately 4% of unbelted occupants incur severe injury or death in rollovers when completely contained; this percentage declines to about 2% for belted occupants. This is in good agreement with Figure 1.

It has long been recognized that tempered glass contains no inherent energy-absorbing capability (Yudenfriend, 1961) and once broken at any point can no longer offer any occupant protection. As early as 1968, LSG has been described as "state of the art" for occupant containment (Hill, 1969). A side benefit of laminated glass in the backlite is the added protection against fire entering the occupant capsule (Severy, Blaisdell & Kerkhoff, 1974). Occupant retention side glazing for automobiles has been effectively demonstrated by Clark and Sursi (1989), who used eight dolly rollover tests to show 100% effective occupant containment, even with unbelted anthropomorphic dummies. A set of pictograms currently applied to many St. Gobain laminated glass side windows is shown in Photo 2, indicating its occupant retention capability (lower left) and intrusion resistance (lower right).

Other technologies are available to mitigate occupant ejection in rollover collisions. The most promising seems to be side curtain airbags that are designed to contain occupants rather than to only provide impact amelioration. As with frontal-impact airbags, LSG provides a reaction surface, increasing the effectiveness of the airbag. Furthermore, arms and legs can excurse between the bottom of the curtain and the top of the sill (beltline), producing life-altering, if not fatal, injury.

Entrapment

The converse of unwanted excursion is unwanted restraint post-accident. The subject of entrapment has been around for generations and represents a primal fear. Certainly, the threat of death through drowning or burning while trapped in a vehicle is sobering. One company advertises the "Life Hammer," which is intended to fracture tempered glazing in the event of vehicle immersion or other entrapment emergency. However, the site's testimonials include no examples of lives saved or injuries prevented.

It is true that neither tempered nor laminated glazing is easy to penetrate without tools, although laminated glass can be kicked through with multiple impacts while tempered may not. Quasi-static pushout tests in moveable sidelights have shown tempered glass to take more than 500 lb of force without fracture or dislodging from the weather stripping.

In 1964, Cornell Aeronautical Laboratory issued a report regarding automobile glazing as an injury factor in accidents (Campbell & Bopens, 1964). The report concluded that situations such as this are rare and require all of the following conditions to be true (note: emphasis in original): "All car doors jammed shut or otherwise blocked *and* all windows rolled up *and* all windows jammed such that they could not be rolled down *and* all glass surfaces intact."

Furthermore, the occupant(s) must have survived the initial accident to make egress relevant. The authors studied 30,000 accidents, of which only 755 cases presented a situation where escape through doors was not possible.

> In only 12 of these was there a need for immediate escape because of fire or immersion. In none of the 12 was there a clear-cut indication that egress depended upon the necessity for breaking a glass surface. Three hundred of the 755 were studied individually and the indications were that egress would have been possible without resorting to breaking glass in most, and perhaps all, cases . . . it stated with confidence that the number is extremely small (Campbell & Bopens, 1964).

A second comprehensive report regarding submerged vehicles listed as its purpose "to determine the sequence of events when an automobile is suddenly submerged in water deeper than the vehicle itself, what passengers can do to save themselves and how passengers can be rescued" (Kuhn, 1962). Four passenger cars were used for data acquisition and three others were used for test feasibility studies. Forty-nine tests were conducted with 12-ft deep water. The recommendations regarding proper actions required 20 pages of text and a 20-min film to summarize. Escape recommendations included:

- Following impact, for a vehicle entering on its top, the occupant can escape by keeping his head against the floorboard, inhaling deeply, and leaving the vehicle through the open windows which are under the surface.
- If the occupant is unable to escape through the front windows after impact, he should position himself to the rear of the passenger compartment in the existing air so as to provide more time to plan his escape, as the vehicle will descend to the bottom on its top, engine first. Escape at this time can be accomplished through an open window or by opening a door.

According to Morris, Hassan, Mackay, et al. (1993), "whether using laminated side and rear glass would in fact make it difficult for an entrapped occupant to escape can only be speculated at this stage since field data is not available to allow conclusions to be drawn." They conclude, "In summary, we have shown that ejection is an undesirable outcome and that retention is more desirable. Introduction of any alternative security glazing material in the side and rear windows would be welcome, especially as it is anticipated that it would reduce the incidence of ejection."

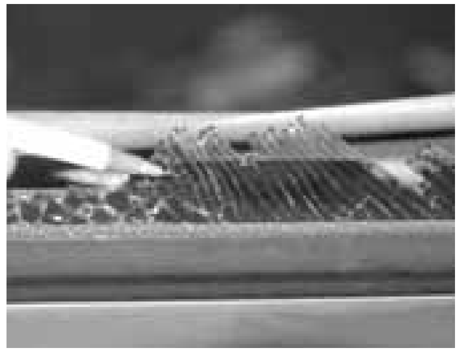


Photo 3 (left): Lacerative potential of tempered fragments, fixed quarter lite, lower edge.

Photo 4 (below): Blunt headform impactor testing of commercial laminated side glazing.

Patrick (1995) believes that laminated glass gave a slight performance edge over tempered glass in entrapment situations, but felt this was not a problem even in Holland, which has a high number of canals along the roadways. Hassan, Mackay, Foret-Bruno, et al. (2001) studied the implications of laminated side glazing for occupant safety and concluded that "occupant entrapment is not likely to be a major problem." Anecdotal evidence indicates that the crush of doors, pillars and roofs is the dominant mode of vehicle entrapment. Such deformation can prevent the opening of doors; limit access necessary to unlatch belts; diminish window portal size; and even trap occupants via binding long hair between the headrest and the headliner.

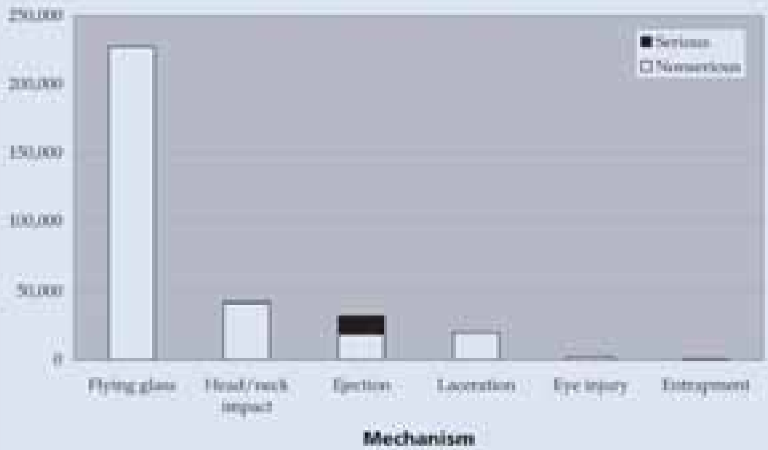
Laceration

The most prevalent injury due to glazing, by far, is that of laceration (Patrick, 1995). By studying the dominant automobile accident mode, the frontal collision—which represents approximately 60% of all accidents for passenger vehicles and light trucks (NHTSA, 2004)—one can rely on historical data of completely unrestrained occupants to gain insight into the lacerative potential of windshields and, by extension, tempered and laminated side glazing. The contact mechanics are comparable; in Europe, tempered windshields were produced side-by-side with the new HPR-formulated windshields.

Analysis of these data has led to alignment of western Europe with the U.S. in requiring HPR-laminated glazing for all windshields of passenger vehicles. Patrick, Trosien and DuPont (1970) indicated,

Figure 7

Estimates of Side-Glazing-Related Injury Occurrence by Type



Note. *1999 estimates of side-glazing-related injury occurrence by type side glazing injury statistics—towaway collisions, passenger vehicles. From* Ejection Mitigation Using Advanced Glazing: Status Report II, *by NHTSA Advanced Glazing Research Team, 1999.*

"Severe lacerations resulted in all impacts in which tempered glass broke. Less severe lacerations were found for the laminated windshield impacts at comparable speeds." They also indicate that the consensus of German researchers in the 1960s was that penetration of tempered windshields caused severe facial lacerations and eye injuries ranging from minor injuries to total loss of sight. They recommended the usage of laminated over tempered windshields.

Recall that the formulation of laminated glazing was changed in the mid-1960s. Early Stapp Car Crash Conference proceedings display graphic photographs of occupants who have penetrated pre-HPR windshields. Haynes and Lissner (1961) indicated that there is little risk of lacerative injury with totally fractured tempered glass. Both McLean (1969), and Mackay, Siegel and Hight (1970) discussed the severe injuries that occur from the tempered fragments which remain at the frame around the windshield opening. ANSI Z26.1 does not regulate the size or shape of fragments at the periphery of the window.

The lacerative potential of tempered glass depends on how it is handled (Photo 3). Casual handling of dice-like fragments of tempered glass gives an unrealistic impression of their danger. Such fragments contain points and sharp edges. In reporting their crash research, Severy and Snowden (1962) reported:

> Subsequent examination of high speed movies of these experiments revealed that tempered glass fragments may move as clusters, an inch or two across the long axis, so that the comment concerning hazard arising from tempered glass weight should be modified. It was also observed in collecting the fragments that while many particles are cube-like, as described by other investigators, most were by no means free of sharp points or edges, making them very difficult to handle without cutting one's hands.

In door-impact experiments, Yudenfriend and Clark (1997) found that 20% to nearly 40% of the glass fragments flew inward toward the occupant survival space and that they entered this space at velocities as high as 23 km/hr (14.3 mph). The speed, size, shape and sharpness explain why tempered glass fragments produced in automotive accidents have been found to penetrate skin and skull and even enter the brain (Yudenfriend & Clark, 1997). Other citations regarding skull penetration of glazing fragments refer exclusively to tempered fragments, rather than to the annealed fragments produced by laminated glass (Rushworth & Toakley, 1969; Greene, 1976).

In multiple-roll rollovers, the possibility exists for multiple interactions with laminated occupant-retention glass. Batzer, Evans, Allen, et al. (2005) found that the laceration potential did not substantially increase in multiple impacts against EPG-style laminated side glass with multiple impacts without through-glass penetration (Photo 4).

Eye Injuries

When tempered glass shatters in a collision, it is often under the conditions of bending or shock loading, ensuring that stored elastic energy is released and increasing the out-of-plane velocity of the fragments. While laminated glazing spalls and creates small, even dust-like, fragments capable of eye laceration (Mackay, Siegel & Hight, 1970), the quantity of laminated glass fragments detaching from the laminate is generally less than 1% of that from tempered glazing. The shower of tempered glass fragments threaten, but create fewer injuries than many would suspect. In its comprehensive occupant retention glazing studies, NHTSA (1995, 1999, 2001) did not consider this injury mechanism.

Head strikes to laminated windshields versus tempered were studied by Langwieder (1972), who found only one eye injury from HPR-laminated glass (of 228 occupants with head injuries), while tempered windshields brought about 17 cases of eye injury among 545 head injuries. This represents a sevenfold increase in injury for tempered windshields over laminated, and may be explained by the reduced number of fragments. In one side collision with fractured tempered glazing, a woman complained of persistent eye irritation, leading to an X-ray examination that indicated a fragment was lodged behind her eyeball, resting against the optic nerve. This can be explained by gross inertial deformation of the eye during the crash pulse that caused a separation between the ball and the surrounding tissue, allowing introduction of the fragment.

This disproportionate injury rate of tempered windscreens was further confirmed by Mackay (1978). He concluded, "Eye injury from toughened glass windscreens is a substantial problem reflected in the clinical literature from at least 12 countries. By contrast, countries which use HPR laminated glass report no incidence of eye injuries from the windscreen of any consequence."

Huelke, Day and Barhydt (1982) studied a 27-month segment of National Crash Severity Study data (January 1977 to March 1979), representing 106,000 vehicles in towaway passenger car crashes. This included windshields of the pre-HPR formulation. Twenty-nine occupants received serious eye or eye muscular injuries. Various objects caused eye injury (e.g., sun visors, glasses, pillars, a fence), but the predominant agents (~64%) were the windshield and side glazing. Remarkably, no single occupant of the 106,000 accidents studied had been totally blinded.

Table 2

Relative Benefits of Side Glazing Materials

This table shows the most beneficial side glazing material based on each benefit. The most beneficial is marked *X*.

Attribute	Tempered	Laminated
Safety		
Containment		X
Airbag assistance (reaction surface)		X
Laceration		X
Eye injury		X
Entrapment		X
Skull penetration		X
Fire resistance		X
Impact blunt trauma injuries	Neither	Neither
Security		
Intrusion resistance		X
Sharp impact penetration resistance		X
Blunt impact penetration resistance	X	
Shock resistance	X	
Comfort, convenience		
Sound reduction		X
IR reduction		X
UV reduction		X
Optical quality		X
Replacement ease		X
Weight (identical thickness)		X
Surface damage independent performance		X
Temperature-independent performance	X	
Cost	X	
Weathering durability	Neither	Neither

Statistical Analysis of Glazing-Related Injuries in Major Accidents

Automobile designers and federal regulators must study the injury rates related to automobile components in all types of accidents, rather than simply rollovers. Therefore, the following estimates of injury magnitudes with an emphasis on side-glazing-related trauma are based on towaway accidents rather than just rollovers. For the year 1999, approximately 6,279,000 accidents were reported (NHTSA, 2000), of which 2,990,000 were towaway (DOT, 2006); 277,000 of those towaway accidents involved rollover (NHTSA, 2000). Rollover accidents disproportionately injure occupants, representing approximately 8% of the collisions but 21% of the serious injuries and 31% of the fatalities (NHTSA, 2003).

Figure 7 illustrates side-glazing injury rates for towaway accidents based on various sources. In 1999, nearly 227,500 injuries were due to flying tempered glass fragments, making this the dominant injury mode (DOT, 2006). Flying glass caused primarily nonserious injuries, with only one serious chest injury recorded in the NASS-CDS database. The "head/neck impact" entry of ~41,300 nonserious and 740 serious injuries refers to nonlacerative contact injuries (i.e., concussion, contusion, dislocation, fracture, sprain and strain).

For side and rear glazing, lacerative injuries were estimated to be 20,000, all of which were nonserious (DOT, 2006). Side-glazing-related serious injuries and deaths are dominated by ejection—~13,100 instances in 1999 coupled with an additional ~18,800 ejection-related minor injuries (NHTSA, 2001). The national estimate of glazing-related eye injuries report 2,030 instances. All of these were coded as nonserious, since eye injuries (including total blindness) are not considered to be life-threatening (DOT, 2006).

Instances of permanent vision degradation from glazing (including windshields) can be estimated at approximately 520 (Huelke, Day & Barhydt, 1982;

Practical Applications

Automotive safety starts with the driver. Ensure that every occupant is wearing a safety belt. Drive attentively and defensively at moderate speed without multitasking. However, since accidents can and do occur, a driver can take other preventive measures to maximize safety during collisions.

- Research the safety of a prospective new car from a variety of accident scenarios. Insurance Institute for Highway Safety (www.iihs.org) provides crashworthiness data, as does NHTSA (www.nhtsa.dot.gov/ncap).
- Purchase the safest vehicle you can afford; consider buying a used vehicle if cost is a prime consideration.
- Avoid purchasing a vehicle that has a high rollover propensity. If buying a sport utility vehicle, make sure it is equipped with electronic stability control.
- Purchase a vehicle with either rollover-sensor-activated side curtain airbags or laminated side glass to reduce injuries during collisions. Enhanced Protective Glass Automotive Association (www.epgaa.com) lists vehicles with laminated side glass and provides an overview of its benefits. Seatbelts are no guarantee of complete containment during collisions.
- Skip the sunroof. This option significantly lowers the crashworthiness of the vehicle, as occupants may be partially or fully ejected through this portal during rollovers. If a vehicle has a sunroof, it is best to keep the sliding cover closed.
- Consider retrofitting tempered side windows on the inboard side with 4-mil-thick shatterfilm. Any local automotive tint shop can provide this service. Clear, tinted and reflective films are available. Even on a new vehicle with side curtain airbags and tempered side glass, shatterfilm will still be of benefit.
- Drive with moveable windows in the fully up position to maximize ejection mitigation. If a moveable window is down, do not rest an arm on the sill, exposing it to amputation during a side-swipe collision or rollover.

DOT, 2006). The estimate of true instances of glazing-caused entrapment (not injury) performed for this article (Figure 7) is 600, based on the number of towaway accidents recorded for 1999 and the incidence ratio cited previously (DOT, 2006; Campbell & Bopens, 1964); this does not necessarily indicate injury. The statistics show that 99.5% of nonejection-related side glazing injuries are not serious.

For comparison, note that in 1999, HPR windshields yielded 99,015 total laceration injuries, of which only 202 were serious or fatal—a scant 0.2% of interactions (DOT, 2006). The windshield ejection incidence was approximately 4,420 averaged over 1995 to 1999 (NHTSA, 1999) (this number includes fatalities as adjusted to the 1999 FARS), or about 8.6% of glazing ejections. This is despite the fact that frontal collisions represent more than 50% of collisions (NHTSA, 2000). These statistics indicate the effectiveness of laminated glazing as used in the windshield both for occupant retention and injury reduction.

One final observation regarding glass-impact injuries can be garnered from lessons learned from tempered windshields. Rushworth and Toakley (1969) estimated at the time of the their writing that they estimated tempered windshields outnumbered laminated windshields in Australia by 8:1. Furthermore, these ¼-in.-thick (6 mm) tempered windshields required up to 2,050 lb (9,100 N) to fracture. Yet, they indicate that "no serious closed head injuries from impact with the windscreen alone have been encountered by us . . . this aspect appears to be unimportant."

Conclusions

Both tempered and laminated glass materials are currently used within side windows of passenger automobiles. The injury mechanisms of both constructions during rollover collisions have been analyzed. The occupant to side-glazing velocities developed in rollovers are low, and do not present a serious injury potential to either the head or neck. If the glazing is not penetrated, the laceration hazard is limited to abrasion.

The greatest threat to both belted and unbelted occupants is caused by complete or partial ejection and nonglazing contact generated injury. If the side window portal is kept covered in a collision, then similar to the performance of an HPR windshield, occupant containment can be realized. Ocular injuries are relatively rare, and other injuries such as entrapment are even more rare. Table 2 (p. 43) presents the relative benefits of the types of side glazing in general service. ■

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