POST-INCIDENT SURVIVABILITY AND EMERGENCY EGRESS: CONSUMER-FOCUSED APPROACHES TO IN-VEHICLE FIRE AND SUBMERSION SAFETY

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ABSTRACT

This paper examines occupant entrapment during in-vehicle fires or water submersion as a persistent public-safety problem not *addressed* by advances in crash avoidance or crashworthiness More than 20,000 police-reported in-vehicle fire or submersion incidents occur annually in the United States, resulting in over 2,000 occupant fatalities—making these among the deadliest incidents. Consumer-safety programs such as Euro NCAP have recently placed new emphasis on post-crash survivability by evaluating window functionality and an occupant's ability to exit a submerged vehicle, prompting egress-support technologies. This paper quantifies post-incident survivability challenges related to vehicle fire and submersion using available U.S. data, compares post-crash assessment protocols across European, Australasian, and U.S. programs, and evaluates the performance of manual tools and emerging automated egress approaches. We conclude that incorporating egress performance into consumer-safety ratings could drive innovation, improve consumer information and preparedness, and reduce entrapment deaths; we propose a technology-neutral, consumer-focused egress-performance framework.

Keywords: vehicle submersion, in-vehicle fire, emergency egress, occupant entrapment, laminated glazing, consumer safety ratings, post-incident survivability, automatic window lowering, Euro NCAP, automated egress system.

INTRODUCTION

Scope and Motivation

Motor-vehicle safety has advanced substantially over recent decades. Features such as crumple zones, airbags, advanced driver-assistance systems (ADAS), and laminated glazing have significantly reduced crash-related injuries and fatalities. However, these technologies primarily address crash injury mitigation and do not explicitly account for post-crash entrapment scenarios—such as water submersion or internal vehicle fires—where occupants may become trapped and rapid egress is essential. Crashworthiness and crash-avoidance technologies have successfully addressed the dominant causes of roadway fatalities for more than forty years, contributing to sustained reductions in frontal, side-impact, and rollover deaths. When measured per vehicle-mile traveled, traffic-fatality rates have declined markedly, reflecting major improvements in vehicle-safety performance (***Table 1)*** [1].

Despite these gains, fatalities from two categories of vehicle incidents—internal vehicle fires and water submersion—have not declined. In the United States, police-reported crashes involving internal vehicle fires or submersion averaged more than 20,000 per year between 2016 and 2023, resulting in approximately 1,600 fire-related deaths and roughly 500 drowning deaths annually [2, 3, 10, 39]. This stagnation is not due to technical limitations. Instead, it reflects the fact that in-vehicle fire- and submersion-related entrapment remain comparatively understudied, undertested, inconsistently captured in national and international crash datasets, and underrepresented in current safety requirements and consumer-rating programs. While Euro NCAP has recently introduced vehicle-submersion egress scoring within its Rescue, Extrication & Safety protocols, post-crash escape performance is not yet systematically evaluated in most other vehicle-safety assessment frameworks or regulatory test programs. As a result, vehicle technologies have not evolved systematically to assist occupants during the first minute after a fire or water immersion—precisely when escape is most critical.

The widespread adoption of laminated side glazing to meet ejection-mitigation requirements illustrates this gap. Although laminated side windows are effective at preventing occupant ejection and reducing injury during collisions, they may unintentionally hinder emergency egress in certain post-crash scenarios, particularly during vehicle submersion or internal fires. More broadly, contemporary vehicle systems are designed to satisfy defined crash-injury and containment performance requirements, whereas post-crash escape functionality has not historically been a primary evaluation criterion.

Table 1.
U.S. motor-vehicle fatalities and fatality rates per 100 million vehicle miles traveled (selected years). Adapted from NHTSA FARS and FHWA VMT estimates [1].

Year	Fatalities	Fatality Rate per 100M VMT
1985	43825	2.47
1990	44599	2.08
1995	41817	1.73
2000	41945	1.53
2005	43510	1.46
2010	32999	1.11
2014	32744	1.08
2020	39007	1.34
2024	39345	1.2
2025 (Jan–Jun)	17140	1.06

Note: Fatality rate is expressed as fatalities per 100 million vehicle miles traveled (VMT). Data for 1985–2020 are from NHTSA's Fatality Analysis Reporting System (FARS) and FHWA VMT estimates. Data for 2024 and 2025 (Jan–Jun) are NHTSA early estimates and subject to revision.

Fire- and submersion-related entrapment fatalities share key characteristics with crash fatalities prior to modern safety interventions: they are sudden, time-critical, and overwhelmingly survivable if the vehicle provides basic support for escape. Consumer-safety programs contributed to dramatic reductions in crash fatalities by focusing on performance metrics that manufacturers could design toward. A similar transformation is now needed to address emergency egress and post-crash survivability.

Regulatory Context and Emerging Focus on Post-Incident Survivability

Historically, consumer-vehicle safety programs have prioritized crash-injury metrics such as head, chest, and leg injury criteria, with limited attention to injuries or fatalities associated with delayed or obstructed occupant egress during emergencies. In recent years, this has begun to change. Euro NCAP's 2026 Rescue, Extrication & Safety Test & Assessment Protocol includes a dedicated post-submersion egress assessment—an important step toward integrating post-incident survivability into mainstream safety evaluation and awards up to three points for submersion protection, signaling that egress capability is emerging as a legitimate domain of occupant protection [4]. Australasian NCAP (ANCAP) aligns its assessments with Euro NCAP's protocol [5]. In parallel, some manufacturers have introduced design features and software functions intended to assist with window opening or door unlocking during water- or fire-related incidents.

US NCAP, while pioneering vehicle-crash ratings since 1979, currently lacks a specific post-crash survivability metric. However, the National Highway Traffic Safety Administration (NHTSA)'s 2022 SAFE System initiative introduced a "Post-Crash Care" pillar that may provide future avenues for evaluating egress-support systems. Thus, U.S. consumer-rating programs now acknowledge the importance of post-crash survivability in principle, but they do not yet translate this recognition into concrete vehicle-level egress-performance targets or star-rating information regarding a vehicle's ability to facilitate escape during fire or submersion incidents. These developments underscore a growing consensus: reducing entrapment deaths requires systematic evaluation of a vehicle's ability to support rapid egress in both crash-related and non-crash emergencies. Integrating egress performance into consumer-safety programs has the potential to drive innovation, inform the public, and save lives—just as star rating programs did for crash protection.

Focus of this Study

This paper summarizes current knowledge about vehicle egress in fire and submersion incidents, reviews existing consumer-assessment protocols related to post-crash conditions, and compares the capabilities and limitations of manual tools and emerging automated egress systems. We focus on newly manufactured passenger motor vehicles—including cars, light trucks, vans, and sport-utility vehicles (SUVs) with a gross vehicle weight rating (GVWR) of less than 10,000 pounds (4,500 kg) [6] consistent with the vehicle classes addressed by most consumer-safety programs. Egress-support systems for these vehicles are compared based on their ability to facilitate rapid occupant escape across a wide range of emergency situations, including in- vehicle fires (fires originating in the vehicle or post-crash fires that breach the passenger compartment), submersion, floods, and both crash-related and non-crash-related entrapment

scenarios. External hazards such as wildfires or wildland–urban interface (WUI) events, which involve different exposure conditions and evacuation strategies, are outside the scope of this analysis. We propose a technology-neutral framework for incorporating emergency-egress performance into consumer-safety ratings as one component of a broader strategy to reduce entrapment-related fatalities.

Terminology notes. U.S. crash databases (FARS, CRSS) classify vehicle water-entry events as "immersion," while Euro NCAP and ANCAP use the term "submergence". In this paper, we use the term vehicle submersion consistently to refer to water-entry events that compromise occupant egress.

METHODS

This study is a secondary-data synthesis and technology review focused on vehicle egress in post-crash and non-crash fire and submersion scenarios. No experiments were conducted and no new human-subject data were collected. Quantitative results were derived from publicly available crash and fatality datasets, while qualitative findings were derived from consumer-safety protocols, technical reports, and manufacturer documentation. These sources were reviewed to characterize survivability constraints, existing egress technologies, and gaps in current assessment frameworks.

Data Sources

All quantitative crash and fatality data analyzed in this study were derived from United States–based national crash and fatality databases.

Traffic crash and fatality datasets National estimates of police-reported crash incidents involving vehicle fire or vehicle submersion (coded as "immersion" in FARS and CRSS) were derived from the Crash Report Sampling System (CRSS) and Fatality Analysis Reporting System (FARS) for 2016–2023, as compiled in NHTSA datasets and related AAA analyses of vehicle fire and immersion events [2, 10], with updated tabulations provided by Brian Tefft of the AAA Foundation for Traffic Safety [39]. FARS captures fatal crashes occurring on public trafficways that result in a death within the system's reporting window, while CRSS provides weighted national estimates across the full range of police-reported crash severities.

Supplemental non-traffic and non-crash sources To characterize undercounting in traffic-crash datasets and to capture vehicle-related entrapment fatalities that fall outside FARS inclusion criteria, supplemental data were compiled from NOAA/NWS flood-fatality reporting, using annual summaries and/or event-level records in public storm and flood-fatality databases [3]. Vehicle-involved drownings were identified when the narrative indicated that occupants were overtaken while inside a vehicle during flooding or flash flooding (e.g., roadway inundation, underpass flooding, washouts). Annual vehicle-related flood fatalities were summarized for 2016–2023 (***Table 5***).

Data Extraction, Variables, and Inclusion Criteria

National incident and fatality tabulations (*Table 2*) Fire- and submersion-related crashes and fatalities were identified using data from the National Highway Traffic Safety Administration's Fatality Analysis Reporting System (FARS) and Crash Report Sampling System (CRSS) [2, 10, 39]. Vehicle-level records were linked with event-level data to identify passenger vehicles (cars, pickup trucks, vans, minivans, and SUVs) that experienced any fire or submersion event at any point in the crash sequence, regardless of whether these events were coded as the most harmful event. Fire and submersion were identified using the sequence-of-events variable in the VEVENT file, and event records were collapsed to the vehicle level. Fatalities were counted using the FARS vehicle-level death count, which reflects the total number of occupants (drivers and passengers) who died in each affected vehicle. National estimates of fire- and submersion-involved crashes were derived from CRSS using survey weights. Rollovers that also involved fire or submersion were excluded from rollover-only counts to avoid double-counting.

State-level fatality ranking (*Table 3*) State rankings were computed using FARS fatality records aggregated over 2016–2023 [2, 39]. The analysis was restricted to passenger-vehicle occupants and stratified by hazard mechanism (fire vs. submersion), consistent with the study scope. States were ranked by total fatalities, and the top states were reported (***Table 3***).

Age-group stratification (*Table 4*) FARS person-level records were used to summarize occupant fatalities in vehicles identified as fire- or submersion-involved by age group for 2016–2023 for fire and submersion categories [2, 39]. Age-group categories were defined to align with the table structure in the Results section (***Table 4***).

Statistical Approach
Analyses were descriptive. For each hazard mechanism, annual counts, multi-year means, ranges, and proportions were calculated. Trend interpretation was based on year-to-year patterns and pre/post period summaries (e.g., pre-2019 versus post-2019), rather than inferential hypothesis testing, given known sampling variance (CRSS), classification limits, and cross-dataset denominator incompatibilities. Results are reported as counts and percentages rounded to practical reporting precision.

Protocol Review and Technology Characterization
Consumer-rating and regulatory protocol review A document review was conducted of public protocols and technical documents describing post-crash and post-submersion assessment elements in major consumer programs (Euro NCAP, ANCAP, and US NCAP/NHTSA SAFE "Post-Crash Care"). Documents were reviewed to extract information on the existence and scoring weight of post-submersion and egress criteria, applicable test conditions (e.g., time windows for operability), treatment of glazing type and power dependence, and whether criteria address single occupant versus multi-occupant egress assumptions.

Technology landscape review and classification Egress technologies and interventions were identified from peer-reviewed literature, safety-organization reports, agency publications, and manufacturer documentation, supplemented by publicly available demonstrations and technical descriptions. Technologies were grouped into three functional categories used in the Results section: (1) manual tools; (2) integrated mechanical breakers; and (3) automated egress systems.

RESULTS
Hazards, Glazing, Data, and Human Factors
FMVSS 226 "Ejection Mitigation" and the laminated-glass paradox Federal Motor Vehicle Safety Standard (FMVSS) No. 226, titled Ejection Mitigation, was issued by the National Highway Traffic Safety Administration (NHTSA) in 2011 to reduce the likelihood of occupant ejection through side windows during rollovers and side-impact crashes [8]. Canada's CMVSS No. 226 reflects similar ejection-mitigation objectives [9]. To meet the dynamic containment requirements of this standard, manufacturers commonly deploy side-curtain airbags and advanced glazing systems, including laminated side windows. By 2018, approximately one-third of new vehicle models sold in the United States featured laminated side windows, according to a study by the American Automobile Association (AAA) [10], and that number has since increased. Although FMVSS 226 is a U.S.-specific regulation, laminated side windows are increasingly used in global vehicle platforms, particularly in premium models—even without equivalent international mandates, due to additional benefits such as noise reduction, acoustic insulation, UV protection, heat insulation, and improved energy efficiency.

Tempered side windows are engineered to fracture into small granules upon impact, enabling relatively easy breach for rescue or self-extrication. Laminated glazing, by contrast, consists of two glass layers bonded by a polymer interlayer that holds the pane together and resists penetration even when cracked. This fundamental difference underlies the laminated-glass paradox: glazing that improves ejection mitigation can simultaneously hinder rapid escape or access [11, 12].

In the same study, AAA evaluated six commercially available window-breaking tools—including both hammer-style and spring-loaded punch mechanisms—tested on modern vehicle glazing. The results were unambiguous: four tools successfully broke tempered glass, but none were able to break laminated glazing, which exhibited only surface cracking and elastic deformation [10]. Because laminated glass remains structurally intact after impact, AAA concluded that such tools are generally ineffective for self-rescue or for assisting extrication by emergency responders when laminated side windows are present [10].

AAA's evaluation demonstrated the practical implications of this paradox: standard escape tools failed to breach laminated side glazing. A preliminary study further identified significant mechanical and operational challenges in breaching laminated vehicle glazing during in-water incidents, characterizing the unintended entrapment risk as the "glass coffin" paradox [11, 12]. However, even tempered glass—though easier to break—does not guarantee escape. In vehicle-submersion events, most occupants are uninjured and power windows may remain functional, the primary issue is whether occupants open the windows in time. This highlights a broader limitation: reliance on manual intervention is inherently unreliable, regardless of window type. To address this survivability gap, vehicles must be equipped to autonomously support occupant escape when critical thresholds are detected.

Vehicle submersion and the 1-minute escape window *Table 2* summarizes police-reported submersion fatalities in the United States from 2016 to 2023, based on FARS and CRSS data [2, 10, 39]. The number of incidents ranges from a low of 5,730 in 2016 to a high of 9,987 in 2019, with an average of 7,416 incidents per year. Fatalities range from a low of 342 in 2023 to a high of 428 in 2017, with an average of 391 fatalities per year. Both incident counts and fatalities appear to hold across the 2016 – 2023 period. These results also indicate that 5.3% of submersion incidents result in fatality, ten times higher than the NHTSA average fatality rate across all crash types, which remain around 0.5% [1].

Table 2.
Number of police-reported crashes and deaths involving vehicle fire, submersion, or rollover, United States, 2016–2023 [2, 10, 39].

Year	Submersion		Fire		Rollover*	
	Crashes	Deaths	Crashes	Deaths	Crashes	Deaths
2016	6,112	404	15,586	1,394	233,553	6,875
2017	7,909	428	12,856	1,445	220,017	6,579
2018	8,655	371	14,356	1,392	209,364	6,073
2019	9,987	402	10,503	1,255	194,843	5,801
2020	6,956	337	13,511	1,612	190,422	6,567
2021	5,730	421	15,272	1,859	210,955	7,004
2022	7,841	420	15,688	1,811	188,551	6,686
2023	6,139	342	17,037	1,784	189,467	6,057
Total	59,329	3,125	114,810	12,552	1,637,172	51,642

Data: Crash Report Sampling System & Fatality Analysis Reporting System (National Highway Traffic Safety Administration). Data from 2016-2022 are considered final; data from 2023 are preliminary and may be subject to revision. * Statistics shown for rollovers exclude crashes involving immersion or fire.

Rollover involvement further underscores the complexity of vehicle-submersion fatalities. FARS and CRSS data indicate that approximately 58% of submersion fatalities (2016-2023) also involve a rollover, demonstrating that these events frequently occur in combination rather than as isolated hazards [2, 10, 39]. This intersection highlights the importance of survivability measures that extend beyond crash protection to include rapid occupant egress.

Ranking the total number of submersion and fire related fatalities in motor-vehicle crashes, Texas, California, and Florida consistently appear among the top three states across all categories (Table 3) [2, 39]. For submersion fatalities specifically, Florida and California rank ahead of Texas.

Table 3.
Passenger vehicle occupant fatalities involving fire or submersion, by state, 2016–2023 (Top 12 states by total fatalities) [2, 39].

State	Submersion		Fire		Total	
	Number	Rank	Number	Rank	Number	Rank
Texas	186	3	1,524	1	1710	1
California	275	2	1,286	2	1561	2
Florida	446	1	791	3	1237	3
Illinois	115	6	591	4	706	4
North Carolina	128	4	436	5	564	5
Georgia	78	13	435	6	513	6
Tennessee	103	8	393	7	496	7
Alabama	111	7	359	8	470	8
Louisiana	125	5	323	13	448	9
Indiana	99	9	343	12	442	10
Ohio	83	10	352	10	435	11
Missouri	70	15	353	9	423	12

The elevated fatality rates associated with vehicle submersion can be attributed to the physical nature of these incidents. Vehicle submersion is one of the most time-critical entrapment scenarios because escape is governed by the rapid onset of hydrodynamic forces [13]. Hydrostatic pressure prevents doors from opening almost immediately after water entry, making window opening the primary viable escape path. When a vehicle enters deep water, it undergoes a brief flotation phase that typically lasts no more than one minute **(*Figure 1*)** [13, 14, 15]. During this phase, doors cannot be opened: even shallow external water depth produces a pressure differential (ΔP) across the door sufficient to prevent outward movement [13, 14, 15]. While side windows remain above the waterline, they can still be lowered. Once rising water reaches approximately one quarter of the height of the side windows, the same pressure gradient begins to act on the windowpane, progressively preventing lowering of the window operation [14, 15].

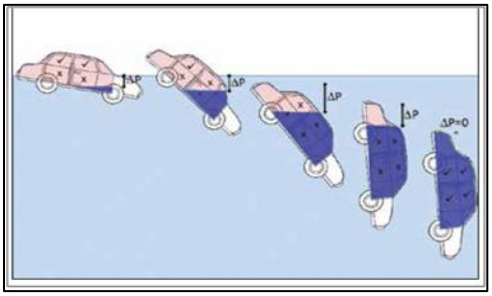

Figure 1. Illustration of pressure gradient (ΔP) as a vehicle sinks. ΔP is equal to difference between the water level outside and inside. ΔP=0 when air has escalated from the air capsule (passenger cabin and trunk). Source: Giesbrecht. The Evidence Base for a New "Vehicle in Water" Emergency Dispatch Protocol. Annals of Emergency Dispatch & Response. 2016;(4):5-9. [13]

After the vehicle transitions into the sinking phase, in which the windows are below the water surface, neither doors nor windows can be opened until the entire air capsule—the passenger compartment and trunk—fills with water and ΔP reaches zero [13]. At that point, escape is close to impossible. The dynamics in ***Figure 1*** apply to conventional vehicles and EVs, with the caveat that differences in weight distribution and water ingress points may influence floatation time and pitch. These physical constraints create a narrow and unforgiving time window for window-based egress during vehicle submersion.

Flood and flash-flood entrapment follow the same physical principles but with different onset patterns. Instead of a sudden plunge into deep water, floodwater may rise from below or sweep laterally across the roadway, initially leaving the cabin dry and giving occupants the false impression that escape is not yet urgent or that remaining inside the vehicle is safer. Hydrodynamic forces, however, act on the vehicle long before full buoyancy is reached: 15 cm (6 inches) of moving water can cause loss of traction, 30 cm (12 inches) can float a passenger car, and 60 cm (24 inches) can float an SUV [16]. Once floating, even a modest water current can move the vehicle off the road into deeper water. In these conditions, vehicles may stall or be swept off the roadway before occupants recognize that the situation is deteriorating, leaving very little time for effective self-rescue.

Across both deep-water submersion and flooding scenarios, survivability depends on acting during the brief period before windows submerge or electrical systems fail. A nationally representative study of more than 1.2 million EMS activations in the United States found that the median response time from a 911 call to EMS arrival was 7 minutes overall, with urban responses averaging approximately 6 minutes and rural responses averaging 14 minutes [17]. In rural regions, 10% of calls waited up to 30 minutes for EMS arrival [17]. Because modern vehicles increasingly rely on laminated glazing and electronically controlled doors, manual escape tools are often unable to breach the glazing. Emergency responders face similar challenges when attempting to break and open laminated windows, requiring specialized tools to access the vehicle. It is also possible for power-dependent egress options to be lost early in the event, although most can last several minutes, by which time water levels can make this a moot point.

These constraints underscore the importance of egress systems capable of creating a timely escape path and providing clear, intuitive guidance during the first minute after water intrusion, when self-rescue remains possible. This time-critical window is reflected in the SWOC protocol (Seatbelts off, Windows open, Out immediately, Children first), developed by Operation ALIVE [13]. The protocol distills recommended self-rescue actions into a simple sequence that prioritizes rapid window-based escape while an opening is still available [13, 14]. Two recent emergency response protocols have been developed for emergency response operators to instruct occupants to follow the SWOC protocol in "vehicle in water" and "vehicle trapped in flood water" scenarios [13, 18]. However, these protocols are not yet universally adopted across jurisdictions.

In-vehicle fires and the rapid loss of survivable conditions

Scope clarification. This section addresses in-vehicle fires (fires originating in the vehicle or post-crash fires that breach the passenger compartment) following a crash or internal ignition. These findings do not apply to wildfire or wildland–urban interface (WUI) fire exposure, where evidence-based guidance consistently recommends remaining inside the vehicle with windows closed to limit radiant heat and smoke intrusion.

Table 2 summarizes fire-involved motor-vehicle crashes and fatalities in the United States from 2016 to 2023, with annual incident counts ranging from approximately 20,000 to 23,000. The dataset shows a relatively stable number of fire-involved fatal crashes, accompanied by a disproportionate increase in associated fatalities over time. Incident counts range from a low of 20,467 in 2020 to a high of 23,530 in 2023, averaging 21,767 incidents per year. Fatalities range from a low of 1,657 in 2019 to a high of 2,280 in 2021, with an average of 1,960 fatalities annually.

These results indicate that approximately 9.0% of vehicle-fire incidents over the eight-year period resulted in at least one fatality— substantially higher than the average fatality rate across all motor-vehicle crashes. This rate is also 73% higher than fatality rates in vehicle submersion, making in-vehicle fires one of the most fatal crash-related incident categories. While the number of incidents remains steady across the study period, the number of fatalities appears to rise—from an average of 1,773 before 2019 to 2,147 after 2019. During the same period, the fatality rate increased from 8.2% (before 2019) to 9.7% (after 2019). This indicates that nearly one out of every ten vehicle fires on U.S. roads between 2020 and 2023 was fatal, suggesting a narrowing survivability window when fire accompanies severe crash events.

Rollover involvement is also common in fire-related fatalities. In the FARS/CRSS data summarized in ***Table 2,*** approximately 23% of fire-related deaths also involved a rollover. This reinforces that in-vehicle fires often occur in conjunction with high-energy crash dynamics rather than as isolated hazards.

Vehicle fires that breach the passenger compartment present limited self-rescue time prior to untenable conditions. Full-scale vehicle fire tests document rapid escalation of interior temperature and toxic gas concentrations following passenger compartment involvement [19, 20]. In crash fire tests of front- and rear-impacted vehicles, flame penetration into the passenger compartment occurred within 0.5–3 minutes for rear-impact underbody gasoline pool fires and 10–24 minutes for front-impact engine-compartment ignition scenarios [21].

Modern vehicle interiors contain substantial quantities of polyurethane foams, plastics, composites, and adhesives that produce carbon monoxide (CO) and other toxic combustion products capable of rapidly degrading survivable conditions [21]. Heat exposure and burns often become life-threatening soon after flames penetrate the passenger compartment, with smoke and toxic gases further contributing to untenable conditions [21]. As a result, flashover-based tenability thresholds substantially overestimate the available time for effective self-rescue. In real-world conditions, once smoke enters the occupant compartment, escape time may be extremely limited [19]. These dynamics underscore the importance of rapid, unobstructed egress during the earliest phase of fire development.

In several tests, the occupant compartment became untenable even before visible flame entry, due to the accumulation of hot gases and toxic combustion products. The time between flame penetration and loss of tenability ranged from approximately −2.5 to +3.2 minutes, indicating that untenable conditions may develop even before visible flame entry into the passenger compartment [21].

Vehicle-design characteristics further complicate egress during interior fires. Electronic door modules, wiring harnesses, and power-window regulators are vulnerable to early thermal degradation, while laminated side glazing—now widely adopted to improve acoustic performance (noise, vibration, and harshness, NVH), occupant containment, and roof-crush performance—may resist tool-based breakage even after heat-induced cracking. These factors can impede both manual and responder-assisted escape once interior fire involvement begins.

Electric-vehicle fires introduce additional hazards, including the potential release of hydrogen fluoride (HF) and other toxic combustion products from lithium-ion battery systems [23]. EV fires may produce elevated hydrogen fluoride (HF) levels and certain metal aerosols, increasing hazard severity, but occupants are generally threatened by rapid interior involvement long before full traction-battery thermal runaway occurs [23].

Unlike submersion events—which often provide a predictable ~1-minute flotation phase during which electrical systems remain operable—vehicle fires offer no reliable window for electrical-system functionality. Thermal damage to wiring, connectors, and control modules may occur abruptly and varies widely by vehicle architecture. Fire-service guidelines (UL FSRI) therefore uniformly instruct occupants to evacuate immediately [24].

These dynamics highlight the importance of assisted vehicle egress during fire events. As with submersion, manual escape tools are often ineffective under low-visibility, high-toxicity, or laminated-glazing conditions. Automated systems that detect interior thermal buildup or smoke, initiate timely window-lowering, and provide clear guidance can preserve a narrow but critical escape interval before conditions become untenable. Importantly, such systems must differentiate between interior-fire conditions—where window-lowering facilitates life-saving egress—and external wildfire smoke or radiant heat, where windows should remain closed to maintain a survivable environment. Given increasing vehicle electrification, cabin-material complexity, and widespread adoption of laminated side glazing, integrated fire-responsive egress support represents a crucial advancement in post-incident survivability.

Human factors and self-rescue behavior Immediate vehicle-enabled rescue through side windows and/or sunroofs is critical [14, 15, 25], as research shows that survival probability is highest during the initial flotation phase and decreases rapidly afterward [14]. ***Figure 2*** charts the probability of survival relative to the time the vehicle is in water, illustrating how occupant stress increases exponentially as time progresses [15].

Unfortunately, research consistently shows that occupants often waste precious seconds on improper actions due to misunderstanding the danger, uncertainty about how to exit, or panic. Common incorrect actions include using cell phones to call for help, attempting to open doors, waiting for the passenger compartment to fill with water to equalize pressure, trying to kick out the windshield, or doing nothing at all [14, 15]. Many occupants are unfamiliar with best practices or forget them under extreme stress. Some keep windows closed to limit water ingress, mistakenly believing that rescue will arrive in time.

These misconceptions and incorrect actions—combined with panic and shock—pose a grave risk to survivability. As a result, many occupants realize too late that they need to escape. This often occurs after water rises to the door level, preventing door opening, or after water level rises above the window level, at which point research shows it is too late [13, 14, 15]. Therefore, an in-vehicle safety technology that removes guesswork by providing exit instructions, notifying emergency responders, and automating window opening can address these behavioral challenges and improve self-rescue outcomes.

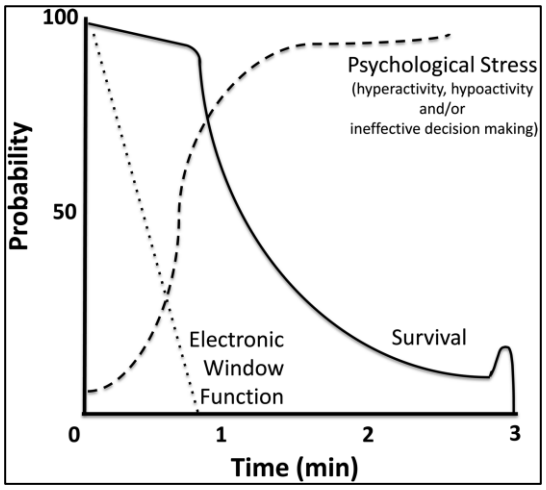

Figure 2. Schematic estimation of relative probability of psychological stress, electric window function, and survival over time in a sinking passenger vehicle. Source: McDonald and Giesbrecht. Vehicle Submersion: A Review of the Problem, Associated Risks, and Survival Information. Aviat Space Environ Med. 2013; 84: 498–510. [15]

Our research also examined the age distribution of submersion and fire fatalities between 2016 and 2023 (***Table 4***) [2, 39]. Fatalities were observed across all age groups, with the largest number occurring among occupants aged 16–24. Submersion and fire deaths claimed 681 lives among children and adolescents under the age of 15, and 1,568 lives among senior citizens (> 65). These findings indicate that vehicle-fire and submersion fatalities are not confined to any single demographic group. This reinforces the need for automated, vehicle-initiated egress assistance that supports escape for all occupants, regardless of age.

Table 4.
Passenger vehicle occupant fatalities involving fire or submersion, by age of victim, United States, 2016-2023 [2, 39].

Age (years)	Submersion Deaths	Fire Deaths
≤7	93	244
8-15	73	271
16-24	731	3,388
25-34	624	3,084
35-44	402	1,910
45-54	377	1,397
55-64	343	1,083
65-74	264	635
75+	211	458
Unknown	7	82
Total	3,125	12,552

Data: Fatality Analysis Reporting System (National Highway Traffic Safety Administration). Data from 2016-2022 are considered final; data from 2023 are preliminary and may be subject to revision. Analysis by AAA Foundation for Traffic Safety.

Beyond cognitive and behavioral factors, physical and physiological limitations may further constrain self-rescue during vehicle-submersion or fire events. Certain occupant populations—including children, older adults, individuals with disabilities, frailty, reduced mobility, pregnancy, or higher body mass—may face additional challenges in rapidly exiting through side windows under time-critical conditions. Although empirical data quantifying these effects is limited, reliance on a single egress pathway may not be sufficient for all occupants. This highlights the need to consider alternative escape options—such as rear-window egress—as well as vehicle designs that facilitate rapid access for first responders, particularly for vulnerable occupants.

Data Limitations

In this study, crashes were classified as fire- or submersion-involved whenever those events occurred at any point in the recorded crash sequence, regardless of the most harmful event (Methods). However, the results presented here remain constrained by the scope of national crash-surveillance systems and by the extent to which post-crash conditions are documented. Accordingly, the counts reported in this paper should be interpreted as minimum estimates, and the true burden of vehicle fire- and submersion-related entrapment is likely higher.

Despite the availability of fire and submersion data elements in FARS and CRSS, entrapment hazards associated with these events are not systematically synthesized, analyzed, or highlighted in publicly available annual crash reports. As a result, the frequency, circumstances, and survivability outcomes associated with vehicle fire and submersion remain difficult to assess at a national level, limiting awareness of these hazards and constraining evidence-based vehicle-safety design and policy decisions.

Both FARS and CRSS are limited to police-reported traffic crashes involving vehicles in transport on public roadways [7]. FARS includes only crashes in which at least one person dies within 30 days as a result of crash-related injury, while CRSS captures a sampled subset of crashes involving property damage, injury, or death [7]. Consequently, many vehicle-fire and submersion events that occur outside police-reported traffic crashes fall outside these systems by definition. They do not include incidents occurring on private property (e.g., parking lots, driveways, garages), events involving vehicles not in transport (such as parked vehicles or vehicles disabled or stopped outside active travel lanes), fatalities occurring more than 30 days after the initiating event, and cases classified as non-injury-related deaths (e.g., natural causes). For example, a vehicle that spontaneously catches fire while parked at a retail location, or an occupant who drowns in a vehicle submerged in a pond or pool on private property, would not be captured in FARS and would be inconsistently represented, if at all, in CRSS. In addition, reporting practices for fire and submersion involvement may vary across jurisdictions and responding agencies, and the level of detail recorded for post-impact fire or water

entry may differ depending on protocols and scene conditions, introducing potential for under-documentation in some cases.

Vehicle-related drownings during floods and other cataclysmic events are similarly excluded from FARS and CRSS, as they are generally classified as weather-related fatalities rather than traffic crashes. Independent national datasets provide further evidence that a substantial number of vehicle-related drownings and fire deaths are not captured in traffic-crash statistics. One such example is the National Weather Service (NWS) and National Oceanic and Atmospheric Administration (NOAA) flood-fatality reports, which include occupants who drown in vehicles during flash floods, underpass flooding, roadway washouts, and other events that fall outside traffic-crash surveillance (***Table 5***) [3]. In 2021, NWS/NOAA reported 146 flood fatalities, including 79 occupants who drowned in vehicles. These fatalities typically fall outside FARS inclusion criteria. Similar discrepancies appear in 2020, 2019, and 2017, when vehicle-related drownings constituted a substantial portion of national flood fatalities. It is important to note that NOAA/NWS fatality statistics are derived from post-event hazard assessments conducted by local forecast offices and may incorporate information from emergency-management summaries, law-enforcement reports, and media accounts. While these datasets capture many vehicle-related drowning events missed by traffic-crash systems, they rely on a different surveillance framework and are not based on standardized crash-investigation protocols [3].

Comparable gaps exist for vehicle-fire events. The National Fire Protection Association (NFPA) provides analogous evidence for fire incidents, documenting driveway and parked-vehicle fires—many involving rapid electrical failure of locks or windows—that are not captured in crash databases [26]. Internationally, specialized resources such as the United Kingdom's Body Recovery from Water (BRW) database illustrate alternative approaches to identifying vehicle-related drowning events outside traditional traffic-crash reporting systems and could inform future studies [27]. These data-system boundaries have practical implications for safety-technology development and policy. Because many vehicle-related fire and submersion deaths fall outside FARS, they also fall outside the datasets that inform U.S. regulatory analyses and consumer-safety programs—systems that guide or incentivize manufacturers to adopt appropriate technical solutions.

Table 5.
Flood-related fatalities by activity in the United States, 2016–2023. Adapted from NOAA/NWS data [3].

Year	Driving	Walking / Hiking	At Home	Boating	Fell in	Working	Other / Unknown	Total
2023	42	6	10	5	5	2	9	79
2022	39	6	43	0	4	0	13	105
2021	79	8	40	2	2	1	14	146
2020	37	4	8	1	4	1	4	59
2019	61	5	5	8	2	2	10	93
2018	57	6	7		5		9	84
2017	65	7	15	1	2	6	40	136
2016	78	5	24	1	2	0	17	127

Taken together, these limitations highlight the need for more comprehensive surveillance systems capable of distinguishing between traffic, non-traffic, and weather-related entrapment events; linking crash sequences with medical outcomes; capturing off-road and private-property incidents; and documenting fatalities beyond the 30-day window. Expanding the scope and resolution of national datasets would improve risk estimates, support development and evaluation of new egress technologies, and enable more accurate alignment between consumer-safety programs and real-world hazards. More complete data would also facilitate international comparisons and strengthen the evidence base for policy decisions aimed at reducing fire- and submersion-related entrapment fatalities.

Regulatory and Consumer Rating Landscape

How vehicle submersion has evolved in the Euro NCAP protocol Euro NCAP addresses post-crash survivability through its Rescue, Extrication & Safety Post-Crash protocols, which evaluate rescue information, post-impact access and extrication-relevant functions, and post-crash technologies intended to support timely rescue and occupant egress. In practice, these post-crash assessments have served as a proving ground for rescue- and survivability-related features, with mature elements later incorporated into broader occupant-protection scoring. Vehicle-submersion protection appears to be following a similar trajectory within the post-crash assessment framework, although it has not yet transitioned into a dedicated crash-injury test domain.

Vehicle submersion was first explicitly addressed in the 2023 Rescue, Extrication & Safety Test and Assessment Protocol, which introduced a preliminary requirement acknowledging the unique hazards of vehicle water entry and egress risk [28]. The protocol states that "in the event of a vehicle entering water during or after an impact, certain vehicle systems can aid the occupants in exiting the vehicle" [28]. This language marked an important conceptual shift by recognizing that survivability in submersion events is influenced not only by external rescue operations but also by the availability and performance of in-vehicle systems during the initial self-rescue window. It required manufacturers to demonstrate that doors could be opened from inside within two minutes following electrical disconnection, and that a single front-row side window (right or left) remained operable for two minutes after water entry—or that an alternative means for window opening or breaking was provided [28]. This requirement acknowledged the egress hazard but represented only a minimal functionality assessment, limited to one window and not addressing full-vehicle or multi-occupant escape performance.

The 2026 Post-Crash Protocol expands the scope and importance of submersion performance [4]. Submersion and egress are now evaluated within the 100-point post-crash scoring framework, which contributes to the overall Occupant Protection assessment [4]. It centers submersion escape on window-based egress, prioritizing electric-window functionality and, where necessary, controlled window breakage, and removes door-opening performance from the submersion evaluation. This shift reflects a move away from door-based assumptions and toward escape pathways that remain viable in real-world submersion scenarios.

OEMs must demonstrate that electric side windows remain operable for at least two minutes following water entry [4]. Notably, the 2026 protocol explicitly recognizes vehicles equipped with automatic window-lowering systems, requiring OEMs to demonstrate that windows are automatically lowered within two minutes of water entry [4]. By formally accepting automatic window actuation as a compliant pathway, Euro NCAP signals a shift toward vehicle-initiated escape functions, reflecting the growing role of automation in post-crash survivability and reducing reliance on occupant recognition, manual action, or external tools during time-critical submersion events. Where electric-window functionality cannot be demonstrated, the protocol permits window breakage as a secondary compliance pathway, reinforcing manual intervention as a fallback rather than a primary escape strategy.

In such cases, the OEM must provide an in-cabin method by which occupants can open or break the front-row side windows and tailgate to exit the vehicle (roof glass and windscreens are excluded) [4]. Vehicles equipped with laminated side or tailgate glass are explicitly excluded from receiving credit for manual window breakage [4], reinforcing the limitations of breakage-based escape solutions.

Euro NCAP effectively recognizes that rapid escape from water intrusion is a fundamental survivability requirement. The evolution of its protocols demonstrates that emergency egress is becoming a mainstream component of occupant protection and that survivability is emerging as a new area for consumer-safety innovation.

ANCAP ANCAP aligns its assessment with Euro NCAP, including the same single-window evaluation and scoring. This harmonization advances global consistency but also highlights a shared limitation across programs [5].

U.S. NCAP and NTHSA SAFE Post-Crash Care In contrast to Euro NCAP's evolving post-crash assessment, current U.S. consumer ratings do not yet include explicit metrics for emergency egress. The U.S. New Car Assessment Program (US NCAP) continues to center its star ratings on occupant-injury criteria in controlled crash tests and on a growing set of active-safety features, such as automatic emergency braking and lane-keeping assistance. At present, its ratings do not evaluate whether occupants can rapidly exit a vehicle in fire or submersion scenarios, nor do they assess the operability of windows, locks, or doors after partial power loss.

NHTSA's broader SAFE System approach, launched in 2022, identifies "Post-Crash Care" as one of four strategic pillars, emphasizing improved emergency-medical response, data systems, and care coordination [29]. However, the Post-Crash Care pillar does not yet define vehicle-level performance requirements analogous to Euro NCAP's post-submersion egress checks. As a result, U.S. consumer ratings acknowledge the importance of what happens after a crash in principle, but they do not currently provide manufacturers with concrete egress-performance targets or consumers with star-rating information about a vehicle's ability to facilitate escape in fire or submersion incidents.

Global programs Global programs differ in how they account for glazing type and power dependence. Laminated side windows are increasingly common, particularly in premium vehicles, but most assessment protocols do not explicitly distinguish between tempered and laminated glass when awarding credit for manual tools or emergency devices. Similarly, egress solutions that rely on high-voltage or low-voltage power, that are linked only to airbag deployment, or that depend on complex software logic are not evaluated for robustness under partial power loss or non-crash immersion and fire scenarios.

Consumer-facing information about egress capabilities also remains limited. Star ratings and safety brochures rarely describe whether windows remain operable in water, whether doors unlock automatically after power loss, or whether integrated escape mechanisms exist for rear rows or tailgates. Without clear, comparable metrics, consumers cannot differentiate vehicles that provide robust egress support from those that do not, and manufacturers have limited incentives to invest in innovative solutions. These gaps underscore the need for more comprehensive, harmonized, and performance-based egress criteria across NCAPs and regulatory frameworks.

Remaining gaps in Euro NCAP and ANCAP programs Although Euro NCAP and ANCAP have taken early steps to incorporate submersion and post-crash egress into their consumer ratings, important gaps remain. First, fire-related egress is not yet directly addressed in any major New Car Assessment Program. Existing protocols focus on post-crash rescue and electrical safety but do not assess how quickly occupants can exit once interior conditions become untenable due to fire or smoke. As a result, there is no harmonized performance benchmark for systems that assist escape during vehicle fires, despite the high lethality and rising fatality rates associated with these incidents.

Second, current submersion assessments are narrow in scope: they primarily evaluate the operability of a single front window or the availability of an alternative escape device, rather than verifying that occupants in all seating positions have a viable escape pathway under realistic conditions. Rear-seat occupants, children in restraints, and mobility-limited passengers may therefore remain unprotected even when a vehicle nominally meets the protocol.

Existing Egress Technologies: Manual, Mechanical and Automated

A range of technological approaches have emerged to support occupant egress, including manual tools, integrated mechanical solutions, and automated systems. This section compares these approaches based on activation logic, operating principles, compatibility with different glazing types, and applicability in fire and submersion scenarios. Many integrated and automated solutions have evolved in response to Euro NCAP's increasing emphasis on post-crash egress for vehicle submersion.

Manual window-breaking tools Manual glass-breaking tools, such as hammers and spring-loaded punches, remain the most common aftermarket egress aids. As summarized in ***Table 6***, the 2019 AAA vehicle-escape tool evaluation demonstrated that while several tools successfully fractured tempered side glass, none were able to breach laminated glazing [10]. These tools therefore retain potential utility in vehicles where side windows are tempered, but their effectiveness is constrained in vehicles that use laminated side glass for ejection-mitigation or noise-reduction. Manual tools also present practical challenges. Occupants must be able to quickly locate the tool, position it correctly against the glass, and apply sufficient force. All that while experiencing stress, disorientation and possible injury. Tool placement, training, and maintenance influence real-world performance. As a result, manual devices may function as supplementary options rather than primary egress strategies in modern vehicles with mixed glazing types and may require multiple attempts to create the breach.

Table 6.
Results of AAA's evaluation of the top six leading manual tools used for vehicle escape, 2019. Source: Adapted from AAA report [10].

			Tempered glass		Laminated glass	
Tool Type	**Tool No.**	**Test No.**	**No. Strikes to break**	**Pass/Fail**	**Strikes to break**	**Pass/Fail**
Hammer Type Tool	#1	1	1	PASS	Did not break	FAIL
		2	1	PASS	Did not break	FAIL
		3	1	PASS	Did not break	FAIL
	#2	1	Did not break	FAIL	Did not break	FAIL
		2	Did not break	FAIL	Did not break	FAIL
		3	Did not break	FAIL	Did not break	FAIL
	#3	1	Did not break	FAIL	Did not break	FAIL
		2	Did not break	FAIL	Did not break	FAIL
		3	Did not break	FAIL	Did not break	FAIL
Spring-Loaded Tool	#4	1	3	PASS	Did not break	FAIL
		2	1	PASS	Did not break	FAIL
		3	1	PASS	Did not break	FAIL
	#5	1	3	PASS	Did not break	FAIL
		2	1	PASS	Did not break	FAIL
		3	1	PASS	Did not break	FAIL
	#6	1	1	PASS	Did not break	FAIL
		2	None	FAIL	Did not break	FAIL
		3	5	PASS	Did not break	FAIL

Integrated mechanical breakers Some manufacturers have integrated mechanical escape devices into specific vehicle models. The Zeekr 7X, for example, includes a spring-loaded breaker integrated into the driver's-door armrest [30]. When the lever is pulled, the mechanism delivers an impact sufficient to fracture the tempered side glass used in that model, creating an egress pathway even if power-operated windows are inoperable. Because this system operates through a mechanical (spring-loaded) design rather than an electric motor, its activation does not depend on vehicle electrical power. However, its usefulness depends on occupant reaction and decision-making, physical reach, awareness of its location, and the physical ability to actuate the device under stress. Placement on a single door may limits accessibility for passengers in other seating positions. These implementations illustrate one approach to providing an integrated, power-independent egress aid for scenarios in which tempered side glass is used.

An additional limitation is the absence of standardized placement, labeling, or actuation logic for integrated mechanical breakers ***(Table 7)*** [31]. Trigger locations may vary across manufacturers and even across model years, increasing cognitive load during time-critical emergencies. From a human-factors perspective, emergency egress should not depend on memory or prior vehicle familiarity, underscoring a structural limitation of current implementations.

Table 7.
Variability in emergency mechanical-release design across selected Tesla vehicle models. Source: Adapted from Glassey, S. (2025), Swiftwater Rescue Technician Vehicle: Rescue Methods.

	S	**3**	**X**	**Y**	**R**	**Cybertruck**
Emergency Door Release (Front)	Under carpet, cable pull	Accessible lever	Hidden behind speaker grill	Accessible lever	Above Window Switch	Cable under map pocket mat
Emergency Door Release	Under carpet, cable pull	Hidden behind trim or under cover in door	Hidden behind speaker grill	Hidden under cover or behind trim	N/A	X

Collision-linked egress Some manufacturers have implemented egress-supporting behaviors that activate when crash sensors detect an airbag-deploying event. NIO documentation for certain models (e.g. ET7) specifies that, following airbag deployment, the vehicle automatically undertakes several safety measures—including cutting high-voltage power, unlocking all doors, turning on hazard lights, and lowering the windows—to assist passenger exit and facilitate rescue [32]. The manual notes that window opening is intended in part to help prevent entrapment if the vehicle comes to rest in water. Because this strategy is tied to airbag deployment, it may support egress in collision-related events that also involve water intrusion or obstructed doors. However, most submersion scenarios—such as vehicles swept into water during flooding or entering water at low speed—do not produce sufficient deceleration to trigger airbag deployment. In such cases, this type of collision-linked activation would not be expected to occur. Even so, the approach illustrates how existing crash-sensing architecture can be extended to provide targeted forms of egress assistance under specific trigger conditions.

Automated egress systems Automated egress systems are designed to detect hazardous environmental conditions and create an egress opening without requiring occupant action. Their primary goal is to act within the short time opportunity before hydrostatic pressure, thermal damage, or electrical failure render conventional exits unusable. One such example is the Automatic Window Opening System (AWOS), a sensor-driven system designed to autonomously open side windows upon detecting water or fire conditions. Based on available demonstration data, AWOS uses a combination of water-level sensing, dynamic vehicle orientation and thermal cues to infer when an egress path should be initiated. Immersion is detected within 3–5 seconds, and the system commands the window regulators to lower the glass within the flotation phase of submersion (when hydrostatic pressure is still low enough for powered-window operation [25]). Because it relies on the vehicle's own window mechanisms, it is compatible with both laminated and tempered glazing and retain manual actuation by the occupant.

The system includes orientation sensors to delay the activation if the vehicle has an incorrect attitude, helping to prevent premature cabin flooding when inverted, for example [25]. In addition to submersion, the system is designed to respond to other emergency entrapment conditions—such as fire—using integrated sensor inputs and safety logic to determine when escape facilitation is appropriate. It can also interface with telematics systems to dispatch location-linked emergency alerts with GPS coordinates and may add audible guidance to assist occupants in high-stress situations or in-dash support for the SWOC protocol reminders. AWOS advancing in its development for both OEM and aftermarket with systematic validation to evaluate its performance under diverse real-world conditions and refine its operation to meet upcoming safety protocols.

Comparative summary Existing approaches can be grouped into three broad categories—manual tools, mechanically actuated systems, and automated egress systems—as summarized in ***Table 8.*** Manual tools are power-independent but ineffective on laminated glazing and highly dependent on occupant behavior. Integrated mechanical breakers can provide a power-independent option for vehicles with tempered glazing but still rely on occupant reach and physical capability. Automated systems have the potential to respond quickly and consistently across a wider range of scenarios—especially when they can operate on both laminated and tempered glazing and are not solely tied to collision triggers—but they require careful design to manage false activations, power-loss conditions, and diverse use cases.

Table 8.
Comparison of Emergency Egress Technologies

Egress Approach	Typical Examples	Activation Logic	Power Dependence	Glazing Compatibility	Egress Path	Key Limitations
Consumer grade manual tools	Hammer-style tools, spring-loaded center punches	Occupant-initiated	None	Variable effectiveness on tempered glass; ineffective on laminated glazing	Single window	Require occupant action and correct use under stress; limited to single-window breach;
Integrated mechanical breakers	Built-in spring-loaded breakers (e.g., Zeekr 7X)	Occupant-initiated (mechanical actuation)	None	Variable effectiveness on tempered glass; ineffective on laminated glazing	Single window	Limited accessibility (e.g., driver-door only in Zeekr 7X); Require occupant action and correct use under stress lack of standardized placement and labeling
Collision-linked electronic egress	Automatic door unlocking and window lowering after airbag deployment (e.g., NIO ET7)	Triggered by crash/airbag sensors	Yes	Compatible with tempered and laminated glazing	Vehicle-level multiple windows	Not activated in many non-crash submersion events; dependent on crash detection thresholds; window-lowering behavior tied to airbag deployment logic
Automated egress systems	Sensor-based automatic window-lowering systems (e.g., AWOS)	Environment-based detection (water, fire, orientation, thermal cues)	Yes	Compatible with tempered and laminated glazing	Vehicle-level multiple windows	Requires robust sensing and logic to avoid false activation; performance depends on power availability and system validation

A technology-neutral approach to egress evaluation needs to emphasize performance characteristics rather than prescribing specific technologies. Relevant considerations include:

1. The ability to create or maintain an opening large enough for occupant egress
2. Compatibility with the glazing types present in the vehicle
3. Robustness under partial power loss (high voltage disconnect on EVs) or sensor failure
4. Clarity and accessibility across seating positions and intuitive or automated operation

The examples summarized above illustrate how different approaches can address these performance dimensions. Future consumer-rating programs could build on such metrics to recognize vehicles that provide a reliable and intuitive path for emergency egress while allowing manufacturers flexibility to refine how those outcomes are achieved.

DISCUSSION

Importance of Rapid Self-Rescue

Both vehicle fires and submersion incidents leave occupants with a narrow window for self-rescue. In submersion, survivability depends on acting during the brief early interval before hydrostatic pressure prevents practical egress (as discussed in Vehicle Submersion and the One-Minute Escape Window), making egress performance fundamentally time-critical and poorly suited to strategies that rely on delayed response or improvised actions. Similarly, in-vehicle fires eliminate survivable conditions extremely rapidly, with fatality proportions far exceeding the national crash average (as discussed in In-Vehicle Fires and the Rapid Loss of Survivable Conditions). Together, these realities make clear that occupants must act immediately and that egress systems should operate autonomously without relying on occupant intervention.

Why Manual Tools Are Insufficient

Manual escape tools, such as hammer-style devices and spring-loaded punches, are widely promoted as low-cost solutions. However, their effectiveness is constrained by both material and behavioral factors. As shown in AAA's

testing (***Table 6***) none of six commercial tools could breach laminated glazing, which is increasingly common in modern vehicles. Even when tempered glass is present, occupants must locate and properly use these tools under significant stress. As discussed in Human Factors and Self-Rescue Behavior, human-factors research shows that panic, disorientation, and ineffective actions consume most of the critical window of opportunity for escape. For these reasons, manual tools should be considered supplementary rather than primary escape strategies, particularly in vehicles equipped with laminated side windows.

Technology Egress Performance Requirements

Laminated side glass saves lives by preventing ejection in rollovers, but it severely limits post-incident survivability. As discussed in In-Vehicle Fires and the Rapid Loss of Survivable Conditions, vehicle fires may disable electronics within tens of seconds, meaning that egress systems cannot rely on stable power. As discussed in Vehicle Submersion and the One-Minute Escape Window, submersion produces rapid hydrostatic pressure that prevents window lowering within about one minute. Euro NCAP and ANCAP already recognize the limitations of manual tools: vehicles with laminated side windows receive no credit if they rely solely on a hammer or center punch. This scoring structure sends a clear message to manufacturers: passive escape aids are insufficient; vehicles must actively help their occupants by ensuring an opening is created automatically when needed.

A technology-neutral rating system should evaluate whether a vehicle provides an accessible opening or maintains window operability under adverse conditions, regardless of mechanism. Mechanical breakers and automated systems can satisfy these requirements if they function independently of crash triggers and vehicle power.

Recommendations

Euro NCAP's forthcoming post-crash and post-submersion assessments represent important progress, but the current focus on a single front-side window does not reflect real-world conditions. Occupants in rear rows, passengers with limited mobility, and children in restraints may not be able to reach the tested window.

To more accurately represent real-world escape needs, NCAP programs and consumer-rating programs worldwide should consider:

1. Multi-window / multi-row egress validation to ensure all seating positions have a viable escape route.
2. Explicit consideration of glazing type, given the well-documented inability of manual tools to breach laminated side windows.
3. Assessment of automated or power-independent egress mechanisms capable of creating an opening even after electrical failure.
4. Standardized trigger location and placarding wherever an in-built mechanism is included.
5. Inclusion of the above requirements in owner manuals and emergency-response guides.

Egress evaluations should also consider occupants who cannot reasonably escape through side windows even when fully opened. Bariatric occupants, pregnant occupants, and others with limited mobility may be unable to use narrow window openings and may instead rely on the larger rear hatch (if present) as their only viable exit. Current protocols do not assess whether the rear hatch can be opened after loss of power, whether it can be opened from inside near the hatch itself, or whether a simple mechanical interior release is available. Including rear-egress criteria—such as low-force mechanical pulls or other power-independent mechanisms—would ensure that survivability assessments reflect the needs of the most vulnerable occupants.

Comparison to Other Mandated Safety Technologies & Regulatory Precedents

Automatic Emergency Braking (AEB) and rear-visibility systems illustrate how regulatory action can drive rapid uptake of life-saving technologies. In April 2024, NHTSA finalized a Federal Motor Vehicle Safety Standard requiring AEB on nearly all new passenger vehicles and light trucks sold in the United States by 1 September 2029. According to NHTSA's announcement, the rule is expected to save at least 360 lives annually and prevent 24,000 injuries [33].

The European Union adopted its General Safety Regulation in 2019, making advanced emergency braking mandatory for new vehicle types from July 2022 and phasing it in for all vehicles through January 2029 [34]. These active-safety technologies address crashes that would otherwise occur; however, they do not aid occupants once a vehicle is already on fire or in water. The estimated 2,200 post-incident fatalities each year in the U.S. remain unaddressed by AEB or other crash-avoidance systems. Rear-visibility technology provides another example of targeted regulation. In 2014,

NHTSA issued a rule requiring all vehicles under 10,000 lb. to be equipped with a rearview camera by May 2018 [35]. NHTSA noted that back over crashes cause around 210 fatalities and 15,000 injuries annually [35, 36].

While important, the lives saved by rear-visibility systems are modest compared with the hundreds of drowning and fire deaths documented annually. These precedent supports integrating egress-performance metrics into consumer-safety programs. These technologies were widely adopted following Congressional action or voluntary industry commitments, and later codified through federal regulation—demonstrating that targeted policy intervention can rapidly accelerate deployment of life-saving safety features [33, 35, 36, 37]. Just as AEB and backup cameras were phased in to address specific crash modes, smart-exit assistance should be required to mitigate post-incident hazards.

Public Education & Human Behavior

Public-education campaigns can increase general awareness of flood and fire hazards, but available evidence suggests they have had limited impact on reducing vehicle-related entrapment fatalities. For example, an LSU master's thesis evaluating the National Weather Service's widely promoted "Turn Around, Don't Drown" campaign found no convincing evidence that the slogan reduced vehicle-related drowning deaths; regression models showed no significant change in incident rates since the campaign's introduction [38]. These findings indicate that even well-designed risk-communication efforts may not meaningfully influence outcomes in time-critical emergencies.

As discussed in Human Factors and Self-Rescue Behavior, occupants experiencing sudden submersion or fire often face acute stress, sensory overload, and rapidly changing environmental conditions. Under these circumstances, human decision-making becomes highly variable and may diverge from recommended practices, even when individuals are aware of them. This is a well-documented human-factors challenge rather than a behavioral fault.

Because emergency egress depends on rapid, correct action within a very narrow time window, post-incident survivability cannot rely solely on occupant behavior or public education. Vehicle-based systems that automatically create or preserve an escape opening—or provide immediate, intuitive guidance—offer a more consistent and reliable means of supporting self-rescue during the first critical seconds of an emergency. Integrating such performance into consumer-safety ratings would help ensure that survivability does not depend on perfect human performance during inherently chaotic events.

LIMITATIONS

While this work advances understanding of post-crash vehicle egress, several limitations should be noted. One important limitation concerns the diversity of occupant body types and mobility needs. Individuals who are bariatric, pregnant, or otherwise mobility-limited may not be able to exit through side windows even when fully opened. This paper focuses primarily on side-window egress pathways and does not evaluate larger-aperture alternatives such as rear-hatch escape performance. Future vehicle designs should therefore include alternative egress mechanisms—such as an interior pull-ring that jettisons the rear window or unlocks the back hatch in vehicles equipped with one—to provide a larger opening for occupants who cannot reasonably self-rescue through a side window. Future work should include full-scale testing across a broader range of occupant anthropometry and mobility profiles to ensure that egress solutions address the needs of all users. This paper synthesizes existing studies and manufacturer demonstrations; consequently, some data points are approximate and derived from secondary sources. Published tests and demonstrations may not fully reflect real-world conditions, including occupant panic, inverted vehicles, debris, or partial electrical failure. The AWOS system is still under development, and its performance may differ in production vehicles. We did not conduct new bench tests; our evaluation framework relies on reported results. Future research should include full-scale vehicle tests across multiple propulsion types (internal-combustion, hybrid, and electric), human-factors studies, and cost–benefit analyses of automated egress technologies.

CONCLUSIONS

Vehicle entrapment during fires and submersion is a persistent safety issue that is not adequately addressed by current crash-avoidance and crashworthiness measures. Police-reported data from the United States indicate that in-vehicle fires remain common with rising fatality proportions, and that submersion incidents, although less frequent, have disproportionately high fatality rates. In both cases, occupants typically have less than one minute to escape before hydrodynamic forces, thermal effects, or loss of electrical power prevent normal window and door operation. Comparable incident patterns reported in other countries suggest that rapid, vehicle-enabled egress is a global problem, not a jurisdiction-specific anomaly.

The analyses presented in this paper show that modern design features—such as laminated side glazing, electronically controlled door locks, and distributed electrical architectures—can improve crash protection yet simultaneously restrict post-incident escape options. Manual escape tools exhibit limited and inconsistent performance, particularly on laminated glass, and time-critical conditions leave little opportunity for effective use under stress. Public-education efforts remain important but cannot overcome the physical constraints and human-factors limitations inherent in these events.

Taken together, these findings support the need for integrated vehicle-based systems capable of preserving or creating an egress opening early in the incident sequence and supporting rapid self-rescue. Consumer-safety programs are beginning to address this gap. Euro NCAP's forthcoming post-crash protocol establishes an initial benchmark by awarding credit for submersion and egress performance. Extending similar, technology-neutral, performance-based criteria across global rating programs would provide manufacturers with clear design targets and a structured mechanism to demonstrate robust egress capability across seating positions, glazing types, and power-loss conditions. Such criteria would complement existing crash and active-safety metrics and have the potential to materially improve post-incident survivability in both fire and submersion scenarios.

DISCLAIMER

The opinions expressed in this paper are those of the authors and do not necessarily reflect the views of AWOS Technologies, the University of Manitoba, Motsai Research, the Public Safety Institute of New Zealand, the Automotive Safety Council, North Carolina State University, or any regulatory agency. Some authors have professional affiliations with AWOS Technologies. The analyses and recommendations presented here were developed independently. Other authors participated in an academic capacity and reported no relevant commercial relationships. This work synthesizes publicly available data and does not report new human-subject research.

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