Vehicle Submersion: A Review of the Problem, Associated Risks, and Survival Information

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McDonald GK, Giesbrecht GG. ***Vehicle submersion: a review of the problem, associated risks, and survival information.*** **Aviat Space Environ Med 2013; 84:498–510.**

Background: Of all drownings, 3 to 11% occur in submersed vehicles, yet scientific study of this topic seems limited. ***Methods:*** A search was made of digital medical, drowning, transportation, and rescue databases regarding vehicle submersion drownings. ***Results:*** The major risk factors include driving on ice or roadways near water, flooding of roadways or bridges, slippery roads, curved roads, and darkness. A new definition of a Flotation Phase (from water impact until water rises to the bottom of side windows) defines a period when escape is easiest. Since survival probability is highest during this period (generally the first minute)—and then decreases rapidly—cell phones should not be used to call for help because this will only squander the optimal window for survival. It is virtually impossible to open a door until the vehicle is almost completely full of water. Since there is little or no trapped air, this period provides a very low chance of survival. Before exit, children should be released from their restraints. Breaking windows is difficult without a center punch or rescue hammer, which should be visibly mounted within reach of the driver. ***Conclusions:*** Prevention includes installing adequate guardrails, barriers, warning signs, and road markings, or placing roadways at a greater distance from water. Areas at high risk for flooding should have signs and public warning systems for flash flooding should be improved. Public education should also focus on the dangers of driving on flooded roads or bridges, and on ice roads.

Keywords: aquatic accident, cold water immersion, drowning, egress, escape, exit, fatality, highway safety, motor vehicle, underwater, vehicle accidents, water related fatality.

MOTOR VEHICLE submersions have the highest fatality rate of any type of single motor-vehicle incident (44), resulting in approximately 400 fatalities in North America each year (2,33,52). Many victims die from drowning rather than from trauma (2,7). Because the absolute numbers are small, less attention is given to this type of incident, except when sensationalized in the popular media. In several industrialized nations vehicle submersions account for 3–11% of all drownings and up to 4.7% of all motor-vehicle fatalities (**Table I**). Presumably, many of these drownings could be prevented if vehicle occupants had proper knowledge and took quick, correct action.

Previous research on vehicle submersion has focused on vehicle-sinking characteristics both in North America (9,20,39) and in Europe (44). A few generally epidemiological research studies have addressed human escape during vehicle submersion (1,52). Systematic studies on occupant exit strategies (excluding aircraft simulations) have been limited (38,44) until recently (12,14,15). A better understanding of this problem could help develop preventative measures and advice to increase survival. An initial review of educational and public service information, plus a university student survey (14) identified three possible contributors to the high fatality rate during vehicle submersion: 1) ‘authorities’ provide an inadequate description of vehicle-sinking characteristics; 2) contradictory and incorrect advice is often provided; and 3) there is poor public perception of how to escape successfully.

First, authorities describe vehicle-sinking characteristics using one variable, “Flotation Time” (9). However, the conditions, and chance of survival, change considerably during this inclusive period and should be described more effectively to reflect different phases (14). Second, the public is commonly advised to: let the passenger compartment fill with water to open the doors; wait until the vehicle hits the bottom for orientation; kick out windshields; open the door to exit; have window breaking tools in inaccessible locations; and breath ‘trapped’ air in the passenger compartment (20,23). Third, many individuals identify with some escape option that involves staying in the vehicle while it fills with water or sinks to the bottom (14). These strategies seem to decrease the chance of survival since the vehicle would be well below the water surface when pressure is equalized and the door can be opened. Additionally, passengers would have only one chance to complete a flawless escape after taking a ‘last breath.’

A recent drowning of an ice road worker (19) in Canada prompted the University of Manitoba and Government of Manitoba to conduct Operation ALIVE (Automobile submersion: Lessons In Vehicle Escape), a systematic study of human safety and survival in sinking vehicles in both real and simulated environments (12,14,15). In addition, a search was made for all information related to this topic. The following review is presented with the goal of educating emergency personnel, educators, policy makers and the general public.

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This manuscript was received for review in July 2011. It was accepted for publication in December 2012.

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DOI: 10.3357/ASEM.3151.2013

TABLE I. VEHICLE SUBMERSION STATISTICS. (AVERAGE/YR) [% OF ALL SUBMERSION DEATHS THAT ARE DUE TO DROWNING].

Country/Area (Reference)	Accidental Drownings	Vehicle Submersion Deaths*	% of All Accidental Drownings	Number of MVA Fatalities	% of Traffic Fatalities in Submersed Vehicles
Australia 1992–1997 (25)	2673 (382)	86 (12.3)	3.2	-	-
Canada 1991–2000 (7)	5535 (55.4)	488[†] (48.8)	8.9	-	-
Finland 1969–2000 (24)	9710 (324)	547[†] (18.2)	5.6	-	-
Netherlands 1964–1968 (44)	-	360 (72)	-	13,240 (2648)	2.7
Netherlands 1983–1986 (50)	-	377 (94)	-	-	2.0* **
Netherlands 1997–2000 (49)	-	368 (62) [53%]	-	-	-
New Zealand 1977–1993 (40)	2718 (181)	280[†] (18.6)	10.3	-	-
New Zealand 1980–1994 (21)	2606 (174)	302 (20.1)	11.6	-	4.7
Sweden 1992–2006 (42)	-	83 (5.5) [92%]	-	>600	1.5
USA 1988 (3)	4966	350 (350)	7.1	48,024	0.73
USA 2004–2007 (2)	-	384[†]	-	36,946	1.0
Imperial County, CA 1980–1989 (1)	317 (31.7)	48[†] (4.8) [61%]	[‡]	-	-
Minnesota 1980–1985 (18)	541 (90.2)	40[†] (6.7) [100%]	[‡]	-	-
North Carolina 1996–2000 (35)	189 (38)	17 (3.4)	9	-	-
Oklahoma 1970–1971 (39)	-	31 (15.5) [39%]	-	1391 (695.5)	2.2
Sacramento County 1974–1985 (52)	-	79[†] (6.6) [99%]	-	-	-
Washington 1980–1995 (32)	709 (47)	60 (4.0)	8.5	-	-

[†] Includes both enclosed and non-enclosed vehicles (i.e., all-terrain vehicles, snowmobiles, motor cycles, tractors etc.).
[‡] Not calculated because number of enclosed vehicles is not known.
* Average per year in parentheses; percent of all submersion deaths due to drowning in brackets.
** Data for 1986 only.

METHODS

Several digital databases were searched, including: medical (pubmed.com); drowning (redcross.ca, redcross.com, lifesavingsociety.com, and who.com); transportation (apta.com, bts.gov, trb.org, got.goc, statscan.ca, ntsb.gov, nhtsa.dot.gov, atsb.gov.au, tsb.gc.ca, ts.gc.ca, and swov.nl); and rescue (therescuecompany.com, diverescueintl.com, and nfrmag.com). The following search terms were used for Mode of Transportation: motor vehicle, vehicle, automobile, land transportation, car, truck/lorrie, and SUV; and for Incident Type: submersion, immersion, sinking, aquatic accident, accident, in water, drowning, drown, water-related fatality, sank, plunge, and dunk. The information from English sources (and four Dutch reports) was compiled and presented using four headings: media reports; epidemiologic research; empirical research; and recommendations and policies. The focus of this review is submersion of enclosed land-vehicles (e.g., cars and trucks, but not snowmobiles, ATVs, motorcycles, etc.).

Media Reports

Media reports provide most of the information available to the general public and rescue professionals. They cannot be substituted for rigorous epidemiological research; however, valuable information regarding trends and issues can be identified. In total, 133 reports from 2004–2009 were located using www.googlenews.ca (see **Fig. 1**, **Table II**, and **Appendix** for details and summary).

Epidemiologic Research

In total, 40 studies related to vehicle submersion were identified. Of these, 29 focused only on epidemiologic research and 1 included both epidemiologic and empirical research (44). Five reports focused on submersions caused by flooding and provided state (26,54) or national (11,30,41) statistics. Of the 25 epidemiologic reports on submersions from all causes, 4 were state-based (18,32,38) [with 1 focusing on children (35)], 2 were county-based (1,52), and 19 provided national statistics for the following: Canada [6 reports produced by the Red Cross Society (5–7), the Lifesaving Society (22), and Transport Canada (33,46)]; the Netherlands [5 reports, 1 in English (44) and 4 reports in Dutch (48-51)]; New Zealand [2 reports (21,40)]; and the United States [2 reports (2,3)], with 1 report each from Australia (25), Finland (24), and Sweden (42). One additional report provided statistics for American service personnel in Iraq and Afghanistan (17).

Two studies reported that vehicle submersion drowning data is unreliable (24,40). First, incidents are classified by “external cause” codes (E-codes) and most are given only one code based on the first incident. Thus, if a collision occurs first it would likely not be recorded as a vehicle submersion. Second, several E-codes related to vehicle submersion include non-enclosed vehicles (e.g., snowmobile). Additional incidents are missed due to unfinished reports, E-codes not being universally used (24), or unreported incidents; this tends to occur in rural areas and organizations that do not participate in record keeping/sharing (18,38). ‘E-code only’ searches miss between 5% (Australia and Finland) to 18% (New Zealand) of drownings, with the majority missed from vehicle submersions (21,25,40). Finally, it is important to note that E-code data do not include information on level of submersion, final vehicle position, details of rescue efforts, and cell phone involvement. Limitations notwithstanding, Table I summarizes important vehicle submersion statistics from several countries, states, and counties.

Vehicle submersion was considered the “Dutch” problem for many years (44) because of their prevalence of

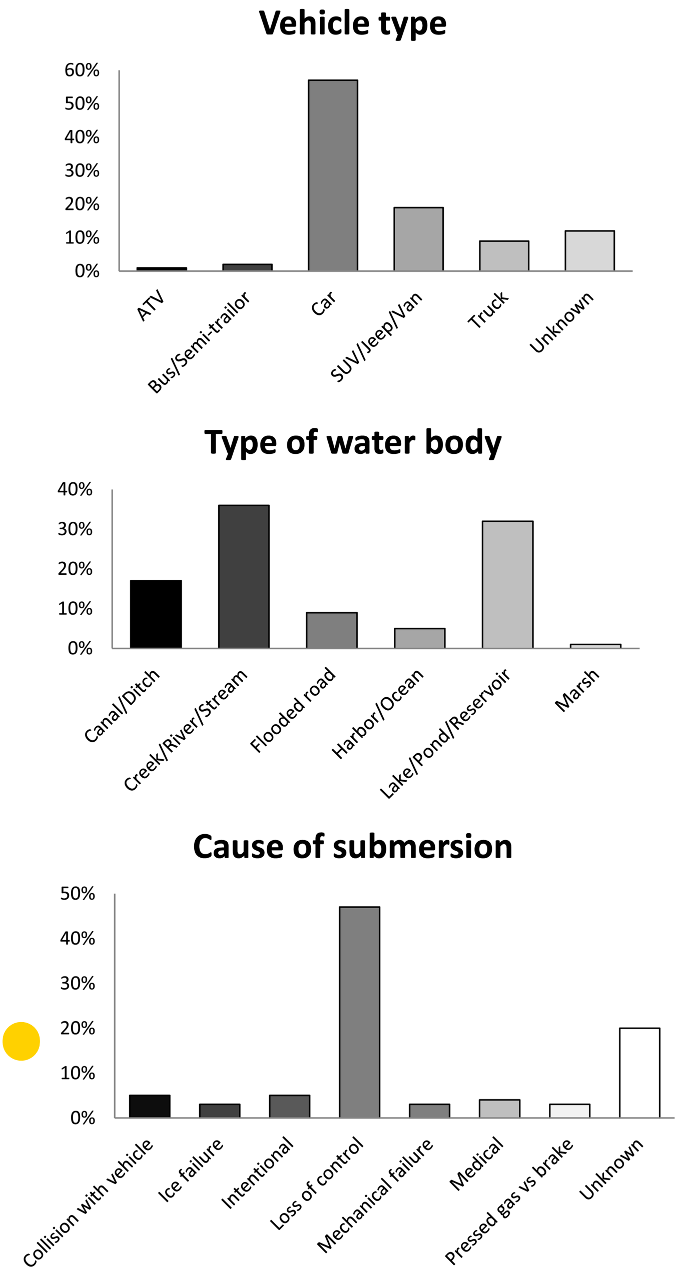

Fig. 1. Description of the types of vehicle (top panel), water body (middle panel), and causes of submersion (bottom panel), summarized from 133 media reports on vehicle submersion from 2004–2009.

roads near waterways, and has resulted in the most research. In the 1930s tests were conducted to describe vehicle sinking characteristics; however, the advice based on these tests became controversial and new research was required. The first major epidemiologic data was published in 1973 (44) (see Empirical Research). Although it was acknowledged that some cases were likely unreported, results revealed that the mortality rate of crashes into water (mean, 7.6%; range, 5.2–8.9%) was much higher than the mortality rate for all types of incidents combined (mean, 0.9%) from 1960–1969. Most vehicle submersions involved cars (75%), occurred during the winter (56%), and during the day (75%); the mortality rate, however, was almost twice as high in submersions at night compared to the day (12.1% vs. 6.2%, respectively). Drowning (82%) accounted for the majority of deaths. Finally, high-risk roadways were identified ("black spots") and crash barriers were advised (44).

Two subsequent reports (50,51) evaluated the effectiveness of revised safety recommendations made in the 1970s. It was found that 7% of people injured in vehicle submersion died; the probability increased from 5% in ditches/trenches to 20% in deep water. Two more reports from the Netherlands in 2002 were compiled by van Kampen (48,49). From 1997–2000 there was an annual average of 50 injury incidents involving vehicles in deep water and 750 involving vehicles in ditches/gullies. Again, the fatality rate was much higher in deep water (44% of incidents claimed a total of 22 lives per year) than for ditches/gullies (5% of incidents claimed a total of 40 lives per year) (48). Of the 62 deaths per year, 33 were classified as drownings. From 1983 to 2000 total road deaths decreased by 35%; however, only a 20% decrease was seen in deep-water incidents. This was interpreted as a relatively greater problem of drowning in car submersion incidents. The other report (49) reviewed 137 vehicle submersion cases from the year 2000 to determine whether technical aspects of vehicles (e.g., electronic locks or windows) affected survival rates. Although there were no reports of technical difficulties interfering with escape, it was proposed that as more vehicles use electronic devices, technical aspects may affect survival in the future.

The University of Oklahoma published two reports in 1970 (see Empirical Research) (39) and 1972 (39). The second report included epidemiological data from Oklahoma for 1970–1971. It was proposed that vehicle submersion incidents would be rare in Oklahoma, due to limited rainfall and small numbers of lakes and rivers; these incidents accounted for 2.2% of all non-pedestrian motor-vehicle fatalities. A total of 152 people were involved in 98 vehicle submersions. Of these victims, 31 (20.3%) died; 39% due to drowning and 61% due to trauma (39).

Transport Canada reported (33) on trends in motor-vehicle incidents from 1988–1997. There were an average of 36 fatal vehicle submersions per year with 24 per year (67%) resulting from previous collisions before entering water and 12 per year (33%) occurring in vehicles entering directly into water. Data from the Traffic Accident Information Database (46) indicates that from 1998–2002 there was an average of 260 vehicle submersions per year. Previously described reporting limitations do not allow calculation of an accurate mortality rate for this type of incident.

In 1991, collaborations between the Canadian Red Cross, Life Saving Society, National Association of Coroners, McGill University, and the Canadian Institute for Health Information created a Canadian Surveillance System of Water-Related Fatalities. Reports from these organizations consistently indicate that ~15% of drownings are related to air and land transport incidents (5,7,22). From 1991 to 2000, 5535 (94%) of 5900 water-related deaths were due to drowning (5,7,22). Of all the

TABLE II. SUMMARY OF 133 MEDIA REPORTS (2004–2009) ON VEHICLE SUBMERSIONS*.

Submersion Level	Final Vehicle Position	Self-Rescue	Rescue Initiated by Eyewitness	Rescue by ERS	Fatality
Full	Upright	47 (41%)	15 (13%)	1 (1%)	51 (45%)
Full	Inverted	1 (33%)	1 (33%)	0 (0%)	1 (33%)
Full	Unknown	14 (32%)	0 (0%)	0 (0%)	30 (68%)
Partial	Upright	33 (28%)	50 (42%)	25 (21%)	12 (10%)
Partial	Inverted	4 (14%)	6 (21%)	11 (39%)	7 (25%)
Unknown	Upright	4 (44%)	1 (11%)	0 (0%)	4 (44%)
Unknown	Inverted	2 (33%)	0 (0%)	0 (0%)	4 (67%)

* Percent of total within each category; ERS, emergency response system.

drownings, 488 (8.9%) occurred in on-road and ice travel incidents. Although the average number of drownings decreased by 16.5% from 1991–1995 (603/year) to 1996–2000 (504/year), the proportion of drownings in vehicles remained consistent. The most common causes of vehicle submersions were driving off the road (80%) or bridge (12%), and breaking through ice (2%) (7). Because of its northern latitude, a high percentage (36.3%) of drownings in Canada occur in cold water of < 10°C (8). From 1991 to 2000, 15% of the cold-water drownings (N = 2007) occurred in land transportation vehicles, but these data did not differentiate between enclosed and nonenclosed vehicles.

In addition to the data presented in Table I, the following trends were determined. Generally, most vehicle submersion deaths were primarily caused by drowning in the United States (1,18,52), Canada (7,8), and Europe (42,44). Oklahoma (38) was the only area where the primary cause of submersion deaths was due to trauma (61%). The majority of submersion deaths occur when vehicles crash into open water. Even northern countries (Canada and Sweden) report a low incidence of ice-related submersion drownings (respectively, 3.4/year and 0.33/year, accounting for 7% and 6% of submersion drownings) (8,42). Sweden was the only country to report that vehicle submersion drownings occur with equal frequency throughout the year (42). Normally the highest incidence occurs in the summer while the death rate may be higher in winter. Vehicle submersions are usually single-vehicle accidents, involving men ages 18 to 35 yr, in which cars drive into rivers, creeks, or streams. Darkness and alcohol are common factors. Other contributing factors include road conditions (e.g., slippery and poor visibility), limited distance between roads and water, and lack of barriers and visible signs. Hammett et al. (17) also documented 71 vehicle-related deaths of U.S. service personnel in Iraq and Afghanistan from 2003–2005. In 29 separate events, 52 deaths resulted from drowning, with 90% of events involving rollovers into ditches or canals.

Flood-Related Vehicle Submersions

Finally, five studies focused on flood-related drownings. Most flood-related deaths are attributed to flash floods (11) and more than 50% are associated with motor-vehicles (41). In the United States from 1969–1981, there were 1185 flood-related deaths (11). In 190 cases the cause of death was known; 93% were due to drowning, with 42% (N = 80) occurring in cars. Twice as many deaths occurred when flood warnings were considered inadequate. Flash floods in Puerto Rico (January 1992) claimed 23 lives (41), with 20 of those deaths occurring in 13 motor-vehicle submersions; many of the deaths occurred before warning systems were activated. Hurricane Floyd caused 52 deaths in North Carolina in 1999 (54). Motor vehicle-related drowning was the leading cause of death, with 19 incidents accounting for 14 fatalities. The death rate was 74% in the 14 fully submersed vehicles with no fatalities in the 5 partially submersed vehicles. The death rate was 91% when the vehicle was swept away and 25% when the vehicle remained stationary. Floods in Texas claimed 216 lives from 140 submersed vehicle incidents from 1950–2004 (26). In most cases drivers purposefully drove onto low-lying flooded roads or bridges. In fact, Parker (30) has shown that drivers who deliberately enter a flooded roadway usually become submersed, with a mortality rate of greater than 50%.

In conclusion, several preventative measures have been suggested, including: placing guardrails on curves of more than 20° that are longer than 1000 ft (42,52); placing clearly visible center and edge lines (1); and installing reflective signs and markings at T-intersections (52). Additional recommendations regarding flood-related submersions included better prediction (e.g., detailed analysis of meteorological and rainfall data), warning (e.g., identify roads likely to flood beforehand, post permanent signs, transmit radio, TV, and local warning systems e.g., such as sirens, in high-risk areas) and prevention measures (e.g., public education and quick barricade response).

Empirical Research

Only 11 studies were identified; 10 evaluated vehicle-sinking characteristics and 1 focused on the effect of water on electric window and lock mechanisms. Until recently however, only two of these studies, included systematic trials with human subjects (38,44).

Netherlands Research—1930s

The first attempt to study vehicle-sinking characteristics—about 50 unoccupied trials—was conducted by the Amsterdam Fire Brigade and the Naval Divers Department. Recommendations from the Royal Dutch Life-Saving Association—summarized in two subsequent reports (20,44) (a complete summary of advice for victims has been presented in **Table III**)—included: remain calm; roll up the windows if they are open; turn on the interior and exterior lights; remove seatbelts; determine the order of exit if there are multiple occupants; grasp each other's clothing; take a breath; open the door; exit and ascend to the surface (Table III). Occupants were advised to remain in the car until it filled with water because outside water pressure made it impossible to open the doors and there was a belief that air would be trapped in the vehicle, supplying an air source lasting 3-6 min. Specific advice was given not to open or break the windows because this would increase the rate of descent and increase the potential of injury from flying glass. It is important to note that in the 1930s, high rounded car roofs and heavier vehicle frames made it more likely to sink in a horizontal position and for air to be trapped if the vehicle remained horizontal.

Michigan Research—1960s

The first major written research report found on vehicle submersion was conducted in 1961 (20). There were 6 cars used in 49 unoccupied submersion trials. Vehicles were either rolled off ramps or lowered by a crane in different entry positions (upright, inverted, or on the side). Vehicles always tilted during descent, with the engine end down and the angle increasing with time. One-piece windshields shattered three times at entry speeds of 26 km/h but did not at 22 km/h. When vehicles entered water at 22 km/h, with windows closed and remaining intact, they floated, until complete submersion, for 2-6 min (**Table IV** compares flotation time for different studies in this section). If windows were open or a windshield shattered on impact, vehicles sank in as little as 12 s. When vehicles entered the water inverted or on the side, they righted themselves into an upright position if the windows were closed and intact.

Air continued to escape through the trunk as water entered the vehicle. The trials were conducted in 12 ft of water and vehicles ended up in an upright position in 41 of 49 trials. When windows remained closed and intact, the amount of air that was trapped in the roof area was limited, ranging from 60-190 L (1–6% of passenger compartment volume); air trapping was likely possible because vehicles settled on the bottom in an upright position and some of the models (from 1953 to 1961) still had high rounded roofs. Kuhn (20) theorized that it was possible to survive with this size air pocket for up to 65 min; however, this has not been demonstrated experimentally.

Because of the increased water pressure outside the vehicle, doors and windows could not be opened before complete filling, and the roofs consistently caved in. Although no pressure measurements were made inside the passenger compartment, there was indirect evidence that air pressure increased as the vehicle sank below the surface. The rear window of one car and the rear door of a station wagon repeatedly were forced open, presumably due to increased inside air pressure.

As a result of these studies, the generally accepted advice for this scenario was changed. New advice was to escape early through the windows while the vehicle was still on the surface (Table III). Other advice was questionable, however. If water was above the bottom of the windows, occupants were advised to completely close the windows and wait for the vehicle to fill with water. Third party rescuers were even advised to instruct occupants to close the front windows and move to the back seat if they could not exit from the front. It was not explained why a viable escape route should be closed, however.

Oklahoma Research—1970s

The University of Oklahoma Research Institute conducted the first systematic study of occupied vehicle submersions (38,39). A crane was used to lower a 1967 four-door sedan into a pool five times. Detailed analyses were made of sinking characteristics and four scuba divers were submersed in the last four trials with windows either closed or open. The flotation times were shorter than reported by Kuhn, averaging between 2-3 min. The water level inside the car rose linearly for about 70 s, after which the rate increased substantially; this coincided with the time when water reached the level of the air intake grille at the base of the windshield. Water reached the bottom of the front side windows after about 44 s.

The vehicle tilted forward, reaching 45° from horizontal after about 90 s and 80° at first impact with the bottom. Water pressure caved the roof downwards ~15 cm. Finally, cabin air was compressed to a maximum pressure increase of 225 mmHg at the pool bottom (4.4 m); this corresponds to one-third of an atmosphere or breathing compressed air at ~3 m depth. This latter result supported previous cautions about possible air embolism if the ascent from a submersed vehicle occurred with a closed glottis (20).

While on the surface, all four divers were able to exit through their respective windows within 10 s. When they stayed in the vehicle as it submersed, they could breathe for a varied amount of time, but no sufficient air pocket formed as the vehicle reached the bottom. When exit commenced after the vehicle was full of water, three of the doors could not be opened. This was proposed to be due to deformation; this effect was reversed once the vehicle was raised from the water. The authors agreed with Kuhn, that exit should occur as soon as possible while on the surface. They also concluded that vehicle roofs are likely to cave in and this may cause injury or restrict escape.

Netherlands Research—1970 to Present

As vehicle construction evolved to a lighter body, the engine had a greater influence, causing the vehicle to sink in a vertical engine-down position. This, combined with a flatter roof design, greatly decreased the probability of a significant amount of air being trapped after submersion. In 1968 the Dutch Institute for Road Safety Research (SWOV) conducted new research and made changes to existing recommendations. In 1972, about 48

TABLE III. EXAMPLES OF ADVICE FOR VICTIMS OF VEHICLE SUBMERSION (INT, INTERIOR; EXT, EXTERIOR).

Source	The Netherlands 1930s (44)	Michigan 1961 (20)	The Netherlands 1973 (44)	Miami Dade Fire Rescue 2001 (29)	Mildford Police Department 2001 (36)	RICAS Safety Training 2001 (37)	Lifesaving Resources 2006 (10)	University of Manitoba 2010 (14)
Acronyms or slogans	--	--	--	POGO	--	--	SOS-GO	Seatbelts, Windows, Children, Out
Preliminary advice	Remain calm Roll up windows, turn on int/ext lights	Roll up windows initially	--	--	--	--	Stay calm Assess the situation	No cell phone
Regarding seatbelts	Remove seatbelts	--	Seatbelts	Pop seatbelt	Seatbelts	Seatbelts off Hand on door handle	Slow your breathing	Seatbelts
Regarding windows	Determine exit order Grasp each others clothing Take a breath	Open or break window	Windows	Open window	Roll down window	Other hand open window Turn on headlights Let water fill vehicle Final deep breath	Open window(s) or door(s) Disengage your seatbelt Form human chain	Windows Children
Regarding doors	Open door	--	--	--	Unlock door	Open door	--	--
Regarding exit	Exit	Exit	Out	Get Out	Climb out	Exit	Get Out	Out

vehicle submersions were conducted to determine effects of dynamic entry into water on vehicle flotation and submersion characteristics. This was only the second set of systematic studies to include human subjects during the submersions; this occurred in 13 of the trials (44).

Regardless of how vehicles entered the water, they attained a horizontal floating position as long as the windows were closed and remained intact. Entry speeds of above 50 km/h caused significant vehicle damage. High speed film analysis indicated that vehicles experienced considerable decelerations on impact of 40-50 $m \cdot s^{-2}$ for a few tenths of a second; these values are much higher than the value of 8 $m \cdot s^{-2}$ experienced during an emergency stop on a dry surface.

If vehicles crashed on the side or upside down, structural damage often prevented doors and windows from opening. Presumably due to lighter body construction, vehicles tilted in an engine-down angle and in almost no cases were any appreciable air pockets found. Because of outside water pressure, exerting a force of up to 750–1000 N, subjects could not open the doors, even immediately after impact. It was also determined that floating time actually increased with the weight of the car, presumably because lighter frames experienced more deformation on impact, causing more leakage. Two static vehicle submersions revealed an increase in cabin air pressure of ~18 mmHg when the roof was 2 m below the surface; this was considerably smaller than the 225 mmHg increase reported by Sliepcevich et al. (39). The reason for this discrepancy is unknown.

Based on the human trials, occupants were advised to first unfasten safety belts, and then escape immediately through the windows (Table III). If windows could not be rolled down, it was suggested that they be broken by applying pressure with a foot or shoulder to a corner of the window. All actions should occur while the vehicle is still afloat as it was virtually impossible to break a window once the cabin was submersed. Finally, researchers clearly stated that doors should not be locked while driving, as this would make it impossible for third-party rescuers to open the doors. The value of this advice today is negated by automatic door locks in most current models. It is important to note that only side windows, which are made of tempered glass, can be broken (28). Laminated front and rear windows cannot be broken, nor can synthetic laminates, which are becoming more popular. Further research is needed regarding these latter two safety measures, which may prevent escape in this scenario.

The most recent study reported on the effects of water on separate components such as electronic lock and window mechanisms (4). In 19 current car models tested, window operating mechanisms were unreliable after contact with water and only worked properly in 2 cars. Car batteries continued to function in all cases. Although the malfunctions could be traced in some cases to the window control button or motor, the most common problem was with "intelligent components" that actually control the electronic motor system. It is important to note that these components are located within the

TABLE IV. SUMMARY OF VEHICLE SINKING CHARACTERISTICS FROM EMPIRICAL RESEARCH.

Vehicle Type (Reference)	Study Dates	Surface Times with Vehicle Intact	Surface Times with Frame Deformed or Windows Open/Broken	Significant Air Pocket Detected?
Cars (20)	1930s	3 to 6 min	--	Yes
Cars (20)	1961	2 to 6 min	12 to 138 s	Yes
Cars (38)	1970	2 to 3 min	--	No
Cars (44)	1972	1 to 3 min	5 to 120 s	No
Cars, Vans (9)	1991	1.5 to 4 min	--	No
Bus (9)	1991	--	16 s	No
Busses (43)	1997	3.5 min	9 to 30 s	No
Cars (14)	2010	1.2 to 2.5 min	30 to 37 s	--
5-ton truck/plow (15)	2010	3–4 s	3–4 s	No
1-ton truck/plow (15)	2010	81 s	--	--

Surface times include the time from water contact to complete submersion.

passenger compartment and would be affected only once the dashboard was immersed.

Michigan Research—1990s

Noting a 20-yr gap since the last systematic submersion studies, Operation STAR (Submerged Transportation Accident Research) was initiated in 1991 by the Michigan State Police, the Michigan National Guard, and the United States Coast Guard (9). There were 31 vehicle submersions conducted on 20 passenger vehicles (including 1 school bus) which were self-propelled, towed off a floating bridge, or lowered with a crane. Although the stated purpose was to determine escape methods and self-rescue techniques, these trials did not involve human subjects (except for one final demonstration trial with two scuba divers).

Vehicles remained visible at the surface for 1.5–4 min, depending on the integrity of side windows and weather seals around the trunk lid. It was determined that windshields and rear windows could not be kicked out because they are glued in place in newer models. Scuba divers demonstrated that vehicle electronics, such as window wipers and lights, worked for between 5-10 min after initial contact with water. Although the electric windows and locks worked "to full capacity" once the vehicle settled on the bottom (and was presumably full of water), the power windows failed on the water surface in the single human-occupied submersion test; the reason for this failure was not given.

It was correctly theorized from the unoccupied trials that early exit through the window was preferable. This was the first study to correctly identify that although it might be possible to open a door immediately after impact, two complications might occur: rapid water influx would cause the vehicle to sink faster; and exterior water pressure may force the door to close quickly and injure or trap the occupant. There were, however, several limitations to making escape recommendations from unoccupied trials. The authors stated that if the outside water level is above the bottom of a side window, opening that window will cause a water surge that would incapacitate the occupant; this effect has since been shown to be minor (14). They then theorized that once the inside water level rises above the entire side window, it can then be opened easily. This has also been later disproven as greater outside water pressure pushes all windows against the frame until both the cabin and rear trunk areas are almost completely filled (14). Finally, even though the power windows failed in the one occupied trial, it was stated that "the functional time factor of the electrical components is insignificant. A 5 to 10 minute allowance provides an ample window of opportunity to effect any number of (self-rescue) escape options." The Dutch study, however, clearly demonstrated that power locks and windows cannot be relied upon when central components are exposed to water (4).

The one bus submersion trial provided a disturbing result. The bus, which entered the water at only 13 kph, had its windshield pushed in by impact with the water and sank in a startling 16 s. This prompted a separate study of buses in Operation STAR II in 1997 (43). Two types of school buses (65- and 12-passenger) were studied. When they were rolled off a floating bridge at ~13 kph, water consistently imploded the windshields and opened the folding front doors, and air was forced out of emergency roof hatches. The 65-passenger buses sank within 9-30 s and 12-passenger buses sank in as little as 9 s. When one 65-passenger bus entered the water slowly enough that the window and door remained intact, it floated for 3.5 min. Since most bus entries into water would involve some speed, it was concluded that current bus designs result in very limited escape options in this scenario.

Manitoba Research—2000s to Present

Operation ALIVE (Automobile submersion: Lessons In Vehicle Escape) was only the third set of systematic trials to include human subjects. In over 100 submersions, 97 of which involved human subjects, 5 cars and a 1- and 5-ton truck were used (14,15). Since the main focus was human escape behavior, dynamic entries were not studied; vehicles were either lowered with a crane or slowly pushed down a ramp. Subsequent studies involved submersion in a vehicle simulator (12, and G McDonald, GG Giesbrecht. Escape from a submersible vehicle simulator wearing different thermoprotective flotation clothing. Aviat Space Environ Med. In Press.).

The first new result from these trials was a different evaluation of vehicle sinking characteristics. Previous descriptions of 'floating time' included the entire time from contact until complete submersion below the surface. This new report (14) divided the submersion process into three phases, which corresponded to differing probabilities of escape. The "Flotation Phase" included the time from initial water contact to when water reached the bottom of the side window; during this period functional windows could easily be opened or broken and exit was simple. For example, three passengers were able to exit with a child manikin through a single driver side window in only 53 s. The second "Sinking Phase" was defined as the subsequent period until the vehicle was completely submersed; during this period windows could not be opened because outside water pushed the window against the door frame. The final "Submersion Phase" included a period of complete submersion, in which some air was initially still present inside the vehicle; thus, a vehicle was well below the surface before it completely filled and equalized pressure allowed for opening of the doors. The distinction in definitions is demonstrated in one vehicle which floated—according to previous definitions—for 150 s; however, the newly defined Flotation Phase (i.e., the realistic opportunity for escape) only lasted for 63 s.

Although one trial demonstrated that it was possible to force a door open immediately upon water contact, Donohue's (9) predicted danger was demonstrated, as the vehicle then sank quickly and the door slammed shut on the subject's hand (no significant injury was sustained). In subsequent trials using a 5-ton truck with a front-mounted snow plow, there was virtually no Flotation Phase as the truck was completely submersed within 3-4 s; when all windows were closed, the rapid pressure buildup consistently imploded the windshield (15).

Escape advice generally followed that from previous reports with the additional focus on child passengers. The simple four-word process was suggested: SEATBELTS unfastened; WINDOWS opened or broken; CHILDREN released from their restraints, from the oldest to the youngest; OUT through the window, with children exiting first (Table III). In heavy machinery this process is impractical as there is no Flotation Phase. For these vehicles, it was recommended that roof escape hatches be installed; in many cases the hatch blows open before submersing below the water's surface, thus providing an immediate exit route.

Pilot studies were also conducted to determine the potential effectiveness of attaching external flotation devices to a 1-ton truck/plow in preventing or slowing down the sinking process (15). Normally, because of the front-mounted plow, the truck quickly tilted forward, decreasing the Flotation Phase to only 7 s. Attaching 1-3 empty 200-L drums to the top of the plow increased the Flotation Phase by 30-40 s for each drum, thus providing more time for escape. Further work is warranted in this area to determine practical implementation of this principle.

Winter roads workers form a high-risk group for vehicle submersions because of possible ice failure on roads over frozen waterways; therefore, many jurisdictions require workers to wear thermoprotective flotation clothing when driving over ice. Studies using a submersible vehicle simulator were conducted to determine whether clothing bulk or buoyancy interfered with exit from vehicles, and the effects of buoyancy on the ability to swim horizontally (e.g., against a current from a vehicle resting on the bottom to the hole in the ice) (12, and G McDonald, GG Giesbrecht. Escape from a submersible vehicle simulator wearing different thermoprotective flotation clothing. Aviat Space Environ Med. In Press.). Flotation jackets and overalls did not interfere with exiting through a window; however, an inflatable personal flotation device (PFD) did provide some difficulties. Because of the high buoyancy (142 N), the inflatable PFD significantly reduced the horizontal swim distance compared to the flotation jacket (69 N) and overall (95 N). Therefore, flotation jackets or overalls were recommended for all vehicle travel over ice, while inflatable PFDs were considered a liability.

Recommendations and Policies

So far, this review has pointed out that there is a high degree of awareness of the vehicle submersion problem, yet there are very few systematic studies on which to base advice and policy. Much of what the public knows comes from a few media demonstrations and written recommendations from nonscientific, non-refereed articles in the popular press or from professional organizations. Some official policies are based on scientific information, while others rely on nonscientific or outdated information (see Appendix for detailed demonstration sources).

Recommendations

Many non-vetted recommendations appear in the popular press and publications from various organizations. As expected, content and completeness of advice varies. For example, both a popular handbook (31) and a trade magazine (34) simply advise to open the windows and get out. As mentioned above, this advice fails to remind victims to unfasten seatbelts. A Dutch company offered realistic simulator training (37). However, they did not even conduct surface exit trials, but focused only on submersed exits. They advocate turning the headlights on while waiting for the vehicle to fill, and then opening the door.

Specific survival advice was given by rescue personnel in two television programs. In the first, the Miami-Dade Dive Rescue uses the acronym "POGO" to advise: Pop your seatbelt; Open the windows; and Get Out (29). The Milford Police Department uses slightly altered recommendations: first unfasten the seat belt, then roll down the window, unlock the car door, and climb out (36).

Finally, one safety training company uses the acronym SOS-GO (10) (Table III). In an attempt to mimic helicopter escape strategy, occupants are advised to disengage seatbelts only after the windows are opened.

Helicopter training assumes that the aircraft will quickly roll to an inverted position and seatbelts should remain fastened until exit to maintain spatial awareness. Most sources, however, advocate unfastening seatbelts first since many vehicle studies confirm that vehicles are intrinsically stable in the upright position and will return to an upright position from an inverted position if windows are closed and intact, and it is better to complete this process early in the event while stress levels are lowest.

Policies

Official policies are generally related to ice failure, which is a special category for vehicle submersion; in Canada, 51 deaths occurred in motorized vehicles breaking through ice between 1991–2000 (8). Because of the increased risk, several policies address prevention of or survival after ice failure incidents for vehicles on winter roads. Preventative measures include rigorous ice thickness testing, reduced speed limits (normally 15 kph and maximally 25 kph), and a "never work alone" policy (16,47,53). Before driving on ice, vehicle windows should be opened and doors either unlocked (22) or actually removed or lashed open (47). Seatbelts must NOT be worn (47). Certified approved flotation clothing (one- or two-piece) must be worn and a self-extraction tool (e.g., ice picks) should be carried (27,53). Finally, vehicle occupants are warned that inflowing water can carry pieces of ice and debris, which may cause injury (23).

Summary and Conclusions

Vehicle submersion has the highest fatality rate of any type of single-vehicle incident, accounting for as many as 11% of all drownings. The major risk factors for vehicle submersion include driving on ice, roadways near water, flooding of roadways or bridges, slippery or curved roads, and poor signs or road markings. Vehicles generally sink in a predictable way. The old definition of flotation time (from water impact to complete submersion) is probably inadequate. A new understanding of a Flotation Phase (from water impact until water rises to the bottom of side windows) better defines a period when survival probability is highest. The ability to open doors depends on timing. Immediately in the Flotation Phase a door may be opened, but this brings the double risk of rapid filling and immediate submersion, and forceful door closing against the victim's body. After this, it is impossible to open a door until the vehicle is almost completely full of water. Since there is little or no trapped air, this period provides a very low chance of survival.

Advice to occupants of submersed vehicles must be simple and easy to remember. Research is required to determine if acronyms are more effective if the letters stand for the most important word (e.g., seatbelts) rather than a nonspecific command (e.g., pop). The most important aspects of successful escape seem to be unfastening the seatbelt, opening the window, and getting out. Extra tasks, which have only secondary importance, such as unlocking the doors or turning on the lights, may diminish the critical message and may make it difficult to remember. It may be advantageous, however, to add specific reference to children, with special attention given to removal of a car seat itself, or rapid unfastening of all strap connections.

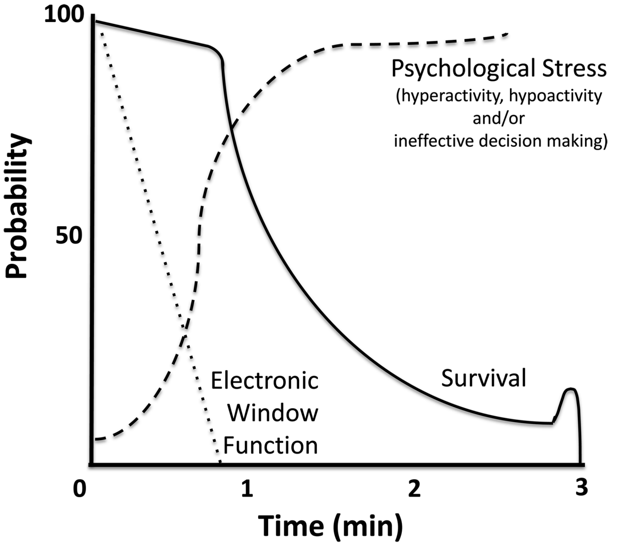

Fig. 2. Schematic estimation of relative probability of psychological stress, electric window function, and survival over time in a sinking passenger vehicle.

Fig. 2 provides a framework for the preferred order of actions. The probability of survival is highest during the first minute and then decreases rapidly; therefore, exit should be attempted as quickly as possible through the windows. Cell phones should not be used to call for help because this will only waste the optimal period for escape. Once the vehicle is full of water, a brief increase in survival probability would occur if doors or windows could be opened; however, if this attempt is unsuccessful, death is imminent. Over time psychological stress will likely increase rapidly, with increased probability for either hyperactivity (e.g., agitated, inefficient movements), hypoactivity (e.g., tonic immobility plus cognitive paralysis) (e.g., doing nothing or "freezing") and/or ineffective decision-making (i.e., using a cell phone) (13).

Because psychological stress will likely be lowest initially and quickly escalate, the simple and quick action of unfastening the seat belt should occur first. Electric window function is also unreliable and decreases quickly; therefore, windows should be opened or broken next. Breaking windows is difficult without a center punch or special hammer, which should be visibly mounted within reach of the driver. Force should be applied to the front (hinge-side) part of the window for best results. Although these devices work when the window is above water, and less well when the vehicle is fully submersed, it is almost impossible to break a window during the Sinking and Submersion Phases when there is water on only one side of the window. **Fig. 3** presents a vehicle escape algorithm. The probability of survival (indicated by thickness of arrows) diminishes as a vehicle sinks and windows remain closed or intact.

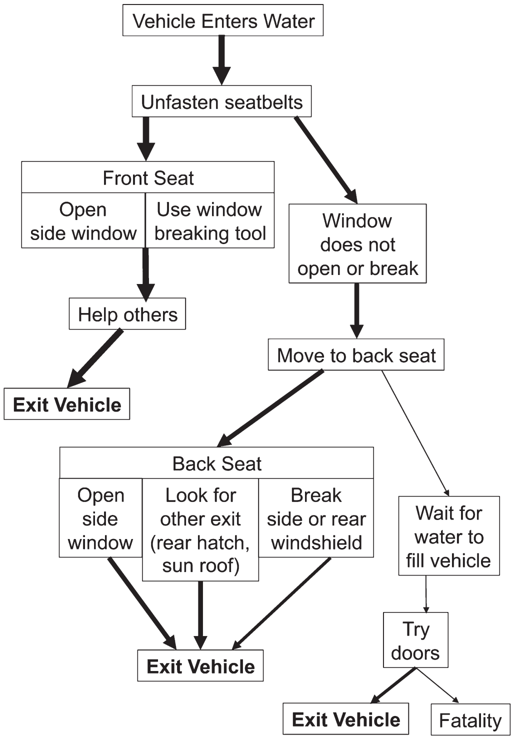

Fig. 3. Algorithm for outcomes following passenger vehicle entrance into water. For each group of instructions (i.e., front & back seats), the order of preference is from left to right. Probability of survival is indicated by thickness of arrows.

Finally, prevention includes placing roadways at a greater distance from water or installing adequate guardrails, barriers, warning signs, and road markings. Areas at high risk for flooding should be well provided with signs, and public warning systems for flash flooding should be improved. Public education should also focus on the dangers of driving on flooded roads and bridges, or ice roads. Although egress training would be advantageous for some high risk professions, it would generally be logistically unrealistic and/or cost prohibitive. Therefore, both proper public and worker education programs should be developed using targeted training materials (16,45). Further research on the effects of flotation on escape, memory and effectiveness of different types of acronyms, and surveys of public understanding of vehicle submersion issues would all be beneficial to increase understanding of occupant survival and safety. Changes in current protocols regarding vehicle submersion incidents should include: standardizing definitions and recording of incidents; have a centralized incident collector; and changing emergency dispatch protocols to help occupants escape the vehicle first.

ACKNOWLEDGMENTS

This work was supported by the Government of Manitoba, Department of Infrastructure and Transportation, and the Natural Sciences and Engineering Research Council (NSERC) Canada. Operation ALIVE is dedicated to the memory of Calvin Wood, Ashley Neufeld, Kyrstin Gemar, and Afton Williamson.

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REFERENCES

1. Agócs MM, Trent RB, Russel DM. Activities associated with drownings in Imperial County, Ca, 1980-90: implications for prevention. Public Health Rep 1994; 109:290–5.
2. Austin R. Drowning deaths in motor vehicle traffic accidents. United States: Paper Number 11-0170, International Technical Conference on the Enhanced Safety of Vehicles (ESV); The 22nd Conference Proceedings. Washington, DC: National Highway Traffic Safety Administration; 2011:1-8. Accessed July 18, 2011, from www-nrd.nhtsa.dot.gov/departments/esv/22nd/.
3. Baker S, O'Neill B, Marvin M, Li G. The injury fact book: vehicle immersion, 2nd ed. New York: Oxford University Press; 1992: 242–3.
4. Buning LR, Kessels JF, Merts M, Pauwelussen JP, Visser AG. Window operating mechanisms and door locking systems. Deleft: The Ministry of Transport, Public Works and Water Management, Rijkswaterstaat Centre for Transport and Navigation; 2008 July 1. Report No: Definitive 1.0.
5. Canadian Red Cross Society. National Drowning Report: Visual Surveillance Report: an analysis of drownings and other water-related injury fatalities in Canada for 1997. Ottawa, ON, Canada: Canadian Red Cross Society; 1999. Report No.: 1-55104-234-7.
6. Canadian Red Cross Society. National Drowning Report: Visual Surveillance Report: an analysis of drownings and other water-related injury fatalities in Canada for 1999. Ottawa, ON, Canada: Canadian Red Cross Society; 2001. Report No.: 1-55104-234-7.
7. Canadian Red Cross Society. Drownings and other water-related injuries in Canada 1991-2000. Report. Ottawa, ON, Canada: Canadian Red Cross Society; 2003.
8. Canadian Red Cross Society. Drownings and other water-related injuries in Canada, 1991-2000; module 2: ice & cold water. Ottawa, ON, Canada: Canadian Red Cross Society; 2006.
9. Donohue W. Operation Submerged Transportation Accident Research (S.T.A.R). Lansing, MI: Michigan Department of State Police; 1991. Final report.
10. Dworkin G. Escape and rescue from submerged vehicles. IJARE 2007; 1:82–7.
11. French J, Ing R, Allmen SV, Wood R. Mortality from flash floods: a review of national weather service reports, 1969-81. Public Health Rep 1983; 98:584–8.
12. Gagnon D, McDonald GK, Pretorius T, Giesbrecht GG. Clothing bouyancy affects underwater horizontal swim distance after exit from a submersed vehicle simulator. Aviat Space Environ Med 2012; 83:1077–83.
13. Giesbrecht G. Bad decisions, poor outcomes: a visual model for how humans make some threatening events worse. J Spec Operations Med 2005; 5:24–7.
14. Giesbrecht GG, McDonald GK. My car is sinking: Operation ALIVE (Automobile submersion: Lessons in Vehicle Escape). Aviat Space Environ Med 2010; 81:779–84.
15. Giesbrecht GG, McDonald GK. Exit strategies and safety concerns for machinery occupants following ice failure and submersion. Aviat Space Environ Med 2011; 82:52–7.
16. Government of Alberta. Best practice for building and working safely on ice covers in Alberta. Edmonton, Alberta, Canada: Government of Alberta; 2009:1–58.
17. Hammett M. Drowning deaths of U.S. service personnel associated with motor vehicle accidents occuring in Operation Iraqi Freedom and Operation Enduring Freedom, 2003-2005. Mil Med 2007; 172:875–8.
18. Hedberg K, Gunderson PD, Vargus C, Osterholm MT, MacDonald KL. Drownings in Minnesota, 1980-85: a population-based study. Am J Public Health 1990; 80:1071–4.
19. Howell MW. Report by provincial judge on inquest respecting the death of: Calvin Sean Wood. Winnipeg, MB, Canada: Provincial Court of Manitoba; November 28, 2005.
20. Kuhn BJ. Analysis of selected events subsequent to submerging of vehicles in deep water (Dissertation). Indiana, IL: Indiana University; 1962.
21. Langley JD, Warner M, Smith GS, Wright C. Drowning-related deaths in New Zealand, 1980-94. Aust N Z J Public Health 2001; 25:451–7.

22. Lifesaving Society. National Drowning Trends Report 1991-2000. Ottawa, ON, Canada: Lifesaving Society; 2003.
23. Lifesaving Society. Breaking through: fundamentals of ice rescue. Ice, the winter killer (a resource manual about: ice, ice safety, ice rescue), 2 ed. Ottawa, ON, Canada: Lifesaving Society; 2003:55–67.
24. Lunetta P, Penttilä A, Sajantila A. Drowning in Finland: "external cause" and "injury" codes. Inj Prev 2002; 8:342–4.
25. Mackie IJ. Patterns of drowning in Australia. Drummoyne, Australia: Royal Life Saving Society Australia; February 9, 1999.
26. Maples LZ, Tiefenbacher JP. Landscape, development, technology and drivers: the geography of drownings associated with automobiles in Texas floods, 1950-2004. Appl Geogr 2009; 29:224–34.
27. Ministry of Natural Resources. Working on ice policy. Peterborough, ON, Canada: Ministry of Natural Resources; 2001:2.
28. Molenaar J, Stoop J, eds. Handbook on drowning: prevention, rescue, treatment. Berlin, Germany: Springer-Verlag; 2006.
29. NBC Dateline. Life on the line [videorecording]. New York: National Broadcasting Company; 2001.
30. Parker JG. The power of water: 50 percent of flood deaths happen on the road. Traffic Safety (Chicago) 2002; 2:14–7.
31. Piven J, Borgenicht D. The worst-case scenario survival handbook. San Francisco, CA: Chronicle Books; 1999:36–8.
32. Quan L, Cummings P. Charateristics of drowning by different age groups. Inj Prev 2003; 9:163–8.
33. Road Safety and Motor Vehicle Regulation Directorate. Trends in motor vehicle traffic collision statistics 1988-1997. Ottawa, ON, Canada: Transport Canada; 2001. Report No: TP 13743 E February.
34. Roberts DJ, Roberts BG. Surviving vehicle submersion. Situation Critical 2007; 2:4-8. Retrieved 20 November 2007 from http://www.northmemorial.com/healthcareprof/winter07.pdf.
35. Sanford CP, Givens J, Radisch D, Smith JB. A review of the epidemiology of unintentional drowning deaths of children in North Carolina from 1996 through 2000. Raleigh, NC: North Carolina Department of Health and Human Services, Injury and Violence Prevention Program; 2001.
36. Sastre J. Handling submerged vehicle incidents. 2001; retrieved 27 May 2005 from: http://www.911dispatch.com/video/miami/powerphone.html.
37. Scrivener Z. The drowning pool. 2001; retrieved 20 December 2007 from http://www.caranddriver.com.
38. Sliepcevich CM, Steem WD, Purswell JL, Ice JN, Welker JR. Escape worthiness of vehicles and occupant survival. Final Report. Norman, OK: U.S. Department of Transportation; 1970. Report No: 1729-FR-1-1 December 1970.
39. Sliepcevich CM, Steen WD, Purswell JL, Krenek RF, Welker JR, et al. Escape worthiness of vehicles for occupancy survivals and crashes. First part: research programs. Norman, OK: U.S. Department of Transportation; 1972. Report No: 1770-FR-1-1.
40. Smith GS, Langley JD. Drowning surveillance: how well do E codes identify submersion fatalities. Inj Prev 1998; 4:135–9.
41. Staes C, Orengo JC, Malilay J, Rullan J, Noji E. Deaths due to flash floods in Puerto Rico, January 1992: implications for prevention. Int J Epidemiol 1994; 23:968–75.
42. Stjernbrandt A, Öström M, Eriksson A, Björnstig U. Land motor vehicle-related drownings in Sweden. Traffic Inj Prev 2008; 9:539–43.
43. Submerged Transportation Accident Research Operation (STAR) II [videorecording]. East Lansing, MI: Michigan State Police; 1997.
44. SWOV. Submerging vehicles. Report for the Minister of Social Affairs and Public Health. Voorburg, NL: Institute for Road Safety Research (SWOV); 1973. Report No: 1973-1E 1973.
45. The cold, hard facts of winter roads safety [videorecording]. Winnipeg, MB, Canada: Province of Manitoba (Infrastructure and Transportation Department) and the University of Manitoba; 2007.
46. Transport Canada. Traffic Accident Information Database (TRAID). 2005; retrieved 15 October 2005 from http://www.tc.gc.ca/eng/roadsafety/resources-researchstats-menu-847.htm.
47. Treasury Board Secretariat. Safety guide for operations over ice. Ottawa, ON, Canada: Treasury Board Secretariat; 1993. Retrieved 6 December 2006 from http://www.tbs-sct.gc.ca/Pubs_pol/hrpubs/TBM_119/CHAP5_3-1-eng.asp.
48. vanKampen LTB. Problemen met ontsnapping en bevrjding uit auto's te water? (Problems with escape, and liberation from cars to water?). Leidschendam, NL: Institute of Road Safety Research (SWOV); 2002. Report No: R-2002-28 I.
49. vanKampen LTB. Omvang, aard en ernst van ongevallen met auto's te water (Size, nature and severity of accidents with cars in the water). Leidschendam, NL: Institute of Road Safety Research (SWOV); 2002. Report No: R-2002-28 II.
50. Vis AA. Auto's te water. Leidschendam, The Netherlands: Institute of Road Safety Research (SWOV); 1989. Report No: R-89-16.
51. Vis AA. Auto's te water! Leidschendam, The Netherlands: Institute of Road Safety Research (SWOV); 1992.
52. Wintemute GJ, Kraus JF, Teret SP, Wright MA. Death resulting from motor vehicle immersions: the nature of the injuries, personal and enviromental contributing factors, and potential interventions. Am J Public Health 1990; 80:1068–70.
53. Winter Road Safety Committee. Inspector's safety guidelines for the construction and maintenance of winter roads, 6 ed. Manitoba, Canada: Manitoba Transportation and Government Services; 2004:1–67.
54. Yale JD, Cole TB, Garrison HG, Runyan CW, Ruback JKR. Motor vehicle-related drowning deaths associated with inland flooding after hurricane Floyd: a field investigation. Traffic Inj Prev 2003; 4:279–84.

APPENDIX. VEHICLE SUBMERSION INFORMATION FROM MEDIA SOURCES.

Media reports often provide most of the information available to the general public and rescue professionals who do not have a special interest in this particular type of incident; additional information about rescue and survivors is also often available. The following information highlights some of the key media reports, demonstrations, and recommendations easily assessable to the public. Public interest is sparked by sensational cases such as a family who drowned in a van after it fell from a ferry into the ocean (A8) and three young women who drowned after making a desperate cell phone call for help after their SUV went into a pond at night (A17).

A total of 133 news reports from the period 2004 to 2009, inclusive, were located using www.googlenews.ca. Although a review of media reports cannot be substituted for rigorous epidemiological research because: a) information provided is not in a uniform format, and is often incomplete; and b) not all cases are reported, much valuable information can be gleaned and various trends and issues can be identified which might direct further work. In fact, some information may not be revealed in epidemiological studies because various reporting methods might not include specific information that may be of interest (e.g., the details of how a survivor is successfully rescued from the vehicle or, in some cases, what caused the vehicle to enter the water in the first place).

Type of Vehicle

Vehicle types range from cars to buses and even semitrailer trucks, with the majority (57%) of submersed vehicles being cars (Fig. 1, top). In total, 76% of vehicles involved in submersion incidents are passenger vehicles, which can be explained due to their frequency of use. Vehicles most commonly ended up in moving water (rivers, creeks, and streams), followed by lakes, ponds, and reservoirs (A17), with a large proportion also occurring in canals or ditches (A12, A17) (Fig. 1, middle). The majority of vehicles going from the road into water (74%) are traveling on roads that pass by a body of water. While 17% end up in bodies of water that run alongside the road, 9% are driven in intentionally. The most common cause of vehicle submersion (Fig. 1, bottom) was a loss of control (47%), which included: excessive speed (15.8%); talking on a cell phone (2.3%) (A4, A10); slippery road conditions caused by water or ice (6%); roadway infrastructure issues such as curves, lack of guardrails, and missing signs (2.3%); and driving off a bridge (5) (5.3%) or down a boat ramp (A16) (4.5%). The cause of the loss of control was not reported in 10.5% of reports. Other common causes were flash flooding (A11) and intentional submersions (A3, A7). Extreme situations included a single mini-bus submersion that claimed six lives (A1) and a dangerous canal area in which 19 persons have drowned over a period of 52 yr (A12). Overall, only 18% of the vehicle submersion incidents are from intentional exposures (e.g., intentionally driving into water, attempting to drive on a flooded road, or driving on ice).

Rescue Method

Table II summarizes the influence of submersion level and position on the survival rate and success of various sources of rescue. As expected, the fatality rate when vehicles are fully submersed is much higher (48%) than when vehicles are only partially submersed (13%); for one thing, the later condition can provide a constant source of air even if the occupants are trapped for a long period of time.

Survivors of full submersion incidents rescue themselves most (78%) of the time. Virtually all third-person rescues are conducted by on-scene bystanders (defined as laypersons or professionals who respond immediately because they happened to be at the scene at the time of, or immediately after, the incident). These rescues were performed by opening doors, breaking windows, towing vehicles to shallow water, and holding a victim's head above water. In fact, only one report was found of an emergency professional actually responding to a call and successfully "rescuing" a victim from a submerged vehicle (Joey Darby, Foley Fire Dept. Personal communication; 2009); although the victim had drowned, she was resuscitated and survived. Indeed, emergency personnel function primarily in a "recovery" mode at full submersion scenes. This is due to the disparity between response time and survival time.

Partial vehicle submersion allows a longer, if not indefinite, period of survival and, therefore, provides more opportunity for third-person rescue. In this scenario, professionals who were responding through the emergency response system rescued 36 of 129 survivors (28%). Compared to bystanders, emergency response personnel accounted for half as many rescues from upright vehicles, but twice as many rescues from inverted vehicles; this likely reflects the increased technical difficulty of dealing with an inverted vehicle.

Occupant Use of Cell Phones

Cell phone use by vehicle occupants is generally detrimental (A17, A22). Not only have cell phones potentially been the cause of vehicle entry into water in the first place (A4, A10), there was only one report of a call from a victim's cell phone successfully affecting rescue (Joey Darby, Foley Fire Dept. Personal communication; 2009). In fact, in two fatal cases, multiple calls were made (A12, A14). Using a cell phone greatly reduces the possibility of self-rescue because vehicle floatation time -- a period during which self rescue is most possible—is expected to be less than emergency response time.

Four cases were found in which occupants of partially immersed vehicles were actually able to maintain an airway above the water line and call for help from within the vehicle. However, bystanders arrived first to help rescue them, not emergency response personnel (A9, A15, A23). In conclusion, the information contained in media reports is neither complete nor similarly formatted; however, several trends can be identified. Most vehicle submersions involve cars entering rivers, lakes, or canals because of a loss of vehicle control. The fatality rate is much higher in full vs. partial submersions, and bystanders who are on scene at the time of the incident usually conduct third-person rescue. The only time emergency response personnel can usually affect a rescue is when partial submersion allows the victims to position their heads above the water level for an extended period. Calls for help from a cell phone are generally not successful in fully submersing vehicles (A6) and should only be used after a vehicle is partially submersed, stable, and self-rescue is not possible.

Media Demonstrations

Much of what the public knows comes from a few media demonstrations and there are many written recommendations from nonscientific, non-refereed articles in the popular press or from professional organizations. Some official policies are based on scientific information, while others rely on nonscientific or outdated information. A complete sampling of submersion demonstrations includes a magazine report (A16), three television news magazine programs (A2, A14, A18), and three specialty programs (A13, A20, A21). In each case, a reporter or host participated in one or several submersions in a passenger vehicle. The first report, from a 1961 article in Today's Health (16), reinforced the thinking of that era by focusing on letting the vehicle fill with water before opening the doors. It was also stated that an air pocket would last for 10-15 min. This included the first reference that considered children. Adults were advised to push children out of the vehicle first.

Televised demonstrations from the last decade demonstrated that exit through windows while floating on the surface was easy and successful. However, it was generally impossible to open the car doors during the Flotation or Sinking Phases (A13, A14); the Mythbusters program showed that this was possible only when the water was at ankle or knee level inside the vehicle, and only with considerable effort (A13). In three programs in which an escape attempt was made after the vehicle was full of water (A2, A13, A18), only one reporter made a successful exit in the first trial (A18); the others failed and presumably would have drowned in real settings. None of the trials demonstrated a significant air pocket and spring-loaded center punches were recommended to be attached to a dashboard (A14) or placed in a glove compartment (A2). A second reference was also made here to pushing children out of the vehicle ahead of adults (A18).

Rescue personnel gave specific survival advice in two of the programs. In the first, the Miami-Dade Dive Rescue use the acronym "POGO" to advise: Pop your seatbelt; Open the windows; and Get Out (A14). It is interesting that under the stress of the first trial in this program, the reporter forgot to unfasten his seatbelt and this prevented his first exit attempt. This emphasizes the importance that advice to the public must not only be simple, but easy to remember; Table III summarizes exit advice from various sources. The Milford Police Department use slightly altered recommendations: first unfasten the seat belt; then roll down the window; unlock the car door; and climb out (A19). Presumably the door should be unlocked in case it must be opened later when the vehicle is full of water, or to allow easy access to outside personnel during rescue or, more likely, during recovery.

Three important issues emanate from these demonstrations. First, the danger of using cell phones to call for help was emphasized. There are several cell phone calls on record; in most cases, the callers later drowned. Emergency dispatch protocols should be adjusted so that the focus, with a call from a vehicle in water, should shift from finding out the location to advising the caller to get out as soon as possible and how to do so. Second, the importance of unfastening seatbelts was supported by the fact that many vehicle submersion drowning victims are found with the windows open but seatbelts still fastened (A14). Finally, although three of the programs concluded that window exit on the surface was preferable, several exits were purposely delayed until vehicles were full of water; in fact, Mythbusters (A13) did not even show a surface exit. Thus, the message of delaying exit might be reinforced for the public by these entertaining and memorable trials.

REFERENCES

A1. Allen N. Dozens dying in Russia cold but believers still take an epiphany dip. 2006; retrieved 17 July 2012 from http://www.google.ca/url?sa=t&rct=j&q=dozens%20dying%20in%20russia&source=web&cd=1&sqi=2&ved=0CCIQFjAA&url=http%3A%2F%2Fwww.telegraph.co.uk%2Fnews%2Fworldnews%2Feurope%2Frussia%2F1508246%2FDozens-dying-in-Russian-cold-but-believers-still-take-an-Epiphany-dip.html&ei=4xpET9CcBOLH0AGcu_3hBw&usg=AFQjCNF7N6DWyfUTsG2K6dHUaFhTy6_H0g&cad=rja.

A2. Anderson Cooper 360 Degrees [videorecording]. Atlanta, GA: CNN News; 2005 May 26.

A3. Associated Press. Smith convicted of murder. Gadsden, AL: The Gadsden Times; 1995 June 23; Sect. A:2.

A4. Breeden J. Trucker who pulled women from flooded car an 'angel'. Little Rock, AR: The Trucker; 2006 December 4; News Section.

A5. Canadian Red Cross Society. National Drowning Report: Visual Surveillance Report: an analysis of drownings and other water-related injury fatalities in Canada for 1997. Ottawa, ON, Canada: Canadian Red Cross Society; 1999. Report No.: 1-55104-234-7.

A6. Clark M. Sink to your death: agencies do little to ensure motorists escape sinking cars. 2010; retrieved 17 July 2012 from http://www.naplesnews.com/news/2010/dec/11/florida-drown-car-canal-lake-fatal-Mary-Catania/.

A7. Drowned brothers struggled to escape sinking car. 2005; retrieved 17 July 2012 from http://www.smh.com.au/news/national/drowned-brothers-struggled-to-escape-sinking-car/2005/09/05/1125772465568.html.

A8. Government of Canada. Fatal accident to passenger vehicle involving the ferry "Queen of New Westminster". Departure Bay, BC: Transportation Safety Board of Canada; 1992. Report No: M92W057.

A9. Hixson J. Rescuers pull woman, dog from submerged car. Plano, TX: Star Community Newspaper; 2006 November 7; Community News Section.

A10. 'I'm drowning,"and the phone went dead. 2006 February 7th; retrieved 17 July 2012 from http://asianfanatics.net/forum/topic/202907-im-drowning-and-then-phone-went-dead/.

A11. Manitoba flood claims driver's life. 2011; retrieved 17 July 2012 from http://www.cbc.ca/news/canada/manitoba/story/2011/04/09/manitoba-floodway-homes.html.

A12. Mother, son perish in icy canal plunge: a mother and her four-year-old son desperately tried to escape their SUV after it plunged into a canal north of Toronto, but emergency workers were too late to save them from the submerged vehicle. 2006; retrieved 17 July 2012 from http://www.canada.com/cityguides/toronto/story.html?id=02ddfdfe-5f39-43bd-aef2-244d7bb38b8d&k=33869.

A13. Mythbusters, Episode 72: underwater car [videorecording]. Silver Spring, MD: Discovery Channel; 2007 January 24.

A14. NBC Dateline: Life on the line [videorecording]. New York: National Broadcasting Company; 2001 February 27.

A15. NBC 24 Hour News 8. Two teens saved from sinking car in Ottawa County [videorecording]. Lancaster, PA: National Broadcasting Company; 2006 March 13.

A16. Orphan D. Cheating death; how to escape from a submerged automobile. Today's Health; 1961 June; 38-9, 82 Note, headquartered in Chicago, published by the Am Med Assoc.

A17. Preliminary autopsy shows North Dakota college students drowned. 2009; retrieved 17 July 2012 from http://www.trurodaily.com/Living/Education/2009-11-07/article-821845/Preliminary-autopsy-shows-North-Dakota-college-students-drowned/1.

A18. Road Rebels. Great escapes [videorecording]. Virginia Beach, VA: Video Atlantic Teleproductions; 1996.

A19. Sastre JR. Handling submerged vehicle incidents. 2001; retrieved 17 July 2012 from: http://www.911dispatch.com/video/miami/powerphone.html.

A20. T.B.S. Worst Case Scenario. How to escape from a sinking car [videorecording]. Atlanta, GA: Turner Broadcasting System; 2002 July 31.

A21. The Oprah Winfrey Show. What should you do? [Videorecording.] Chicago, IL: Harpo Productions, Inc; 2003 July 15.

A22. Three drown in SUV accident. 2004; retrieved 17 July 2012 from http://files.embedit.in/embeditin/files/BMgR6dJBy6/1/file.doc.

A23. Young heroine challenges icy river to rescue family. 2006; retrieved 17 July 2012 from http://www.evangelicalnews.org/indiv_pr.php?pr_id=7592.