My Car Is Sinking: Automobile Submersion, Lessons in Vehicle Escape

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Introduction: In North America ~400 individuals per year die in submersed vehicles, accounting for 5–11% of all drownings. About half of people surveyed would let the vehicle fill with water before attempting exit. ***Methods:*** We used a crane and two passenger vehicles of the same make, model, and year—one with passenger compartment intact (I) and one with holes (H) in the floor (area~2200 cm^2)—to conduct occupied and unoccupied submersions. ***Results:*** Three phases of submersion were identified: 1) FLOATING, vehicles floated for 15 s (H) to 63 s (I) before the water reached the bottom of the side windows; 2) SINKING, the subsequent period until the vehicle is completely under water, but before it fills completely; and 3) SUBMERGED, the vehicle was full of water and several feet below the surface. Total time to submersion was 150 s for I but only 37 s for H. Opening the door to exit Vehicle I decreased submersion time from 150 to 30 s. Even the most difficult exit strategy attempted (three men and a child manikin through one window) was quickly performed from Vehicle I (only 51 s). During one exit attempt, initiated during the sinking phase, it was impossible to open the doors or windows until the vehicle was completely full of water. ***Conclusions:*** A vehicle is most easily exited during the initial Floating Phase. We suggest the following escape procedure: SEATBELT(s) unfastened; WINDOWS open; CHILDREN released from restraints and brought close to an adult; and OUT, children should exit first.

Keywords: traffic accidents, highway safety, drowning, exit, egress, underwater, fatality.

SUBMERSED VEHICLES account for approximately 400 deaths in North America annually. Vehicle submersions have one of the highest mortality rates of any type of single-vehicle accident, accounting for 5–11% of all drownings in several industrialized nations (**Table I**) (5).

Few research studies address the topic of human escape during vehicle submersion (1,11) and they are generally epidemiological in nature. Although egress from helicopter simulators has been well studied these data are not completely relevant for automobile drivers. First, helicopter egress training prepares for the cockpit to roll over soon after impact, while automobiles are generally stable in the water (if windows remain intact they will even right themselves from an inverted position) (8). Thus, training which focuses on an inverted position is not relevant for most automobile scenarios. Second, where helicopter egress training is common (i.e., for transport to offshore oil platforms), passengers are generally mandated to take initial in-depth training and to review emergency procedures before each flight. This is in contrast to virtually all automobile passengers who have no in-depth training or any reviews. Also, for this latter group, advice must be simple, direct, and easy to remember.

A review of educational and public service information, plus a university student survey identified three probable 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 generally describe vehicle characteristics in water with only one variable, "flotation time." This includes the entire period from when the vehicle lands in the water until it is completely submersed (3). However, our preliminary trials indicated that conditions, and chance of survival, change considerably during this inclusive period and should be described more effectively to reflect different phases.

Second, several sources advise the public to stay in the vehicle and take actions such as: let the passenger compartment fill with water so that it will be easier to open the doors; wait until the vehicle hits the bottom in order to maintain orientation; kicking out windshields; opening the door to exit; having tools for breaking the windows but placing them in the glove compartment or under the seats; and reliance on breathing air that is 'trapped' in the passenger compartment (7,9). Many of these questionable ideas and practices are reinforced in the popular media (9,10).

Third, many individuals identify with some escape option that involves staying in the vehicle while it fills with water or even until it sinks to the bottom (5). These strategies would seem to decrease the chance of survival since the vehicle would be well below the water surface before it fills up with water, pressure is equalized, and the door can be opened. Additionally the passenger would have only one chance to complete a flawless escape after taking a "last breath" as the vehicle fills with water.

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TABLE I. VEHICLE DEATHS IN WATER REPORTED AS A PERCENTAGE OF ALL DROWNING DEATHS AND ALL VEHICLE DEATHS.

Country (year)	Drownings in Vehicles	% of all Accidental Drownings	% of all Vehicle Fatalities
Canada (1997)	56	10.0	2.2
New Zealand (1977-93)	18	11.4	4.7
Norway (1999)	78	11.0	2.3
Finland (1997)	17	5.6	3.9
USA (1999)	350	10.0	1.0
United Kingdom (2002)	20	4.7	0.6

Thus there seems to be a significant need for research focused specifically on automobile egress, as we believe that many drownings could be avoided if the public had more accurate information regarding this challenge. *Operation ALIVE* (Automobile submersion: Lessons In Vehicle Escape) was aimed at providing information on how people can deal with different exit challenges that occur with different types of vehicles in summer and winter conditions.

This report summarizes experiences and observations from several vehicle submersions with volunteers attempting egress. The goals were as follows: 1) to confirm passenger car sinking characteristics and factors that might affect these characteristics; 2) to determine ease or difficulty of vehicle egress under different conditions; 3) to determine how quickly various subject groups can exit a vehicle before it sinks; and 4) to propose an educational approach to decrease the fatality rate for these accidents.

METHODS

In *Operation ALIVE* a crane was used to conduct repeated vehicle submersions with the vehicle either unoccupied or with trained volunteers attempting various exiting strategies throughout the submersion process. The submersion protocols were approved by the University of Manitoba Education Nursing Research Ethics Board. All submersions were video taped for later analyses. Testing was conducted on one occasion in the ocean at Homer, Alaska, in summer, and on two occasions in a quarry near Winnipeg, Manitoba, in fall and winter. A total of 35 vehicle submersions were conducted with two different 1992 Ford Tempos. Both vehicles had manual window cranks. Although most current vehicles have electronic windows, repeated trials would not be possible with these windows, as the electronics would fail during the first trial and remain inoperative during subsequent trials. In the first vehicle, used in Alaska, the passenger compartment was intact (I). In the vehicle used for the later two sessions in Manitoba, the floor had rust holes (H) with a total area of ~2200 cm^2 (350 in^2). After the first unoccupied immersion with Vehicle H, the visible holes were sealed as much as possible.

Vehicles were rigged in such a way that they could either sink completely free of the crane restraints, or under continuous control of the crane. In the former condition, the connection to the rear of the car was permanent. The connection to the front of the car could be disconnected once there was slack in the rigging. Thus, the cars could sink in a normal evolution (i.e., with a forward tilt) but still be raised at any time. This report describes 14 immersions in these sinking conditions. In the latter case, all rigging remained connected and the vehicle could be kept at any level in or under the water. In this condition 21 immersions were completed as various rescue services personnel were allowed to practice scenarios without the time constraints imposed by allowing the vehicles to sink; these trials are not presented here.

In trials involving volunteers the vehicles were equipped with scuba tanks attached in the front and rear of the passenger compartment. Air regulators were secured with two in the front and two in the back. All eight volunteers were trained scuba divers who practiced, and were prepared for, breathing from the emergency air sources within the car if they could not exit the vehicle as planned. The vehicles were never completely disconnected from the crane so they could be raised from the water at any time. Also, two trained safety scuba divers were positioned just outside and/or inside the vehicles to provide assistance if required. In the case of a crane failure, divers were prepared to either open a door or break a window in order to assist the subject(s) to exit. In Alaska, the safety divers were U.S. Air Force parajumpers. In Manitoba, they were members of the Canadian Amphibious Search Team. When scenarios involved a child in a child seat, a child manikin was used. In winter trials, subjects wore thermal insulation under dry suits since thermal stress was not the focus.

Trials were conducted to determine: vehicle submersion rates under different conditions (i.e., with and without holes in the floor, and with the door closed and open); and various combinations of subjects exiting through one or two windows, and the effect of delaying exit.

Due to the difficulty and complexity of the trials, only a small group of volunteers participated, making it impractical to have several volunteers repeatedly participate in several scenarios. Rather, most scenarios were attempted once or twice. Therefore, results reported below are for one trial in each condition and are not suitable for standard statistical analysis.

Finally, two surveys of students at the University of Manitoba were conducted to see what they would do "if their vehicle ended up in water." The first survey of 52 students was conducted near the beginning of *Operation ALIVE* in the fall of 2006. The same question was recently (winter 2010) asked of 143 students; this followed the recent tragic deaths of three young women in a submerged vehicle (4), which resulted in media dissemination of many of the *Operation ALIVE* findings and recommendations. A Chi-square analysis was conducted to determine if results of the second survey were different from the first one.

RESULTS

Public Perception:

Fig. 1 indicates that in 2006, just over half of respondents indicated they would exit immediately through the window. The remaining students indicated other strategies that involved delayed exit and letting the vehicle fill with water; these strategies likely reduce the chance of survival greatly. Surprisingly, there was a shift in responses in 2010. The choice of rapid exit through windows increased from 52% (2006) to 76%, while strategies that delayed exit until after the vehicle fills with water decreased from 48% (2006) to 34% (Chi-square, $P < 0.01$). Thus, there may have been some local effect of increased public awareness and education about this topic.

Car Sinking Characteristics

At the beginning of each set of trials, the vehicle was allowed to freely sink while its attitude and sink rate were determined. Vehicle H sank much quicker than Vehicle I. After the initial submersion of Vehicle H, the holes in the floor were sealed and the trial was repeated (**Table II**). Complete submersion took 150 s in Vehicle I, but only 37 s in Vehicle H; sealing the holes increased this time to 71 s. Thus, Vehicle H still sank in less than half the time than required for Vehicle I. This likely indicates that the entire passenger compartment lacked integrity in several areas that were not visible and/or accessible for repair.

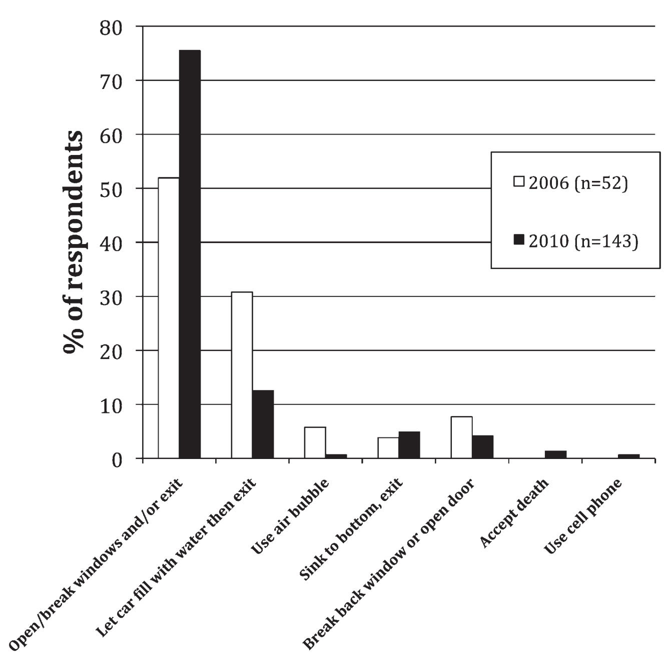

Fig. 1. Responses from university students before and after *Operation ALIVE* ($N = 52$ in 2006; $N = 143$ in 2010) when asked what they would do if their vehicle was in the water (Chi-square, $P < 0.01$).

In the first set of trials (Alaska, Vehicle I), the driver door was forced open in one trial (this can only be done if it is initiated immediately before too great a pressure gradient builds up outside the door). Opening the door reduced the time until complete submersion from 150 s to 30 s (it actually took only 11 s for submersion once the door was opened) (Table II). Importantly, the door forcefully slammed shut due to a rapid pressure buildup as the vehicle submerged quickly.

According to Table II we concluded that passenger vehicles pass through three distinct phases after contacting the water: FLOATING Phase, until the water reaches the bottom of the side windows; SINKING Phase, when water rises above the bottom of the side windows and the water level outside is higher than the level within the passenger compartment; and SUBMERSION Phase, when the vehicle is completely below the water surface and almost filled with water.

Ease of Vehicle Egress

The water level was always lower inside the vehicle until it was full. If exit was attempted before the water rose above the bottom of the side windows, the manual windows could be opened and egress through the window(s) was easily achieved. In one trial, exit was delayed until the water level rose above the side windows (SINKING Phase). In this case the outside-to-inside pressure gradient made it virtually impossible to open the door(s) or roll down the window(s) because it was being pushed against the window frame. The subject had to wait until the passenger compartment was almost completely full of water before a window could be opened.

We have heard suggestions that if the window is open but water is flowing in, escape should be delayed until the vehicle is full of water because it is not possible to exit against the inflowing water. In three trials the driver side window was opened and exit was delayed until

TABLE II. VEHICLE SINKING CHARACTERISTICS.

Submersion Trial	Floating Time (s)	Sinking Time (s)	Total Time to Submersion (s)
Vehicle #1 (I)*—Passenger compartment intact (Doors and windows closed)	63	87	150
Vehicle #1 (I)—Driver door forced open	9	21	30
Vehicle #2 (H)†—Passenger compartment holes in floor area ~2200 cm^2 (Doors and windows closed)	15	22	37
Vehicle #2 (H)—Passenger compartment visible holes repaired (Doors and windows closed)	26	45	71

* I = Intact: passenger compartment intact (trials conducted in Alaska).
† H = Holes: holes in floor (trials conducted in Manitoba).
Data are for one trial in each condition.

maximum inflow of water occurred. In each case, the subjects were able to exit against the flow without significant impediment.

Speed of Egress

These trials were conducted during the FLOATING Phase in which the water had not yet reached the bottom of the side windows. Several trials included one or more subjects exiting through one or more windows. Escape times are presented in **Table III**. When passengers had an appropriate response planned, exit could be accomplished quickly. One passenger exited one window in as little as 10 s, while the most difficult scenario (2 front passengers, one rear passenger with a child manikin in a child-seat) exited a single driver side window in only 51 s; this occurred within the vehicle's FLOATING Phase (63 s). Importantly, the most difficulty in this trial was experienced while attempting to unfasten the child-seat restraint.

DISCUSSION

To our knowledge, this series of trials is the first systematic vehicle submersion study using human subjects participating in multiple scenarios. It was much easier to exit early when the vehicle was still floating. As well, two surveys of university students in Winnipeg were conducted before and after *Operation ALIVE*, and subsequent to a high profile local vehicle submersion tragedy in North Dakota (4). Results revealed a shift toward a preference to exit a vehicle early through the windows. These preliminary results suggest a possible benefit for a larger education and research program on this topic.

Vehicle submersion trials showed that opening a vehicle door once the vehicle is in the water greatly increases the sinking rate, and results in the door being forcefully shut, potentially endangering the escaping passenger, or trapping others inside the vehicle as it rapidly sinks. These trials also demonstrated that a vehicle passes through the following three phases during submersion (6) (**Fig. 2**):

1) Floating: Initially a vehicle floated for 15 to 63 s before the water reached the bottom of the side windows, which provides ample time to exit the vehicle. During this phase windows can be easily opened and used for exit. The doors should never be opened because this allows rapid influx of water and could cause the vehicle to submerge very quickly— i.e., within seconds. Normally there is adequate time to escape during this phase even in restricted scenarios (i.e., several passengers and only one functional window) as long as the proper procedure is initiated immediately.
2) Sinking: The SINKING Phase extends from the time when the water rises above the bottom of the side windows to when the vehicle is completely under water. During this period occupants can breath as water is still rising inside the vehicle. However, the water level is higher outside, which exerts pressure against the doors and windows and makes them very difficult or impossible to open. As the vehicle fills with water, it tilts engine-end down into an almost vertical position. The chances for escape and survival are virtually nil during this phase unless an implement is used to break a window; this could be very dangerous as shattered glass would be forcefully propelled inside the vehicle and could cause serious injury.
3) Submerged: The vehicle is beneath the water surface and remaining air rapidly exits through the car trunk; this can occur either before or after the vehicle lands on the bottom, depending on the water depth. If the vehicle is full of water and on the bottom, the chance of survival is very low.

Our test vehicles floated for 15 s (H) to 63 s (I) before water reached the bottom of the side window. We demonstrated that the latter condition (an intact passenger compartment) provides enough time even for fairly complicated scenarios as long as subjects were prepared for what to do. Alternatively, it is difficult or seems impossible to exit a vehicle once it has reached the SINKING Phase due to the greater pressure on the outside of the vehicle.

The volunteers in this study did not specifically practice for these trials, however, they were similarly trained in other areas and were well prepared. Thus their performance would be expected to be better than those of the general public. However, escape actions are not technically difficult if they are initiated early during the floating phase. This emphasizes the importance of informing the public of these findings so that proper responses become second nature. This would greatly increase the probability of persons initiating the proper exit strategies when faced with an emergency situation with little time to rationally think of a course of action. Clearly the best time to escape from a vehicle is immediately during the initial floating phase. The following escape sequence should be followed: Seatbelts; Windows; Children; Out.

This means: Seatbelt(s) unfastened; Windows open; Children (if present) released from restraints and brought close to an adult who can assist in their escape; and Out; children should be pushed out of the window first, and followed immediately. Additionally, it is important

TABLE III. VEHICLE EXIT TIMES FOR VARIOUS SUBJECT/ROUTE COMBINATIONS.

Subject(s)	Exit Route(s)	Total Exit Time (sec)
* Driver	Driver side front window	10
* Driver, Front Passenger	Driver side front window	22
† Driver, Front Passenger, Rear Passenger	Driver/Passenger front windows	12
† Driver, Front Passenger, 2 Rear Passengers	Driver/Passenger front windows	29
* Driver, Child in rear car seat	Driver side front window	18
† Driver, Front Passenger, Child in rear car seat,	Driver/Passenger front windows	26
* Driver, Front Passenger, Rear Passenger, Child in rear car seat	Driver side front window	51

* Alaska trials;
† Manitoba trials. Data are for one trial in each condition.

Fig. 2. Three phases of vehicle submersion: Top, floating; Middle, sinking; and Bottom, submerged (Manitoba, winter trial).

for anyone using child restraint seats to become completely familiar with how to rapidly release the restraints. Most car seats have a push button seatbelt-type of buckle, which is easy to release. However, many also include a plastic connector that keeps the upper straps together in the chest area. In our trials, it was very difficult to release this connector, especially under stressful conditions.

It is important to note that these results regarding timing are only relevant for passenger cars, as heavy machinery is less likely to have a significant FLOATING Phase (i.e., a five ton truck snow plow sinks within seconds; unpublished observations). Opening electronic windows may be problematic. Since the mid-1990s vehicles were manufactured so that electronic window motors could work for up to 3 min once submerged (3). However, in the recent years changes in the electronic control systems often result in failure upon water exposure, preventing the motors from functioning, sometimes within a few seconds (2). In toto these results indicate the best exit route is through the side windows and that the only way to guarantee exit through windows is to break them. Thus, we recommend that a window-breaking device be mounted visibly in the passenger compartment for quick access. Examples include a spring loaded center punch or an escape hammer; the Netherlands government is currently recommending the latter device (2).

Finally, a growing trend in our society is the tendency to call 911 during an emergency (4), with this process being easier with the increased popularity of the cell phone. The standard 911 Operator response to an emergency call is to gather information about the situation including location of the accident so help can be dispatched. In the case of vehicle submersion, valuable time is wasted as it likely takes more than 60 s to make a cell phone call and provide details and directions; a period that precludes the victim from escaping during the simpler and safer FLOATING Phase. As well, there is no rescue system that guarantees arrival on site within 1 minute, which would be required to even attempt successful rescue.

We suggest that public education focus on immediate self-rescue through side windows during the FLOATING Phase. Also, 911 response protocols should be developed specifically for vehicle submersion cases in which the operator should focus attention on instructing the victim that they must open or break the windows and exit the vehicle as quickly as possible.

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