An automatic window opening system to prevent drowning in vehicles sinking in water

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An automatic window opening system to prevent drowning in vehicles sinking in water

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Abstract: **Objective:** Every year about 400 people die in submersed vehicles in North America and this number increases to 2,000–5,000 in all industrialized nations. The best way to survive is to quickly exit through the windows. An Automatic Window Opening System (AWOS; patent protected) was designed to sense when a vehicle is in water and to open the electric windows, but only when the vehicle is upright. **Methods:** The AWOS consists of a Detection Module (DM), in the engine compartment, and a Power Window Control Module (PWCM) inside the driver’s door. The DM contains a Water Sensor, a Level Sensor and a Microcontroller Unit (MCU). The Level Sensor provides the angular orientation of the car using a 3-axis acceleration sensor and prevents automatic window opening if the car is outside the orientation range (±20° in the roll axis, ±30° in the pitch axis, with a 2 s delay). Systems were installed on two cars and one SUV. A crane lowered vehicles in water either straight down (static tests) or by swinging the vehicles to produce forward movement (dynamic tests). **Results:** In all tests, when the vehicles landed upright, windows opened immediately and effectively. When vehicles landed inverted, or at a very steep angle, the system did not engage until an upright and level position was attained. **Conclusions:** This system may help decrease drowning deaths in sinking vehicles. If occupants do not know, or forget, what to do, the open window could hopefully prompt them to exit safely through that window.

ABOUT THE AUTHOR
Gordon Giesbrecht, PhD, professor of thermophysiology at the University of Manitoba, started Operation ALIVE (Automobile submersion: Lessons in Vehicle Escape) in 2006. He has performed >150 vehicle submersion tests (most with people in them) to research vehicle sinking characteristics, and exit routes and strategies to prevent vehicle drownings. Dr Giesbrecht has published seven papers on the topic and rewritten emergency response protocols for 9-1-1 operators for vehicles sinking in water and stranded in floodwater. These protocols are used in 60% of the English-speaking world and in many other languages. The survival advice, is to perform your own self-rescue rather than wait for rescue personnel to arrive. Simple instructions include four main words: SEATBELTS off, WINDOWS open, OUT immediately, CHILDREN first. This paper introduces an Automatic Window Opening System that opens electric windows when a vehicle is in water. This system should prevent many vehicle drownings.

PUBLIC INTEREST STATEMENT
Each year in North America, over 400 people drown in vehicles which sink in the water. Vehicle sinking accounts for up to 10% of all drownings in North America and likely claims between 2,000–5,000 lives in all industrialized nations. Most victims are uninjured during impact with the water, and drown simply because they do not know, or forget, that to survive they just have to open their side window and exit the vehicle. To ensure vehicle occupants have a guaranteed exit when their vehicle is in water, an AWOS was developed and tested. It senses when a vehicle is in water, and then signals electric windows to open. Therefore, even if occupants do not know, or forget, what to do, the open window would hopefully prompt them to exit safely through that window. This system has great potential to save many lives in sinking vehicles.
1. Introduction

Every year, about 400 people die in submersed vehicles in Canada and the United States, accounting for up to 10% of all drownings (Canadian Red Cross Society, 1999; Wintemute, Kraus, Teret, & Wright, 1990). Vehicle submersion has one of the highest fatality rates of any type of single-vehicle accident (Baker, O’Neill, Marvin, & Li, 1992; SWOV, 1973) and, according to drowning statistics from the World Health Organization, may claim up to 2,000–5,000 lives annually when all industrialized nations are considered.

What makes these deaths so tragic is that unlike other fatal vehicle tragedies (e.g. head-on collisions) or weather disasters (e.g. tornados), most vehicle submersion fatalities are preventable; the cause of death is usually drowning and not trauma (Wintemute et al., 1990).

In most vehicle submersion scenarios, the only way to survive is to exit through the side windows, which need to be opened or broken within about one minute of the vehicle impacting the water (Giesbrecht & McDonald, 2010). Unfortunately, many occupants make bad decisions such as making cell phone calls for help, trying to open the doors, waiting for the vehicle to fill with water so they can then open the doors, or taking no action at all because they panic or don’t know what to do (McDonald & Giesbrecht, 2013).

Operation ALIVE (Automobile submersion: Lessons In Vehicle Escape) has produced two initiatives to decrease automobile submersion drownings. Public education advice has been developed to advise the following, “Don’t panic, do not touch your cell phone and remember four actions: SEATBELTS off, WINDOWS open or broken, CHILDREN oldest to youngest, OUT immediately” (McDonald & Giesbrecht, 2013). Also, two emergency dispatch protocols (e.g. used by 9-1-1 dispatchers) have also been developed for “Vehicle in Water” (Giesbrecht, 2016a) and “Vehicle in Floodwater” (Giesbrecht, 2016b) scenarios.

Successful calls for rescue from within sinking vehicles to emergency dispatch are rare and most of the time vehicle occupants are dependent on their own quick actions if they are to exit and survive (Giesbrecht, 2016a). This requires the following: remembering what to do in the time of crisis (e.g. knowing that side windows should be opened, or broken); and actually taking the proper actions to open or break the side windows and exit through them immediately.

Many individuals simply do not know what to do in highly stressful emergency situations like vehicle submersion, while for those who have heard what to do, memory and execution are often poor (Leach, 1994). Therefore, many lives could be saved if a system could sense that a vehicle is in water and then automatically open the electric side windows. Such a device would reduce the need to remember, or execute, opening a window and thus provide the lifesaving exit route. If occupants do not know, or forget, what to do, the open window could hopefully prompt them to exit safely through that window.

This paper describes the development and testing of an Automatic Window Opening System (AWOS; patent protected) that could potentially prevent many vehicle submersion drownings worldwide each year by automatically providing an exit through which occupants can escape and survive.

2. Methods

2.1. Considerations for system design: Vehicle sinking characteristics

An upright floating vehicle may take 2–4 min to completely submerge below the water surface, however occupants have only one minute (The Flotation Phase) during which escape is possible...
(Giesbrecht & McDonald, 2010). During this period, water is rising against the doors, preventing them from being opened, however windows can still be opened and occupants can exit through them. After the first minute or so, the water rises up against the windows exerting enough pressure to prevent them from being opened as well (Sinking Phase). From this point on, although there is still air in the passenger compartment, none of the doors or windows can be opened and the occupants are confined to death through drowning.

Cars and pickup trucks are inherently stable in the upright position because of the mass and low position, of the motor. Therefore, if passenger vehicles land in the water upside down, and the windows are closed and remain intact, the vehicles will eventually right themselves by rolling in the x axis. Likewise, vehicles landing in water at a steep pitch (angled in the y axis) will also eventually settle in the upright position. Even at a steep pitch of up to 60° or more, from horizontal, a vehicle will penetrate the water and then bob back up in the upright position and enter the Flotation Phase. All of these factors need to be considered in the design of an AWOS.

2.2. Required features for window opening system

The first design question was how the window exit should be established. One option was for the system to break the windows. However, it was determined that it was more efficient and effective to open, rather than break, the windows for several reasons including:

1. If a window-breaking system is tested or activated accidentally, both the windows and the breaking system will need to be replaced.
2. The breaking system would be more costly initially, and would have to be checked, maintained and replaced regularly.
3. There is more danger of injury from broken glass.
4. The trend for manufacturers to transition from tempered to laminated polycarbonate glass in side windows will render window-breaking systems ineffective in the future.

Therefore, the window opening system should include the following features:

1. Rapid detection of water immersion by a sensor within the engine compartment.
2. Immediate activation of all side electric windows to open at their full velocity, but only once it is safe to do so (see next point).
3. Safety design to prevent windows from opening if a vehicle lands in water upside down or at a steep angle (scenarios which would initially allow water to rapidly flow inwards); the system should not engage until the vehicle recovers to an upright position.
4. Mitigation of false alarms by a sensor that differentiates between a water splash and actual immersion.
5. Option for automatic distress call initiated to an Emergency Call Center such as “OnStar” (if system is activated).
6. It must work on all conventional, hybrid and totally electric vehicles.
7. It must work on “standard” as well as “express down” electric windows.
8. The system can be installed during manufacturing or after-market.
9. System reliability can be quickly and easily checked by a certified mechanic.
10. Parts must operate in temperatures from -40 to 100°C.
11. The system must last for years and be robust.
12. Must not be activated by high humidity.
2.3. Systematic development and testing of the system

Two series of bench and field tests were conducted to confirm effective development of each system component and to test functionality in sinking vehicles; these development processes are described in this Methods section. Following this development phase, a final field test was conducted to evaluate the completed system under various conditions of submersion; the main results of this paper refer to this phase of testing (see Section 3).

2.4.1. Series 1

2.4.1.1. Bench tests. A system including a Detector Module (DM, i.e. a water sensor) and a Power Window Control Module (PWCM) was developed and tested by placing the DM in water and demonstrating that the PWCM activated an electric window motor. After successfully demonstrating the proof of concept, the two components were built into units that could be installed on a vehicle for field testing.

2.4.1.2. Field tests. Prototype systems were installed on two used cars at a gravel pit lake near Winnipeg, Canada. All fluids were drained from the vehicles and a crane was used to place the vehicles in the lake either by lowering them straight down into the water (static tests) or by swinging the vehicle into the water to produce forward movement (dynamic tests).

**Upright immersions**: In both static and dynamic tests, the windows opened immediately and effectively when the vehicles landed upright in the water. In each case the windows were open before water rose to the level of the windows and this would have provided time for occupants to exit before water flowed into the passenger compartment.

**Inverted immersions**: One test vehicle was statically lowered into the water in an inverted position. The windows opened quickly and the vehicle sank quickly while remaining in the inverted position. In this scenario, escape would have been unlikely due to a combination of the short time available and being in a disorientating inverted position.

In a second inverted trial, the window opening system was disabled. The windows remained closed and as expected, the vehicle eventually rotated in the $x$ (roll) axis into an upright position. At this point, the water level was still below the level of the windows and occupants would have had time to open the windows and exit before water ingress.

Thus, these trials further informed the design process to include the determination of the orientation of the vehicle, specifically in the $x$ (roll) and $y$ (pitch) axes prior to window opening. Since an airtight vehicle (i.e. with all windows closed and intact) will eventually right itself from an inverted position, a window opening system should not engage until the vehicle is upright enough that water will not flow in through the open windows. It was therefore decided that a Level Sensor should be included to prevent activation of the PWCM until both of two criteria were met: (1) the vehicle is within $\pm 20^\circ$ of upright horizontal in the $x$ axis, and (2) within $\pm 30^\circ$ of upright horizontal in the $y$ axis. This combination of roll and pitch angles forms a cone-shaped range of upright positions in which water will not be touching the windows, and therefore will not flow in when windows are open.

2.4.2. Series 2

2.4.2.1. Bench tests. A new DM was designed to include both a Water Sensor and a Level Sensor. The DM had adjustable activation thresholds for the $x$ (roll) and $y$ (pitch) axes which were initially set at $\pm 20^\circ$ and $\pm 30^\circ$ from upright horizontal position respectively. The new design also resulted in activation of an emergency signal (e.g. to OnStar if activated) if the Water Sensor was activated, and activation of the PWCM if both the Water Sensor was activated and both criteria for the $x$ and $y$ axes orientation were met.
Static submersion of the DM in different positions and dynamic submersions, in which the DM was submersed inverted and rotated in both the x and y axes, confirmed that the emergency signal was activated on submersion and that the PWCM was only activated if the submersed DM was also in the correct near-upright orientation.

2.4.2.2. Field tests. The new prototype was prepared for attachment to a single running vehicle for dynamic testing at a retention pond near Indianapolis, USA. The vehicle had a minimal amount of gas and the openings to all fluid lines and reservoirs (including the gas tank) were sealed to prevent contamination of the pond (this was confirmed after the trial was complete). The single test included driving the vehicle into the water at ~40 km/hr. The purpose was to confirm that the new system worked in an upright submersion, while also adding the realistic stresses of a rapid vehicle contact with the water. In this test, the vehicle windows were activated immediately on water contact and were fully open within 4 s of contact. In this case, some of the water that splashed up on vehicle contact actually came in through the open windows as the water descended back toward the lake. Although this amount was minimal and did not increase the rate at which the vehicle sank, this result revealed a potential need for a delayed activation for splash mitigation to allow the vehicle to first attain a stable upright position.

2.4.2.3. Final system design for field testing. Based on these final field tests, a final design was confirmed. Figure 1 shows a block diagram of the complete AWOS system which consists of a DM and a PWCM. The DM is housed in the engine compartment and is connected to the PWCM which is housed inside the driver's door.

Detector module: The Water Sensor detects the presence of water within the engine compartment using a capacitive sensor. The capacitive sensor is made from three round, copper plates and wires connected to them. There exists a certain capacitance when the sensor is exposed to air (normal) and it dramatically increases when it is exposed to water, since water has a significantly higher dielectric constant than air. It is made of an exterior ground plate, a guard ring and a sense plate.
Gaps separate the plates and form a capacitance. The capacitive sensor is connected to a relaxation oscillator which outputs a square wave with frequency proportional to the capacity of the sensor. When there is water near the surface of the sensor, the capacity increases significantly, which lowers the frequency of the square wave and the Microcontroller Unit (MCU) detects this variation. Submersion will be detected if the frequency coming from the oscillator is lower than a certain threshold frequency.

The DM enclosure is designed to prevent false alarms from water splashes. A strainer limits the water entry and a deflector prevents false alarms that would be due to water splashes. The water has to circulate through the holes and under the deflector to enter the reservoir and trigger the capacitive sensor. Thus, the system will detect water presence only when there is full immersion.

The Level Sensor provides the angular orientation of the car using a 3-axis acceleration sensor (micro-electro-mechanical system [MEMS]), which provides real time values of gravity for the 3 axes.

The DM is installed so the internal printed circuit board is parallel to the front of the car and facing the rear or the front of the car. This is to ensure the MEMS is properly oriented. The roll and pitch can then be zeroed; powering the Zeroed-Level signal for a specified time (i.e. 2 s).

The Level Sensor measures the orientation of the car to prevent automatic window opening if the car is outside the orientation range (initially set at ±20° in the roll axis and ±30° in the pitch axis).

The MCU executes the detection algorithm and interfaces with the various peripherals. It provides an output that is activated as soon as the water is detected. This output may potentially be used to activate a car security system such as OnStar™. Emergency services will then be alerted automatically. When both the Water Sensor and Level Sensor send appropriate signals, an OPEN transistor will be grounded and this will ground the coil of the PWCM relays and the 12 V will power the window motors.

The MCU will compute the frequency at each 0.1 s and as soon as a preset number of consecutive readings (ranging from 5 to 20 for delays ranging from 0.5 to 2.0 s) are lower than a certain threshold, the submersion flag SUBMERSION_FLAG will be set. Note that 5 to 20 is derived from SUBMERSION_DELAY.

The MCU may be programmed using the debug port with the Serial Wire Debugging protocol. The roll and pitch limit can also be programmed by this port. The ROLL_LIMIT and PITCH_LIMIT are changed in the software, then the software is compiled and then programmed into the MCU using the debug port. The MCU is calibrated once by powering the ZERO signal with 12 V.

**Power windows control module:** The PWCM is powered by the master switch 12 V supply (providing enough current to drive the power window motors). The PWCM overtakes the master power windows switch forcing all the electric side windows to open. It is located in the driver’s door allowing easy connection to the power window master switch. It does not interfere with normal functionality of power windows. The PWCM contains four single pole double throw relays which allow opening of four non-express-down windows. For each express-down window, two relays are required, so in some cars two PWCMs may be required to provide more relays. Power switches are activated for 10 s.
2.4.2.4. Final field tests. The upgraded window opening system was installed on two cars (2003 Chevrolet Malibu, 2003 Hyundai Elantra) and one SUV (2005 Ford Escape) at a gravel pit lake near Winnipeg, Canada. Again, all fluids were drained from the vehicles and a crane was used to place the vehicles in the lake. Four manikins were placed in the seats and a 27 kg weight was secured on the trunk floors to simulate fuel. The three four-door vehicles had either one, two or four ‘express down’ side windows with the remaining side windows being ‘standard’ windows.

High speed video was collected from the left, right and behind each vehicle. The Dartfish Video Analysis Software analysis program was used to analyze position and rotation in all axes and to determine the time between initial water contact and window opening. Values for the $x$ (roll) axis were defined as 0° (upright) to 180° (inverted) for rotation in either direction. Values for the $y$ (pitch) axis were defined as 0° (upright) to 180° (inverted) for forward (front down) rotation (none of the vehicles rotated in a backward, or front up direction).

Initial settings on the DM were set at ±20° from upright for the $x$ (roll) axis, and ±30° from upright for the $y$ (pitch) axis, with a 2.0 s delay from initial criteria confirmation until activation of the PWCM. This ensured that the vehicle was within a range of positions in which water would not flow in when windows were open, and this position was held long enough to ensure it was stable before windows opened.

3. Results
In this final series of field tests, each vehicle was lowered in the inverted position (Trials 1–3, Table 1). The cars took much longer to roll upright (Malibu, 32 s; Elantra, 48 s) than the SUV (Escape, 6 s); this difference is mostly because the increased height of the SUV results in; (a) greater buoyancy, and (b) its motor produces more rotational torque.

In all inverted immersions, the windows did not open unless, and until, the vehicles had rolled upright (see Figure 2). After the first trial, the delay was reduced from 2.0 s to 500 ms, and the activation threshold in the $x$ (roll) axis was increased from ±20° to ±25°. Subsequent trials confirmed that the windows did not open until the vehicles were upright and within the proper roll parameters (see Table 1).

In one trial a car was lowered into the water on its side. It first rolled upside down, and then rolled upright, before the windows opened (see Trial 4, Table 1).

One car was then lowered into the water in a steep (60° in pitch or $y$ axis) upright orientation (Figure 3). During initial submersion, the vehicle sunk enough to submerge the front doors and windows. The vehicle bobbed back upwards in an upright position. It levelled out and the windows did not open until the pitch angle decreased to 21.2°.

Finally, a car was lowered (inverted) into water at a depth of about 1.5 meters at the front of the car; this represents a scenario where a vehicle is inverted in shallow water such as a ditch (Figure 4). In this case the front of the car sank and contacted the bottom, thus preventing the vehicle from rolling to an upright position. The passenger compartment filled with water after about 2 min. The car was completely submersed, still inverted, after 4 min and 29 s.
In summary, all vehicles landing inverted in deep water, rolled upright when windows were closed and remained intact. The SUV started to roll upright immediately while the sedan-type cars started to roll within 28 to 37 s. Once a roll was initiated, the vehicles consistently took 5–6 s to complete rolling upright. The system worked properly as windows opened only in a generally upright horizontal orientation (maximum roll angle, 13° in the x axis; maximum tilt, 22° in the y axis). Water did not flow inward through windows in any test, however it is recommended that the delay be set at 2.0 s.
Table 1. Position and timing values for trials where vehicles were immersed in an inverted position in the water (level and upright is 0° in both pitch and roll axes). Threshold settings for window opening were: Trial 1—roll ± 20°, pitch ± 30°, delay 2.0 s; Trials 2 to 4—roll ± 25°, pitch ± 30°, delay 0.5 s

<table>
<thead>
<tr>
<th>Trial # and vehicle</th>
<th>Event</th>
<th>Roll angle (°)</th>
<th>Pitch angle (°)</th>
<th>Time from immersion (s)</th>
<th>Minimum freeboard (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Malibu</td>
<td>Initial immersion</td>
<td>168</td>
<td>154</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Initiation of roll</td>
<td>147</td>
<td>146</td>
<td>28</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Roll completion</td>
<td>8</td>
<td>18</td>
<td>34</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Windows start opening</td>
<td>5</td>
<td>12</td>
<td>36</td>
<td>0</td>
</tr>
<tr>
<td>2. Elantra</td>
<td>Initial immersion</td>
<td>176</td>
<td>157</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Initiation of roll</td>
<td>147</td>
<td>141</td>
<td>37.2</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Roll completion</td>
<td>8</td>
<td>20</td>
<td>42.8</td>
<td>–</td>
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<td></td>
<td>Windows start opening</td>
<td>11</td>
<td>15</td>
<td>43.6</td>
<td>−40</td>
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<tr>
<td>3. Escape</td>
<td>Initial immersion</td>
<td>162</td>
<td>151</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Initiation of roll</td>
<td>162</td>
<td>151</td>
<td>0</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Roll completion</td>
<td>11</td>
<td>7</td>
<td>4.9</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Windows start opening</td>
<td>13</td>
<td>8</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>4. Elantra (lowered on side, rolled to inverted)</td>
<td>Initial immersion</td>
<td>168</td>
<td>150</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Initiation of roll</td>
<td>142</td>
<td>140</td>
<td>35.5</td>
<td>–</td>
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<tr>
<td></td>
<td>Roll completion</td>
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<td>40.5</td>
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<tr>
<td></td>
<td>Windows start opening</td>
<td>12</td>
<td>22</td>
<td>40.1</td>
<td>5</td>
</tr>
</tbody>
</table>

Figure 3. Vehicle enters water at a steep pitch angle (~60° in pitch or y axis). It then rotates in the pitch (or y) axis to an upright level position. At the steep pitch angle >30° (top), windows remain closed and do not open until the pitch angle is <30° (bottom).
4. Discussion

An AWOS has been designed and tested to demonstrate that it can sense when a vehicle is in water and to open all electric side windows. The system will only open the windows if the vehicle is in a relatively upright and horizontal position to ensure that water will not flow in through open windows. Therefore, if a vehicle lands upside down, or at a very steep angle (both of which initially place windows under water) the system will not engage until an upright near-level position is attained. It is recommended that the thresholds for activation be set at ±20° in the x (roll) axis, ±30° in the y (pitch) axis, with a 2.0 s delay to prevent water ingress due to premature opening.

4.1. Potential limitations of the system

The window opening system cannot help if a vehicle lands inverted in shallow water (e.g., a ditch). In this case the vehicle cannot roll upright and sinks inverted. The only way to survive would be to break a window and exit, or if the water is shallow enough, wait for rescue in the portion of the vehicle that is above the water line (e.g. near the floor of the inverted vehicle). The system will also not be effective when the windows are open before, or become broken as a result of, impact with the water. If the vehicle lands upright, an effective window exit will already be established. However, if the vehicle lands upside down, water will rush in and the vehicle will sink quickly making it much more difficult, if not impossible, to escape.
A relatively new development in modern cars, particularly in Europe, is the Pyrotechnic Safety Switch. This battery disconnect switch is used to cut the power to the generator/alternator, and thus the engine, in accidents to prevent post-crash fires. This disconnect is usually triggered by the airbag control unit but does not actually disconnect battery power at the source. Therefore, in these vehicles, the AWOS will still function as long as the system power is connected prior to the battery disconnect switch.

5. Summary
A system has been demonstrated to sense vehicle water immersion and then open electric windows, but only if the vehicle is in a position that prevents rapid water inflow through the windows. The system can be easily installed during manufacture or after-market and will automatically provide an exit in a sinking vehicle at a time when it is likely that occupants will be paniced and less likely to think of the correct survival sequence which includes exiting through an open window as quickly as possible. Many lives might be saved by this system. If occupants do not know, or forget, what to do, the open window would hopefully prompt them to exit safely through that window.

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