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SLAMMING STANDARDS
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Slamming Standards

As awareness of impact injuries on high-speed boats grows, research and debate thrive in the quest for strategies to accurately measure slamming and for practical rules that will keep boaters safe.

Text by Johan Ullman
Graphics courtesy HSBO
(except where noted)

For generations, boaters have experienced the dangers of slamming at speed in rough conditions. Only relatively recently have the causes of injuries on slamming high-speed craft been the subject of more in-depth research, sponsored mainly by military and coastguard agencies in various countries.

Currently, a number of national and international regulatory and certification organizations publish specific standards intended to limit impact exposure on boat passengers and operators. While it is well known in the scientific community that acute injury in slamming events results from impact, not from vibration, most of these standards are based on different methods of reducing complex whole-body vibration (WBV) exposure data to simple single-figure values.

Why has WBV come into this equation?

The short answer is because in the absence of previous standards regulating or limiting exposure to impacts, the European Union committee chose the closest-to-equivalent ones they could find: ISO standards developed to limit exposure of vibration in trucks and forestry machines.

There's no question that exposure to vibration is not good. Vibration can cause various health problems including accelerated aging of spinal disks and cartilage. Those problems contribute to cumulative injuries that can weaken structures and increase the risk of acute injury. However, acute injury is most commonly triggered by impacts.

The most severe injuries caused by slamming in high-speed boats include fractures in vertebrae and extremities, and ruptures of intervertebral disks including those in the neck.

Distortions, chiefly sprains or tearing of soft tissue, are common too but

Above—It's not enough to engineer high-speed boat hulls, superstructures, and systems to endure the impacts of extreme slamming while under way; crew and passenger well-being must be considered as well. Impact injuries—fractured vertebrae, ruptured disks, sprains, and tearing of soft tissue—are increasingly the subject of research and regulation by private and government agencies in numerous countries.

A fast boat in motion even on a relatively calm sea is bafflingly dynamic, making it difficult to accurately predict the slamming loads passengers in a particular boat in particular conditions will be exposed to. It's safe to say that risk of acute injury is proportional to the level of energy absorbed from a particular slam, but accurately predicting the magnitude of any slam is practically impossible.



normally less serious, unless they hit the cervical spine (neck). Then they can act like whiplash injuries resulting in severe, permanent pain and disability. Any weight added to a head—helmets and night-vision goggles—increases the risk of impact-induced injury.

Pain is a physiological function that tells us what *not* to do, so it's a good rule of thumb for boat operators and passengers that anything that hurts is potentially injurious. It is wise not to travel in high-speed craft in such a way that causes severe discomfort or any pain, regardless of whether measured impacts register 4 g or 13 g.

Similarly, it's dangerous to assert that certain wave/wind conditions and directions are more dangerous than others. Head seas may result in harder slamming, but injuries can occur regardless of wave direction.

The risk of acute injury (structural failure of anatomic structures) is proportional to the level of energy absorbed from a particular slam, and the energy acting on the body is proportional to the acceleration level and duration of each impact. When compression or shear forces acting on the spine exceed the strength of its

structure, mechanical failure results. A single impact can cause such structural failure and injury in the body but might not register as potentially harmful under specific standards. The total number of impacts sustained in a certain time period is also relevant, as repeated shock loads seem to increase the risk of injury.

Standards

Let's take a look at the existing standards that might help boat designers and builders determine limits for *how much* and *what kind* of exposure is safe or dangerous.

European Union Directive 2002/44/EC is the law in all EU countries and applies to professionally operated boats, including those carrying paying passengers for transportation or sight-seeing.

The EU directive defines the maximum level of exposure you may subject employees or paying passengers to. These limit values are so conservative that they would normally

be exceeded within a few minutes traveling on a 32.8' (10m) boat at 35 knots in 2.3' (0.7m) waves.

So the claim that with this boat or that seat you will comply with the EU directive, it is just not true. More accurately, it will be true only if you don't leave the dock on a windy day.

The common work-around for boat builders and operators is to obtain a derogation from the EU directive. That can be granted only at the national level, and only on the condition that all reasonable measures are taken to reduce impact exposure. This includes, for example, using the proven best shock-mitigation technologies available. Note: The EU directive does not apply to privately operated pleasure boats, unless they carry paying passengers.

ISO 2631-1 is the original standard for whole body vibration. It is not relevant to slamming on high-speed vessels.

ISO 2631-5 is an updated and amended version of ISO 2631, with algorithms tweaked to give higher values if there are a significant number of high-level impacts in the registered vibration data. The problem is that it doesn't reveal much difference even when impacts are dangerously high. Single severe impacts disappear almost completely. This standard was never meant for, and should not be applied to, any boat producing impacts over 4 g.

Annex 10 of 2000 HSC CODE, International Code of Safety for High-Speed Craft is intended to assure that crew and passenger seats on boats and ferries do not break or detach from the deck during a collision or grounding. The limits for structural failure are lower than the forces acting on a high-speed boat during a severe slamming impact.



COURTESY KNRM

Especially for boats intended for offshore work in harsh weather conditions, designers tank-test slamming performance to quantify the loads the vessel's structure will need to tolerate, and by extension, the forces operators and passengers are likely to be subjected to. Here, a test model of the 62.3' (19m) NH 1816 rescue boat, built in 2013 by Damen Shipyards (Gorinchem, The Netherlands) for the Dutch sea rescue organization KNRM, is put through its paces.

Some of the most extreme slamming must be endured by military, rescue, and other government employees engaged in hazardous duties. This jet-powered 50' (14.9m) Combat Boat 90 (CB90), built for the Swedish special forces by Docksta Shipyard (Docksta, Sweden), can deliver to beach landings as many as 18 fully equipped soldiers at speeds up to 50 knots.



the instant of impact is averaged out over one minute.

VDV, or vibration dose value, is a single-figure value for cumulative exposure. The method is similar to RMS but takes each peak value to the power of 4. The root is then drawn out of the mean value over an 8-hour or 16-hour period. VDV can illustrate clear differences in exposure that completely disappear using RMS.

Crest factor is calculated by dividing impact peak values by the RMS value. This means the

higher the vibration level, the lower the crest factor shows. Crest factor increases with higher impacts; however, it indicates not the impact exposure but the *difference* between the impacts and the vibration.

Sed8 is defined as: "The human exposure for accumulated *spine stress dose*, normalized to an eight-hour exposure." It is another single-value unit based on the ISO 2631-5 standard.

ICI, or Impact Count Index, is a straightforward method for measuring impacts, counting them, and recording how high they were and how many. The ICI method is easy to understand and easy to use in exposure studies.

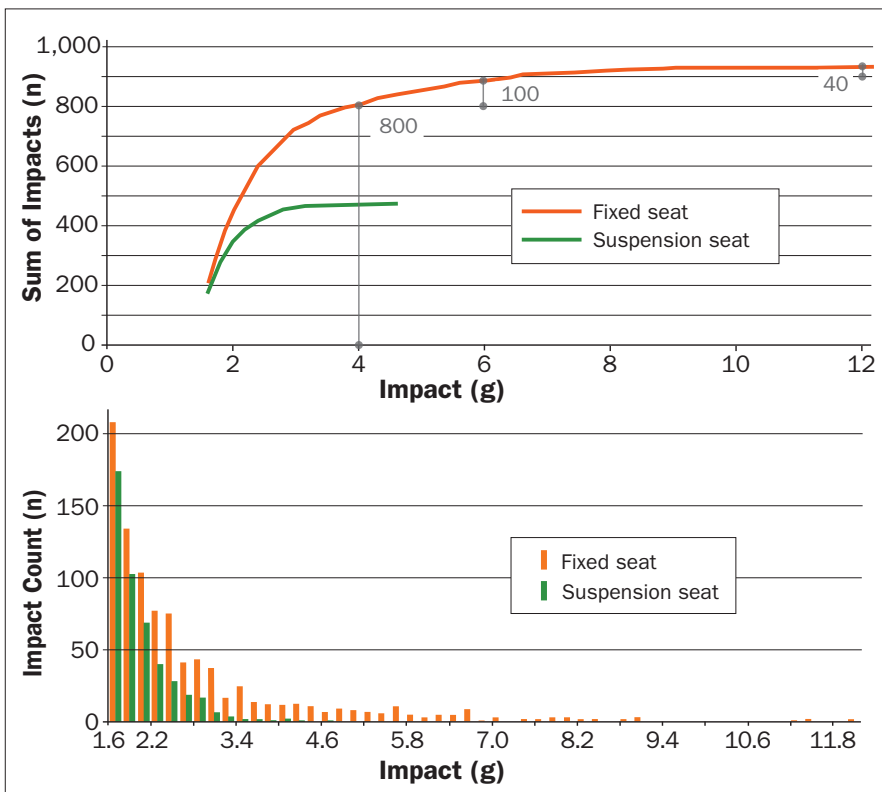
Seats claimed to comply with this standard are known to have failed, contributing to operator injury. This standard has no bearing on the shock-mitigating function or performance of suspension seats.

Maritime and U.K. Coastguard Agency Marine Guidance Note MGN 436 is a relatively new document (September 2011) based on new research and technologies. Its recommendations are relevant.

Common Terms and Units

The above standards can be largely defined by their dependence on a few scientific and regulatory approaches and terms.

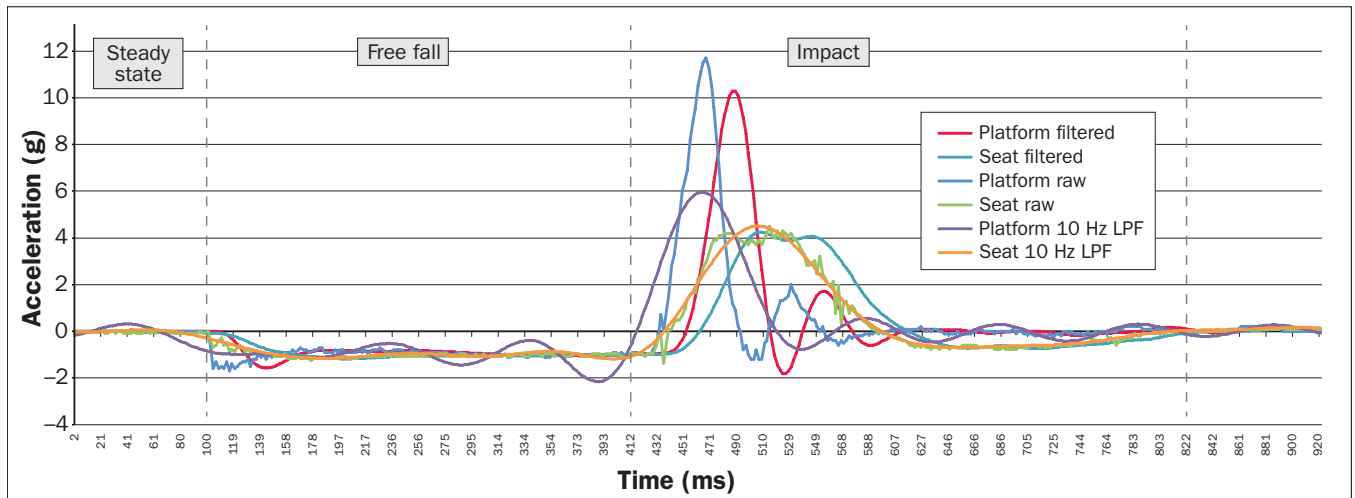
RMS, or root mean square, is defined as: "The square root of the arithmetic mean of the squares of a set of values, used as a measure of the typical magnitude of a set of numbers, regardless of their sign." In the context of these standards, RMS is applied as an average value of how much energy is transmitted through vibration over a period of time. RMS values do not say anything about single impacts and are normally not affected by single impacts. To illustrate the limitations of applying RMS value limits, it is worth considering that a fall from a sixth-floor window might not register as dangerous if the unbearably high-energy absorption of



Two representations of data gathered from all impacts in excess of 1.6 g on crew in two boats, one with fixed seats and one with suspension seats, running side by side for three hours:

Left—Cumulative number of impacts on the Y axis illustrates the efficacy of suspension seats in limiting exposure to high g. It also reveals that even in the fixed seats, the number of particularly hard slams is fairly low: just 40 between 6 g and 12 g, and 100 between 4 g and 6 g. About 800 of the 940 total impacts recorded on the fixed seats were between 1.6 g and 4 g.

Below left—A histogram of the same data affirms that the majority of impacts exceeding 1.6 g in both boats were at the low end of the spectrum, and amplifies the fact that a few particularly high g measures on the far right of the graph were recorded on the boat with fixed seats. Significantly, the same data presented in terms of vibration, root mean square, or vibration dose value revealed no significant difference in exposure between the two boats.



Graphing filtered and raw impact data of seat testing shows how even a good filter can somewhat skew specifics. The difference in magnitude of accelerations is as much as 10%, but there is also a slight displacement in time of the impacts, measured here in milliseconds. As commonly applied by some researchers, a low-pass filter (LPF) at 10 Hz reduces the 11.7 g raw platform impact (dark blue line) to just 5.9 g (purple line). This is why it's useful to retain original (raw) data even if filters are to be applied in the lab.

A limitation of ICI is that it is difficult to make absolute exposure assessments from measurements done on a single platform. For side-by-side comparison of impact exposure, however, today it is the most relevant method used.

POT (peak over threshold) is a useful way to quantify impact exposure. It is a calculation of the mean value of the highest 1% of all peak values of impacts exceeding an arbitrary threshold value such as 2.0 g; normally, impacts below 2 g are not perceived as very uncomfortable.

While there are no scientific experimental data linking any of the above values to definable injury risks, there is one great difference: ICI presents the actual recorded exposure data, which means that you can get an understanding for how high the impacts actually were, and also calculate the compression forces in discrete impacts. ICI also has good correlation to subjective rating of pain and discomfort. It has also been shown to correlate well to physical fatigue, which is assumed to increase the risks of injury. I believe it is a better basis for future, more relevant, standards.

Up for Debate

For the scientists and regulators striving to improve existing human-impact-exposure standards for high-speed boats, there are some subjects of continued debate and research:

Natural resonance of spine and thorax: As research historically has been focusing on vibrations rather than on impacts, the issue of natural resonance in certain parts of the body has received attention. Resonance can probably cause mechanical effects (structural fatigue) when a human body is subjected to a continuous vibration. There is no scientific support for the belief that the resonance frequency should be relevant for single impacts. A single impact does not start a vibration of the spine. Repeated slamming impacts of any relevant magnitude occur no more frequently than once per second.

Filtering: There is considerable debate over what the sampling rate should be for data collection, and whether and how to filter out higher frequencies from those data. Some researchers claim that impacts with frequencies higher than 10 Hz–30 Hz have no mechanical or physiological effect on the human body and should therefore be filtered out. Others, including myself, believe that they do, and hence should be recorded.

The soft tissue in the human body is, in itself, a low-pass filter (filtering out higher frequencies), but this doesn't mean that the high frequencies actually coming through should be disregarded. If the amplitude and energy of an impact are high enough, the soft tissues will compress and become more rigid, allowing transmission of higher frequencies farther up into the body. Also, an impact taken on straight legs will

effectively propagate high frequencies up into the pelvis and spine.

To confirm that high-frequency impacts, even without significant displacement of mass, can have physiological effects: grab a 2' (0.6m) steel pipe firmly at one end and hit its middle or far end hard on a rock. The pain in your palm and your wrist is the physiological response to frequencies from 120 Hz and 300 Hz. What frequencies cause which pain, we do not know. Nor do we know which frequencies cause damage to cartilages; synovial membranes, which lubricate joints; connective tissue; or ligaments.

To be able to analyze the rise time (speed of onset of impact) and the characteristics of different impacts, frequencies significantly higher than 30 Hz must be included in the recorded data.

The risk of injury is proportional to the amount of energy transmitted to and absorbed by the body. The amount of energy transmitted depends on the amplitude (level of acceleration) and the duration of each impact. The higher the level and the faster the rise time, the more violent the impact will be.

The risk of structural failure (injury) is proportional to compression force and the amount of energy absorbed. However, to understand the injury mechanics, even the rise time must be considered.

A very slow onset, going from 0 g to 7 g in 1,000 milliseconds (ms)—like a fighter pilot turning his plane—does not cause structural failure, even

though the duration of the 7 g can last for seconds. A very high onset, like going from 0 g to 7 g in 3 ms to 4 ms, can cause structural failure in the body.

Fast-onset impacts contain more of their energy in the high frequencies. High frequencies can cause higher compression forces inside the body, because different structures are accelerated differently. Different tissues have different capacities to absorb versus propagate impacts.

For research purposes, *do not filter out the higher frequencies, and do not scrap any raw data.* Any required filtering can be done afterward in the lab.

Sampling rate: With the human body we do not need to sample in the MHz range (above 1,000 Hz), as is done in structural analysis of hulls and rigid structures. There is a definite need for standardized methods to measure exposure to whole-body impact. Some in the scientific community are working to reach this consensus. I believe that we will agree to sample at between 500 Hz and 800 Hz—probably 600 Hz.

Safe exposure limits: In addition to what data should be collected and how they should be gathered, we still do not have agreement on what constitutes safe exposure levels. Currently you can go out and get slammed beyond what is healthy and still stay within the limits of an existing standard if you just don't stay out too long. Conversely, you can easily exceed the limits over time without getting injured. That's because too many standards are based on algorithms, based on older algorithms, based on mean values of vibration dose measurements and on comfort ratings done on truck drivers in the 1960s.

These algorithms are based on RMS values, and new standards tweak these values in ever-more-sophisticated ways, in attempts to describe in one single figure the impact exposure during a day at sea. Do we really believe that such a single-figure value can be relevant for assessing risks of injury?

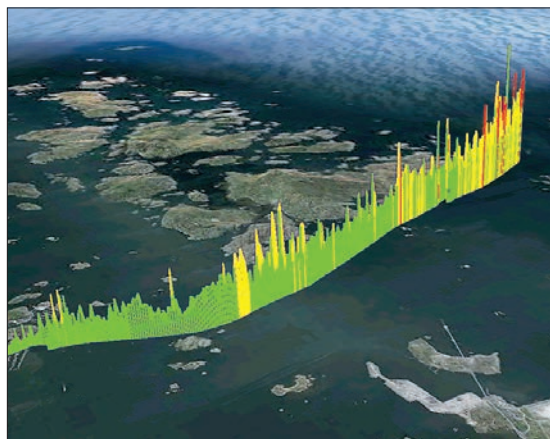
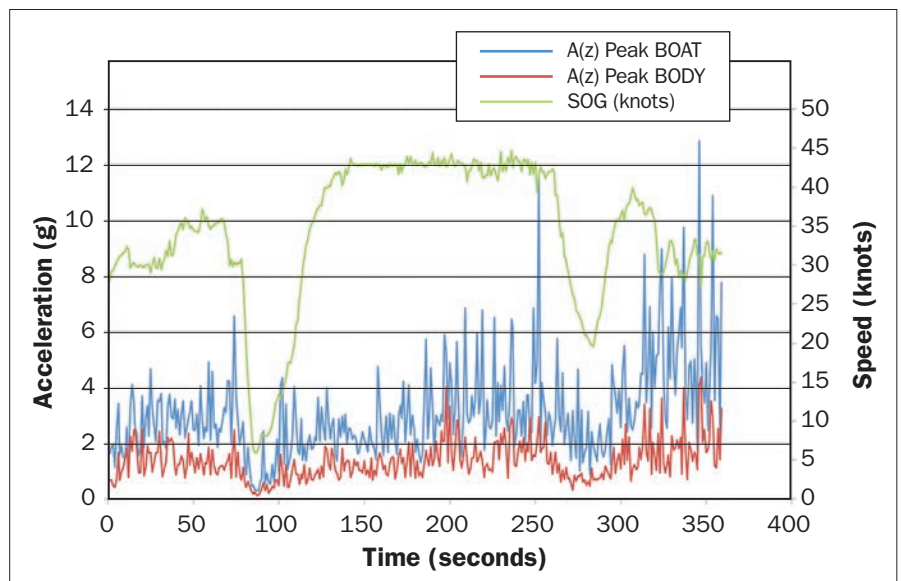
Expressing such exposure as RMS values, or whole-body vibration, is neither particularly relevant nor practical. Those terms should not be used to quantify high-speed boat impacts for the same reasons they are not how we measure the comparable impacts (20 g–23 g peaks) fighter pilots are subjected to by their seats during emergency ejection.

The difference between impact and vibration is easy to understand: watch a boxer jumping rope (vibration), and the same boxer being knocked out (impact). It is not possible to predict the risk of injury caused by that impact by analyzing and quantifying mean values of the preceding vibration. Indeed, it is the limitations of many of the existing standards based on whole-body vibrations that drive discussion and research efforts to better quantify injury risks on high-speed boats.

Linking Exposure Levels to Injury Risk

Pain remains the best indicator of impending injury. If the slamming is really uncomfortable, over time it will wear on structures in your body, such as spinal disks and knee cartilages. To date, the extent of that damage is evident only after it's too late. But pain, as a physiological function, is now possible to quantify (see www.PainDrawing.com).

By comparing impact exposure over time and development of pain over time, it should be possible to pin down a correlation. Establishing such a relationship might give relevant data to serve as the base for new standards for how much impact exposure should be deemed safe versus harmful. This scientific research is ongoing. With new technologies, measuring impacts is now so easy that basically anyone can do it. New devices have user-friendly interfaces, so you can measure the exposure you are subjected to and view the data on your computer screen, presented as the number of impacts and the severity of each. You can even see where you got slammed and when. A major study employing these devices, and supported by three navies and universities, will be conducted during the next Venture Offshore Cup powerboat race being run from London, England, to Monte Carlo, Monaco (see PBB No. 147, page 11).



Accelerometers tied to GPS units allow for this comprehensive graphing of impacts experienced on a specific passage.

Above—Note the spikes in impact followed by speed reduction as the driver throttles back following the physical shock of a slam.

Left—The same data can be graphed on Google Earth to show exactly where the boat and crew encountered which impacts.

The test boat employed to gather the data on page 53 illustrates that even a well-designed V-hull can present a flat surface to the surface of the water and deliver a hard slam and an oblique impact, which is potentially more damaging to the crew's spines than a vertical impact would be.

Limiting Impact Exposure

Regardless of whether or how you want to quantify your exposure, here are some fundamentals that boat designers and builders can consider in their efforts to reduce slamming, and damage to passengers.

- **Hull shape** is important. Deeper-V shapes reduce slamming by displacing water more gradually. Shallower dead-rise yields higher top speeds but harder slamming. Seakeeping is, of course, also determined by many other aspects of hull shape and balance.

- **Suspension seating** to reduce physical fatigue and injury risks is becoming standard equipment for many agencies professionally operating high-speed boats. Note that the term *suspension seat* indicates any seat in which there is some energy-absorbing element present.

- **Bottoming out** occurs when the suspension travel in such a seat is mechanically stopped by the end of the stroke. As they bottom out, some of these seats have been demonstrated to actually multiply, by up to three times, the impacts on the human body. Fixed seats are probably safer than shock-multiplying seats.

- **Good posture** is important for an operator to control the boat and to withstand impact exposure. A slouching, C-shaped spine is more vulnerable than a balanced S-shaped spine. Feet on deck or on fixed footrests allow the legs to absorb energy under impact and provide tactile feedback (see "Designing Consoles for Speed," PBB No. 141).

- **Standing up** can produce three times higher impacts on the spine than those on the hull. An impact from the deck, hitting a person with straight or almost straight legs, will propagate through relatively rigid structures—bone, and joint cartilage—and travel up through the body carrying higher impacts containing higher frequencies than if legs are allowed to flex under impact.



- **Suspended decks and cockpits** have been around for years but have not yet been proven to function well in practice. Some decks with limited travel absorb high frequencies, which is good. Others with more vertical travel also impair tactile feedback and sensory input for balance that normally lets the operator feel what the boat is doing.

- **Soft deck materials** are more comfortable to walk on and can absorb some of the high frequencies in impacts, but not high-impact forces. Wearing a good pair of running shoes on board might also be good, as they distribute pressure on the foot optimized to different load zones.

Deck carpeting marketed with claims that it absorbs the energy in 40-g to 50-g or even 10-g impacts is too good to be true. The amount of energy it is possible to absorb is proportional to the length of suspension travel. Carpet and deck matting just aren't that thick.

- **Sitting on a RIB tube** is dangerous. It can function as a pneumatic catapult absorbing energy over 6.6' (2m) of tube and pushing it up your spine.

- **Lateral/oblique impacts** are more dangerous than pure axial/vertical ones. The spine is better optimized to withstand the latter. In addition, hitting the water surface with the sloping face of one side of the V-bottom produces far higher impact levels than a clean landing on the keel.

- **Driving and handling.** There is a world of difference between traveling with a driver who believes he is the best in the world and someone who actually is. The worst slams occur when you hit the face of a

wave with the entire hull parallel to it.

Handling is, strictly speaking, out of the hands of the designer and builder. Nevertheless, watching professional monohull powerboat racing can be enlightening. Extreme raceboats can, when the wave pattern is right, ride on the tops of the waves without much change in attitude for each wave. This doesn't happen by coincidence; driving skills are crucial. The need for proper practical training is not always given sufficient priority.

Conclusion

In practical terms, to minimize dangerous impact exposure, we need good hull shapes, responsive drivetrains, proper seating, good seamanship, and good driving skills. Even with the best hull shape and the best suspension seats in the world, a reckless boat operator can cause injuries to passengers. Similarly, even the most skilled drivers in the finest boats sometimes find themselves in unexpected situations where accidents and injuries occur.

In regulatory terms, we can do better. There is a need for more research and development to inform adoption of relevant standards that can help boat designers and builders looking to protect people from severe and sometimes crippling impact injuries. **PBB**

About the Author: *Johan Ullman, a medical doctor, researches orthopedics focusing on whole-body impact at sea. He founded Ullman Dynamics, a motion-damping seat manufacturer, and started the High-Speed Boat Operations Forum, a biennial gathering of marine professionals who research the impacts of working in extreme ocean environments.*

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