Personal Watercraft Steering, Braking and Testing

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Surface Propulsion Analysis

Abstract:

With an estimated 1.55 million personal watercraft (PWC) in use, these vessels make up only 8.6% of the U.S. recreational fleet. Yet in 2005, PWC accidents accounted for 1,007 out of a total of 3,451 serious boating injuries (29.2%) and 44 of a total of 163 non-drowning fatalities (27.0%). Hazard level per hour of operation is even more striking: A 2007 study by the California Dept. of Boating and Waterways found that for every hour of operation, a PWC is 24 times more likely to be involved in a serious accident than a canoe or kayak.

While cultural and lifestyle issues associated with PWC ownership may be a factor, there is also considerable evidence that certain design characteristics may contribute to the relatively high accident and fatality count.

This paper explores two important elements of PWC control: off-throttle steering and emergency stopping.

Off-throttle steering refers to the absence of steering control when there is no thrust from the waterjet propulsor. A common accident scenario involves sudden release of the throttle control when a hazard appears or is first noticed, followed by an unsuccessful attempt to turn out of the way. Most PWCs also lack effective reversing buckets, in contrast to waterjet propulsion applications for conventional boats.

Although manufacturers have addressed these problems in various ways, considerable debate remains over the effectiveness of their efforts. The debate extends to the role of various testing and advisory organizations in setting standards which may or may not be adequate.

We also suggest techniques that my be useful to the forensic naval architect in reconstructing PWC collisions.

Loomings

Early versions of the powered personal watercraft (PWC) appear to have sprung from the desire to replicate the experience of water-skiing without the expense and complication of a tow boat. Hence the term "Jetski," which technically refers only to products sold under Kawasaki's trademark, but in practice is used generically to apply to all powered PWC.

Clayton Jacobsen II, a motocross racer from Arizona, is credited with the invention of the powered PWC as we know it today. But the concept can be traced back to the "Amanda Water Scooter," built by the Vincent Motorcycle Company in 1955. It was propeller-driven with a 200cc engine.[1]

Jacobsen, following the Water Scooter by more than ten years, built the first stand-up waterjet-powered PWC prototype. It was introduced by Bombardier in 1968 as a sit-down version, the Sea-Doo model 320.[2] With a 24 hp engine it topped out at 26 knots. The product was discontinued in 1970.

Meanwhile, on a somewhat parallel evolutionary track, Hoyle Schweitzer and Jim Drake were attempting to replicate the experience of surfing but without waves. In the late 1960's, after initially considering powered surfboards, they invented what has become the modern windsurfer.

Cory Reisler, in the early 1980's, successfully operated kite-propelled water skis, developing a technology (and a skill set) that led directly to the modern kitesailor or kiteboard. Although Reisler achieved skiing without a boat, and Schwietzer and Drake achieved surfing without surf, these devices are generally not included in the "personal watercraft" definition as commonly understood.

In the world of paddle-propelled PWC, the traditional American style canoe had been losing market share to the far more seaworthy kayak, which continues to be the most popular form of non-powered personal watercraft if we allow the more liberal definition.

Pop quiz: Why do traditional American canoes have a characteristic sharp upturn of the shear line at the ends, concentrating all the shear curvature right at the bow and stern?

Non-motorized species of PWC, while carrying risks of their own, continue to demand moderate to high levels of operator skill and training. They have not been seen as major sources of waterborne hazard or annoyance to non-participants.

Back on the powered side, between 1980 and the mid 1990s there were powered surfboards in production: The surf jet and later the jetboard. But this approach was eclipsed by the windsurfer and never achieved significant market share.

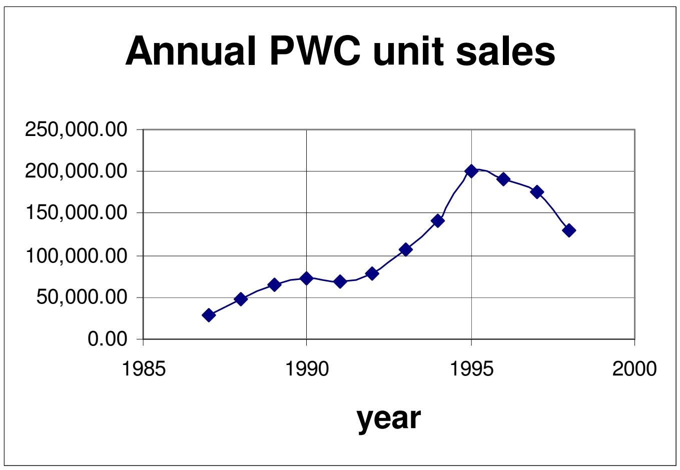
Clayton Jacobsen, after being released from his arrangement with Bombardier, began working with Kawasaki. By that time he had developed a self-righting design with a hinged steering pedestal for stand-up operation. The result was the first Kawasaki Jetski and the first modern powered PWC. Mass marketing begsn in 1973 (and was given a considerable boost by a James Bond movie, The Spy who Loved Me, in 1977). Engine sized passed through the 400 cc mark and continued to increase.

Jacobsen's original Kawasaki Jetski

Early Jetski models attained speeds in the 25-30 knot range, similar to typical water ski speeds. They relied to some extent on the operator's body position and motion to enhance maneuvering. Some of these machines did not have sufficient roll stability to remain upright when stationary, so the rider was in the water frequently and needed to acquire some basic skills to operate the vessel.

In this context, the omission of reversing or braking capability and off-throttle steering devices might have been justified. Speeds were low by today's standards, and "body English" could affect turns even off-throttle. Most importantly, the required skill level and frequent spills restricted interest to a smaller subset of powerboat operators.

Yamaha entered the market with its WaveRunner line in 1987, and Bombardier came back with a new Sea-Doo in 1988. Both companies developed sit-down models, which proved to be far more attractive to the mainstream market and the more casual rider.



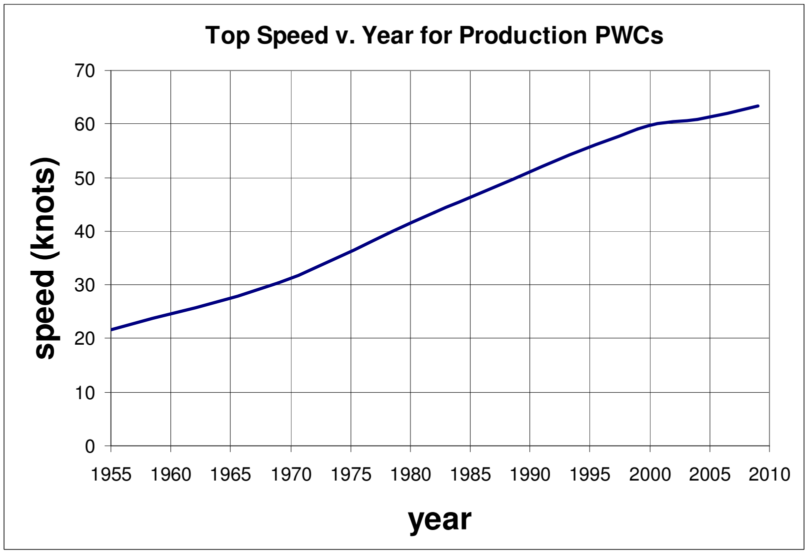
Sales accelerated rapidly from the mid-'80s to the mid-'90s:

> "Such vehicles have made it possible for people from all walks of life to enjoy fast-paced recreation on the open water without the encumbrance or expense of a full-sized boat[3]."

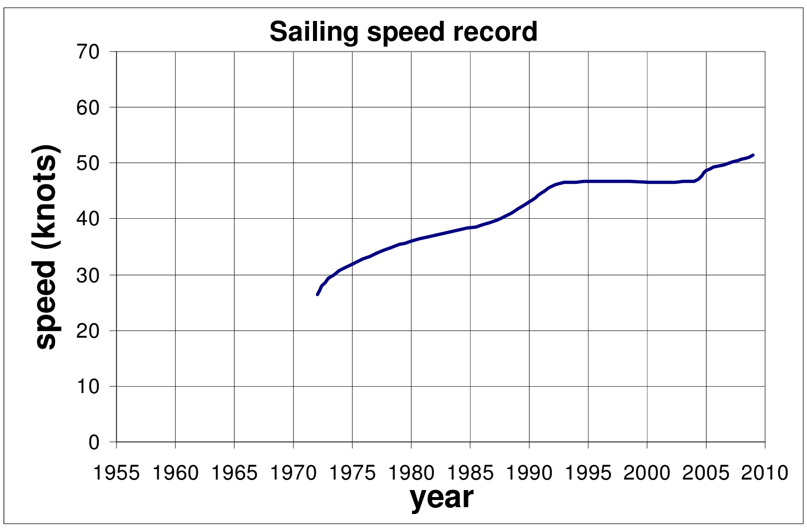
The "sit-down" variant accounted for 97% of all PWC sales by the mid 1990s. These demanded less operator skill, and could also carry one or two passengers in addition to the operator. Bombardier has claimed that its Sea-Doo is the most popular production boat in the world.

Except for the defining "sit-on-top" instead of "sit inside" feature, these modern PWC share more characteristics with high speed powerboats than with water skis.

Consumer PWCs now have top speeds of 60-70 mph. They carry up to three riders, and can be operated without risk of capsize when radical maneuvers are avoided. They have become attractive to, and are marketed to, people with limited experience and skill at boat operation.



Approximate top speed of unmodified production PWCs v. year of product introduction.

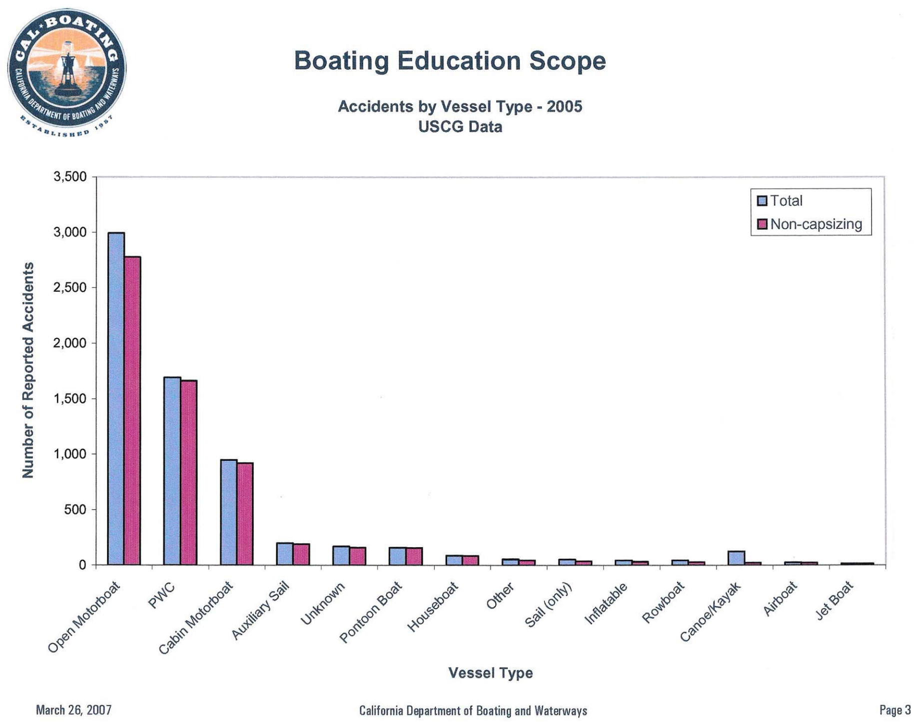


It is interesting to compare with world sailing speed records over the same years

Accident Statistics

"Call them Fishmeal"

With an estimated 1.55 million personal watercraft in use, these vessels comprise only 8.6% of the U.S. recreational fleet. Yet in 2005, PWCs were involved in 1,007 out of a total of 3,451 serious boating injuries (29.2%). PWC were implicated in 44 of a total of 163 non-drowning fatalities (27.0%). Hazard level per hour of operation is even more striking: A 2007 study by the California Dept. of Boating and Waterways found that for every hour of operation, a PWC is 24 times more likely to be involved in a serious accident than a canoe or kayak.



And this ratio is probably conservative on several counts. Average hours of operation per boat are most likely overestimated, especially considering the expected overhaul intervals of the small and high power engines (some designed to operate at 9,000 RPM).

The official statistics may also be misleading because injuries sustained on board kayaks and canoes due to collision with PWCs are often counted as kayak or canoe accidents.[4]

Cultural and lifestyle issues correlated with PWC operation are undoubtedly a factor. After all, these are called "thrillcraft," and one would not expect the PWC demographic to have the same approach to safety as, for example, those attracted to sea kayaks. However there is considerable evidence that certain design characteristics of PWCs contribute to the relatively high accident and fatality count.

The Yamaha VX110, typical of modern PWC. Top speed is over 50 mph. Note that the sales literature always shows riders wearing wetsuits below the waist, because swim suits are insufficient to prevent very serious body cavity injury from waterjet nozzle discharge.

Two elements of PWC control characteristics are implicated: Off-throttle steering, and emergency stopping.

Off-throttle steering refers to the absence of steering control when there is no thrust from the waterjet propulsor. The stopping problem is a function of high displacement-length ratio and the absence of effective reverse thrust or power-off drag elements.

A common accident scenario involves sudden release of the throttle control when a hazard appears or is first noticed, followed by an unsuccessful attempt to turn out of the way. This has become a disturbingly common cause of high speed collisions resulting in serious injury or fatality.

Placards and operator manuals warn that it is necessary to apply power in order to steer with waterjet thrust. But throttle release is a reflexive and intuitive reaction when a hazard is seen. What is not intuitive is that the steering becomes completely ineffective when thrust is lost, a response characteristic that is foreign to people accustomed to road vehicles. Even operators with long experience on boats with rudders or drive legs are subject to the same error.

From the Yamaha Operator's Manual for the "WaveJammer" PWC:[5]

> "A beginner tends to release the throttle lever when trying to steer clear of an obstruction. Do not forget to use the throttle when steering."

Lack of effective braking also contributes to the hazard level. While it may be technically true that "boats do not have brakes," it is also true that conventional propellers offer considerable hydrodynamic resistance to forward motion when stopped. Furthermore, nearly all conventional waterjet-propelled boats are equipped with reversing buckets that can be operated effectively at speed. Although length/beam and power/weight ratios of high power sit-down PWCs are not significantly at variance with conventional high performance small craft, displacement-length ratios for PWCs tend to be considerably higher, typically over 400. A PWC will coast farther than a conventional boat, relative to its size and speed.

According to experiments conduced by Craig Good and Marshal Paulo in 2005:

> "Typical stopping distances were found to be 125 ft to 160 ft at 30 mph and 180 ft to 224 ft at 40 mph. The average deceleration over the full stopping distance was -0.14 g to -0.31 g. If these stopping distances and accelerations are compared to road vehicles, they are similar to those observed on snow and ice." [6]

As speed and power of PWC products increased and operators became more casual, it became clear that a high proportion of accidents were cased by this lack of effective braking or steering after releasing the throttle.

Approaches to Correcting the Problem:

"Herding cats is easy… if you know how to use a can opener"

NTSB 1998

The National Transportation Safety Board (NTSB) took up the issue in 1998.[7] At that time it was noted that fully 51% of all reported boating accidents and 41% of all boating injuries involved PWCs. Yet in 1998 PWCs comprised only 7.4% of the recreational fleet.

Conservatively assuming that PWC operate for one-fifth as many hours per year as most other types of boats, these numbers mean that an hour of PWC operation is about 65 times as likely to result in a reportable accident as an hour of all other forms of boating. This is more than twice the relative risk found by the California Dept. of Boating and Waterways tabulation.

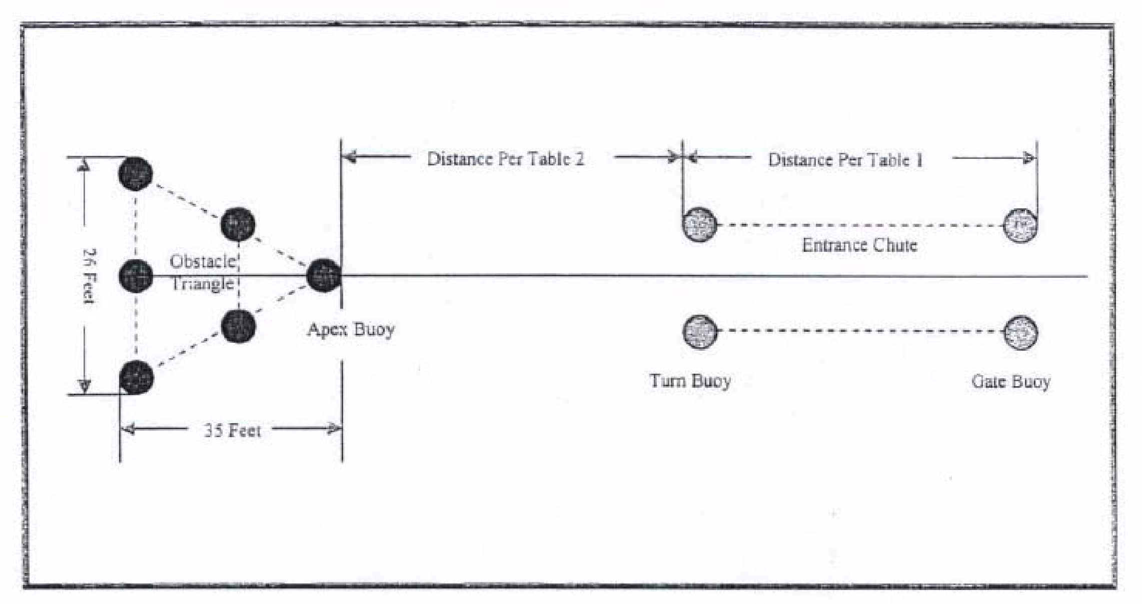
UL 2001

The U.S. Coast Guard then commissioned Underwriters' Laboratories (UL) to investigate the high rate of serious PWC accidents and publish recommendations.[8]

Although "off-throttle steering" does not appear in the Coast Guard's summary of accident causes, it became a major focus of the UL investigation after sampling detailed accident reports.

UL devised a test course in an attempt to quantify the collision-avoidance capabilities of PWC.

Among UL's stated goals: "Design a test course that evaluates the turning characteristics of personal watercraft with respect to their ability to avoid collisions with objects and other craft in waterways."



The UL test course. Distance between gate and turn buoy, and between turn buoys and apex buoy, are variable according to entry speed. Subsequent research focusing on 30 mph approach speed has been conducted with the gate and turn buoys 22 ft apart and the turn and apex buoy 58 ft apart.

It was apparently recognized from the outset that existing standards, such as the ABYC quick turn test, would not be applicable.

The distance between gate and turn buoys is specified to correspond to 0.5 seconds of motion at the approach speed (e.g. 22 ft at 30 mph). But determining the best distance to the apex buoy proved to be somewhat arbitrary:

"The distance between the turn buoys and the apex buoy was set at 43 ft for the research testing. This distance was selected primarily due to the available test run distance on the test site, and secondarily due to its corresponding to approximately 0.5 second time between the turning point and the apex buoy at 60 mph."

In other words, it was the size of the tiny 8.5 acre lake near UL's main office that dictated the main dimension of the test course that is still promoted as an industry standard. [9]

The width of the base of the avoidance triangle is set at 26 ft. This is somewhat less arbitrary, but just barely. It is based on 1999 USCG stats showing that 88.5% of boats involved in accidents are less than 26 ft long.

Finally, we have this statement clarifying the design philosophy driving the test course configuration:

> "It was fully anticipated that the obstacle area would need to be modified following the research testing to incorporate the actual test results."

In other words, this was never intended to test maneuvering safety by any rationally-derived criteria. Rather it was to be fine tuned to be useful as a screen to separate and sort PWC according to existing characteristics and the effectiveness of aftermarket modifications. Perhaps it could distinguish between "bad" and "worse," but the test was never really designed to determine what is actually needed to achieve "good."

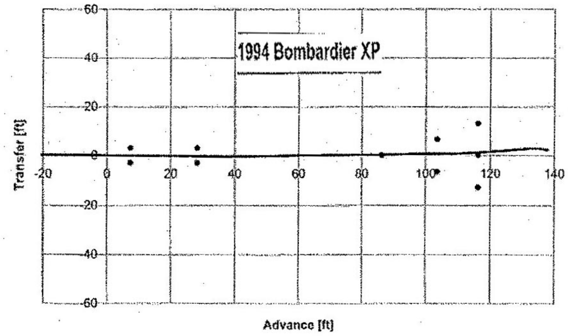
Test Results

"You don't fatten a hog by weighin' it"

The Society of Automotive Engineers (SAE) entered the PWC arena with a standardized maneuvering and test protocol.[10]

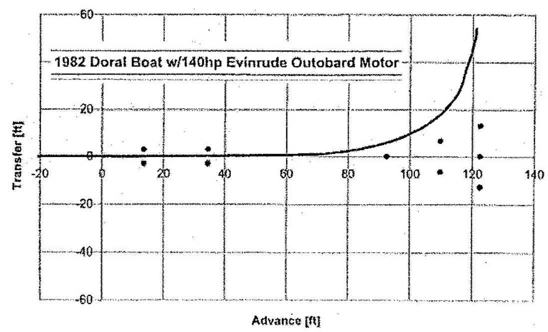
Why SAE? Probably because the larger PWC manufacturers also produce snowmobiles and all terrain vehicles (ATVs), and working relationships between the manufacturers and SAE and UL were already in place.

As it turned out, SAE adopted a geometry very close to that of the original UL test course geometry as part of their protocol. SAE J2608, published in 2003, defines how the test is to be conducted.



1994 Bombardier XP off-throttle turn performance, as measured by Good & Paulo[11]

The PWC approaches the gate at a steady measured speed. Power is cut at the gate buoys. A half second later, at the turn buoys, the helm is put hard over. The test is considered successful if the obstacle array is not contacted. If sufficiently accurate position tracking is used, the obstacle buoys are not required.



Conventional 16 ft outboard boat, also tested by Good & Paulo using the same protocol.

There are some serious problems with the SAE test. Manually timing the throttle release and helm application within the specified position tolerance (less than 0.1 second of time) is questionable. Also, the test does not consider engine spooldown after throttle release. The distance between the gate buoys (the position at which the power is cut) and the turn buoys is set to correspond to 0.5 seconds of motion at the approach speed (i.e. 22 ft for a 30 mph approach)

As reported by Good and Paulo, PWC engines were found to take as long as 1.25 seconds to drop from operating speed to idle, even from a relatively slow 30 mph boat speed. So when steering was applied, there is often some undetermined amount of steering torque available from the nozzle.

This suggests both a strategy for gaming the system and a very simple modification that might actually improve safety with respect to certain categories of accident: Dampen the throttle release, so that the fastest spooldown is at least several seconds. Following the SAE protocol would result in an easy pass.

But is this really a safety enhancement? For avoiding obstacles by steering, probably. For avoiding obstacles by stopping, the effect is clearly negative. But if the SAE test course is actually representative of the majority of PWC collision accidents, then the net effect would probably be a good thing.

The Possible Fix: Off-throttle steering and reverse thrust strategies:

"If you want a new idea, read an old book"

Various methods of correcting the off-throttle steering and stopping problem have been proposed, most of them falling into one of the following categories or subcategories:

- Rudders
  - Fixed
  - Retracting
    - Kick-up
    - Herkus type
- Drag elements
  - Spoilers
  - Off-center brakes
- Roll control
  - Flaps
  - Interceptor plates
  - Active "stabilizer" fins
- Throttle re-application
  - Steering input
  - Steering plus throttle history
  - Steering plus speed
- Steerable reversing bucket
  - "Whale's tail" type.
  - "Turns with nozzle" type

Although manufacturers have addressed these problems in various ways, considerable debate remains over the effectiveness of their efforts. The debate extends to the role of various testing and advisory organizations in setting standards which may or may not be adequate. Specifically, the SAE and UL test protocols may not adequately test for achievable maneuvering performance.

Alternative Steering Systems

There are three basic approaches to providing maneuverability during deceleration on a PWC:

Hydrodynamic appendages

Rudders in various locations have been proposed as auxiliary steering devices for water jet propelled craft. Rudders, including off-centerline rudders and steering oars, have been used for thousands of years.

> It is commonly believed that the term “starboard” derives from the steering oar or “steer board” on that side. Taking this one step further - and conjecturing that, contrary to artists' depictions, deck-sweeping sails were as useful then as they are now, it follows that starboard tack should have right of way over port.
>
> Note however that Chinese dragon boats carry their steering oar on the port side - but we leave it to the reader to connect this fact to driving rules in Hong Kong.

There is also a long history of patents, many specifically for small water jet propelled water craft, that repeat the basic concept of off-center rudders:

Winnen, issued Dec. 1, 1964, is cited as a reference by a number of patents assigned to Bombardier. (see the patent list appendix for full references to all patents cited) Note that Winnen does not specifically cite application to personal watercraft per se, because his device predates the introduction of the personal watercraft. Winnen proposes rudders extended sidewise from pockets in the rear of a small watercraft powered by a water jet, and notes that such a device is beneficial because of the loss of steering effectiveness at reduced water jet thrust.

Nedderman proposes a “Navy Cambered Rudder”, a pair of flexible rudders fitted on the sides of a personal watercraft and also cites the issue of off-throttle steering.

As an alternative to fixed rudders, PWCs could be equipped with "dipping" rudders, flaps, spoilers, wedges or interceptors, and numerous patents have proposed such devices.

Dipping or Herkes rudders consist of a pair of retractable rudders pre-set to an angle of attack. They are used one at a time depending on the desired turn direction, and both are retracted for straight-ahead operation. There is one rudder for turning right and one for turning left, and their vertical immersion in the water is varied to steer. This system is particularly well adapted to catamarans for two reasons: a) The long slender hulls have sufficient directional stability to do without continually immersed rudders for course-keeping, and b) the wide separation of hulls and therefore propellers (or waterjets) allow very effective steering via differential thrust during low-speed maneuvers. Phillip Herkes of Incat catamarans is credited with developing this system.

Side flaps or spoilers also come in pairs, one each on the aft end of the PWC at the chine. The flap on the inner side of the turn is deployed by hinging it outwards from the front edge. The force of water on the deflected flap provides lateral steering forces.

Wedges on the bottom near the chine take advantage of roll-yaw coupling, and also add side force when heeled to reduce skidding out of the turn.

A wedge on one side could be deployed by hinging it away from the craft from the front edge, and this would cause the craft to roll to the inside of the turn and turn away from the deployed wedge.

A wedge hinged at the aft edge could deploy very quickly then pull down on the side towards the inside of the turn. With attention to trailing edge flow clearances it could also pull the stern sharply downward, compensating for the nose-down attitude caused by most reverse thrust devices at high power.

Interceptors with hydrodynamics similar to forward-hinged wedges could also steer by means of the roll-yaw coupling.

One example is the "OPAS" device on some Bombardier PWCs, a combination rudder/spoiler/flap device.)

Note that none of these devices rely on any technology that was not available prior to the introduction of the first PWCs.

Hazards associated with rudders.

There are several possible explanations for the reluctance of PWC manufacturers to fit conventional rudders or related devices on modern PWCs. First is the performance compromise. At high speed, a large portion of total drag is frictional, and adding sufficient rudder area for good off-throttle steering control would reduce top speed slightly.

While this problem could be avoided via one of the various retractable rudder schemes, the problem of exacerbating injury during a run-over accident remains. Manufacturers are understandably reluctant to add appendages that might exacerbate injury to swimmers or other PWC riders that may be run over by the PWC - although there does not appear to be any real data that evaluates the net safety impact of these appendages.

Finally, there are the obvious limitations that conventional rudders might impose on shallow-water operation, trailer-launching and retrieval, and beaching.

Reversing Buckets

The advantage of the reversing bucket approach is that it does not rely entirely on turning to avoid a collision.

Experienced operators generally have no trouble producing a severely skidding turn from moderate speed, and this often results in the boat moving stern-first along a path that is not too far out of alignment with the original path. But the reversing bucket makes short stop capability available to the non-expert rider, and with the right control system it adds a more familiar and intuitive mode of brake function.

Steerable reversing buckets fall into two major categories; The "whale's tail" design, in which the nozzle can be steered independently of bucket position, is the type currently favored. With this geometry, turning the helm to starboard produces a turning torque to starboard regardless of whether the vessel is moving forward, backward or stationary, and regardless of whether thrust is being applied in the forward or reverse direction. Hamilton Jet is a good example of this type.

Note that cars and outboard-powered boats both behave differently than a boat with whale's tail reversing: In both the car and the outboard boat, helm to starboard produces a backing turn that rotates the bow to port when making sternway. With the whale's tail bucket, the bow moves to starboard when backing down with helm to starboard.

With the other type of reversing bucket configuration, in which the bucket turns with the waterjet nozzle, reverse thrust is always directed opposite the nozzle direction. This produces a steering torque in the opposite direction of the helm input when the thrust is reversed.

This behavior is similar to that of an outboard motor or stern drive leg, although the rudder effect of the lower unit might sometimes overcome the thrust effect if the vessel is still moving forward when reverse thrust is applied.

Summary of types of vessel steering control

Boat motion (Forward, Backing, Stopped)	F	B	S	F	B	S	F	B	S
Thrust direction (Forwd, Back, Neutral)	F	F	F	B	B	B	N	N	N

Turn direction / helm input
+ = same
- = opposite
0 = no turning effect

Wale's tail	+	+	+	+	+	+	0	0	0
Bucket turns with nozzle	+	+	+	-	-	-	0	0	0
Outboard or stern drive	+	*	+	*	-	-	+	-	0
Conventional inboard and rudder	+	*	+	+	-	0	+	-	0
Auto	+	-	0	+	-	0	+	-	0

* depends on speed, thrust and rudder or leg characteristics.
** ignoring asymmetrical effects due to shaft angle and differential ventilation.

Integrated throttle/reversing bucket control systems

Some current models of PWCs do have reversing buckets, but in nearly all cases they are designed only for low-speed maneuvering. The reverse lever is typically positioned so that it can only be operated at idle power, requiring the throttle hand to be away from the throttle control to activate the bucket positioning lever.

One recent exception is the 2009 model Bombardier Sea-Doo GTX 215, which features a brake control allowing high speed deployment of the reversing bucket.[12] However the engine speed is carefully regulated by onboard software, and braking effectiveness is limited.

A user-regulated reverse bucket integrated with a throttle cut-off and throttle re-application control is potentially far more effective.

There are several possible ways to configure such a system. One of the simplest is a spring-loaded reverse bucket linkage that simultaneously cuts engine power for the initial bucket deployment. As the control is pressed further, engine power is increased as desired by the operator. The degree to which the operator wants to execute a "crash stop" is determined by the degree of hazard. Most importantly, the operator maintains steering control via thrust direction during the crash stop maneuver. After the vessel is stopped for slowed, a hand lever would retract the bucket and reload the spring.

Note that basic momentum theory demonstrates that reversing the flow produces more thrust than accelerating it. Even after accounting for loss through the bucket and for less than full reversing angles, deceleration will be more than full-power acceleration.

Lab project for airline passengers: Measure the acceleration during the full-power take-off run by holding a small pendulum (keys and dental floss, or a laptop power brick hanging from its thin wire) in front of the window. Compare the angle of the pendulum to the horizon. Forward acceleration in g's equals the cotangent of the angle of the pendulum from vertical.

Repeat the same experiment during landing ground roll with reversing buckets deployed (before wheel brakes are applied). Which acceleration is greater in magnitude? Why?

Effective PWC reverse thrust braking can easily produce sufficient stopping deceleration to cause a spill. But in general, PWC riders expect to fall off the vessel on occasion. Standard safety procedure requires wetsuits to be worn, at least on the lower torso (although this requirement is to reduce susceptibility to body orifice injury from the waterjet, a very significant PWC hazard not easily anticipated by untrained riders, and not the subject of this discussion.)

Powerful but user-modulated braking is somewhat analogous to a bicycle front hand brake: With abuse, heavy breaking locks the front wheel and leads to loss of stability and control. Yet no manufacturer would consider selling a road bicycle without a fully effective front brake.

Another way to achieve user modulation of reverse thrust is to keep the engine power at a high level but control the precise positioning of the bucket for partial flow reversal. This probably requires powered servos to position the bucket quickly and accurately, but careful hydrodynamic design might minimize the servo power requirement. A properly engineered bucket could be pulled into a stable half-way, neutral thrust position by hydrodynamic forces, and from there rely on user-supplied brake lever force for additional reverse power. As the bucket is pulled further into the reverse position, a linkages to engine throttle would be desirable to counteract the operator reflex to cut power when emergency stopping and/or sharp steering is required.

Additional combinations of brake lever, twist grip, manual, spring-loaded, powered, hydrodynamic, and computer-controlled reverse bucket systems are feasible.

To date, no fully effective systems have been implemented, although the Bomardier Sea-Doo GTX 215 iBR system appears to come the closest. See for example two of the most relevant Bombardier patents, Jones, U.S. Patent 6,428,370 (2001) and Jones, U.S. Patent 6,743,062 (2000).

Throttle Reapplication Systems

These devices address the problem by simply advancing, restoring, or retarding the release of the throttle when certain conditions are fulfilled that indicate the operator needs thrust to turn.

A simple throttle-reapplicaton system was demonstrated by Arctic Cat [Christopherson, 2000] as a prototype. This system advanced the throttle whenever the handlebars were deflected beyond a certain angle. Some objections to this device were raised because of the possibility that the throttle might be accidentally reapplied when inappropriate, but Arctic Cat exited the PWC industry shortly thereafter and this device was never widely used. Rheault, 6,336,833, also describes this approach as well as a more sophisticated one using boat speed sensors.

The PWC industry has insisted that throttle should never be applied unless the craft is going fast, though it is not certain that there is a valid risk analysis that proves this. However, if this tenet is accepted, the problem of designing a throttle reapplication system includes detecting “going fast” as well as “handlebars turned hard” so that “going fast” enables throttle reapplication when the handlebars are rotated far enough. An additional task might be to detect “throttle released”, but the need for this depends on the mechanism of throttle reapplication. If the throttle is reapplied through a flexible mechanical link such as a chain, or a lost motion linkage as per Reault, and the operator is already at full throttle, the link will not come taut and will have no effect.

One way of detecting “going fast” is by observing any of the engine parameters that indicate high power. These include engine RPM, engine vacuum, exhaust manifold pressure, voltage on specific circuits or waterjet pump pressure. Note that since the engine is directly connected to the jet pump with no clutch, the thrust produced and power absorbed is tightly linked to engine RPM and related parameters. “Going fast” can therefore be determined by noting that the engine has been producing high power for a predetermined time.

In its least sophisticated form, a system could simply enable throttle reapplication whenever any one of these signals exceeds a certain value and start a countdown timer that continues to enable it for a few seconds after the signal has fallen below the critical value. This would only produce accidental application if the operator unintentionally applied throttle for a short period of time, then released the throttle and quickly pushed the handlebars over. This is a low probability event, requiring two specific successive errors on the part of the operator in a very short period of time, and probably represents an acceptable risk, considering the consequences of accidental throttle reapplication vs. loss of steering authority in a critical situation.

Note that the existing throttle lever, in its exposed position on the handlebar, is also potentially subject to accidental activation, but the PWC industry has not changed to a twist grip or added a shield to the throttle, so accidental activation is apparently not a significant risk.

Kawasaki’s Smart Steering system is a variant on this theme – it simply enables throttle reapplication for a few seconds any time the engine RPM has been in excess of a specific value.

More sophisticated systems are possible by integrating the power time history to estimate speed. At a minimum, this type of approach requires a timing circuit that adds up revolutions over time, monitors the sum, and compares it to a datum. There are many other approaches to measuring power time history, including electrical, mechanical and pneumatic accumulators.

However, the most obvious way to detect “going fast” is to measure speed directly, and this provides yet another option. Speedometers on boats are a well-established technology. It is speed that determines the hydrodynamic forces required to maintain control of the vessel, not power history, (though power history is related to speed) so if speed can be detected directly, it is unnecessary to examine RPM history.

Speed is extremely easy to determine, especially to the crude level needed to decide to detect if thrust for steering control is needed. Note here that the dependence of hydrodynamic forces on speed squared acts in our favor. The signal for “going fast” is much larger than that for “going slow” and it is that much easier to distinguish.

A minimal speed detection device could be comprised of a pitot tube with a pressure switch. The tube itself would not actually have to protrude from the vehicle - it could be recessed in the bottom behind a faired depression. This would not be sufficient for navigational accuracy, but is well within the accuracy needed to determine if throttle re-application should be used.

Some systems may apply a precise amount of throttle. This is probably optimal, but no PWC manual specifies that a certain amount of throttle is required to avoid danger, only some unspecified amount, and the Arctic Cat prototype suggests that some reasonable amount is sufficient. In addition, this could be controlled by the handle bar deflection as noted above.

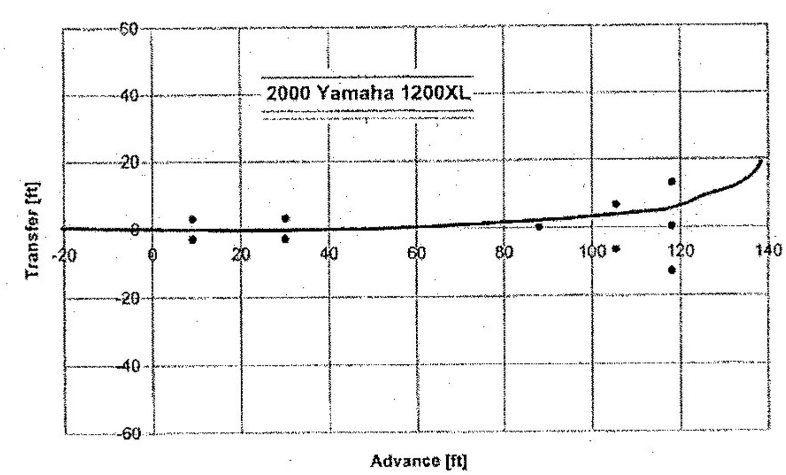
It is also important to understand that any possible engine speed instability is not an issue. The throttle on a carbureted engine increases the resistance to the flow of air and gas mixture into the engine, so rather than having a throttle setting correspond to a specific RPM, it more accurately corresponds to a change in power level. However, a waterjet is comprised of an inlet that admits water to the pump; a diffuser which is an expanding section that takes the high speed flow from the inlet and slows it and increases its pressure;

and then the impeller and stator; a sort of two stage propeller or fan that increases the speed and pressure of the water flow, then the nozzle, which converts the pressure developed by the pump to speed. The diffuser isolates the jet pump somewhat from the external water speed, and eliminates the strong dependence on torque drawn by the impeller on forward speed of the boat.

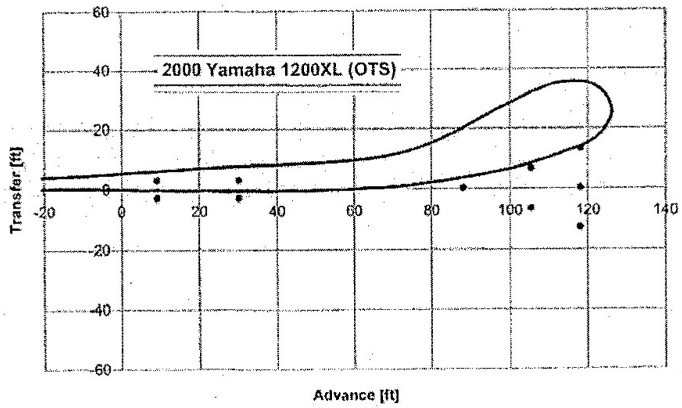
This is one of the great advantages of water jets over conventional propellers. Since propellers are outside the hull in the water flow, they are very strongly affected by boat speed – slowing the boat increases the torque the propeller draws from the engine and speeding up the boat reduces the torque, so in theory, there could be a tendency to "hunt" or change RPM back and forth independently of throttle. However, this is not the case with enclosed pumps. The torque they draw is a function of their RPM cubed. This means small changes in RPM require large changes in power level, so carbureted engines driving pumps are very stable and a given throttle setting will correspond well to a reasonable thrust level. The sophistication of a computer-controlled engine is not required for the sake of achieving an accurate level of throttle reapplication.

Do they work?

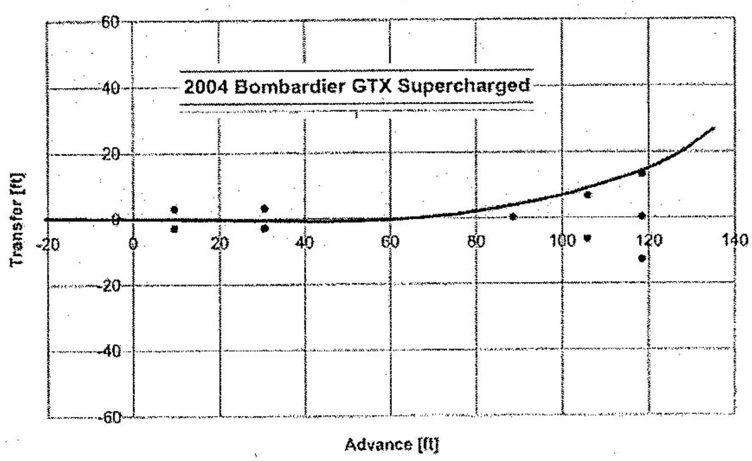
"In theory, there is no difference between theory and practice. But in practice, there is"



Stock Yamaha WaveRunner 1200XL off-throttle steering test, (Good & Paulo)



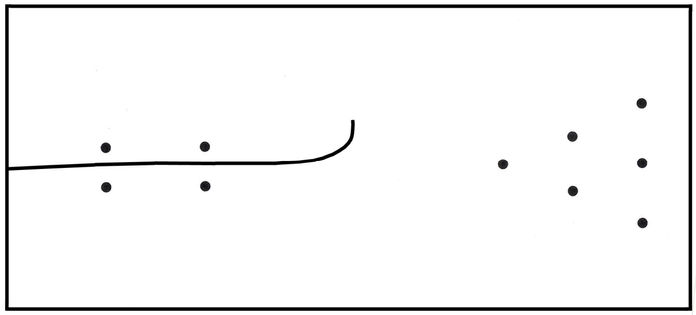
Yamaha WaveRunner 1200XL with retrofitted rudders for off-throttle steering. (Good & Paulo). The rudders were small conventional rudders fitted port and starboard just inboard of the chines so as not to increase navigational draft.



2004 Bomardier Sea-Doo GTX with the O.P.A.S. system. It does better than the Yamaha with retrofitted rudders, but still falls short of the outboard's performance.

Retrofitting a rudder-based off-throttle steering device is sufficient to change the test result from "fail" to "pass." The Bombardier O.P.A.S. system does slightly better, but still falls considerably short of the maneuvering ability of the conventional outboard.

Tests conducted by the author with a retrofitted reversing bucket in late 2009 show much more definitive results, stopping a Yamaha WaveRunner 1200XL in approximately 30 feet from 30 mph. Although the control linkage was not optimal with this proof-of-concept lash-up, the operator was able to apply a relatively large amount of reverse thrust as desired. Decelerations of approximately 1.4 g were well tolerated.



Track of a Yamaha WaveRunner 1200XL with an experimental retro-fitted reversing bucket, representative of tests conducted by the author. The PWC can stop from 30 mph in approximately 30 ft from the point of reverse thrust application. Actual buoys for the tests were configured differently - the SAE J2608 test course configuration is plotted for comparison.

Jetski CSI: Forensic techniques for PWC forensics

"There are no skid marks on the water"

Naval architects are occasionally called upon to investigate serious accidents involving personal watercraft. As often as not, this will begin with the correction of some fairly lubberly analysis by forensic engineers whose primary work is road vehicle accidents. Even the world of ATV and snowmobile forensics bears little resemblance to marine accident reconstruction, although many of the players are the same.

This is not to diminish the skill set of the automotive forensic engineer. For example they are extremely good at determining if a light bulb had been on, off or had previously failed at the time it was broken. But they don't generally work with highly non-linear systems, and often miss critical factors such as unsteady pitch or the mass of entrained water. They don't always appreciate the degree of coupling between various degrees of freedom, and they are helpless at estimating the effects of waves.

Naval architects have access to the analysis tools to perform much more credible accident reconstructions.

Several additional factors make these projects particularly interesting. The budget is often restricted (especially when working the plaintiff side) and the deadlines can be extremely short. But the degree of precision required is relatively low compared to most scientific research. The results need to be valid, but they don't need to reflect the last fraction of a percent. Very often a plus-or-minus 20% tolerance is adequate to make a point that will withstand hostile scrutiny. This environment is ideal for experimenters who enjoy improvising.

Photometric techniques have been particularly useful as a quick and inexpensive alternative to more traditional position and speed tracking technologies.

Why a digital SLR over a camcorder?

1) Compatibility with inexpensive turnkey systems for simultaneous dual camera control and frame synchronization (e.g., Stereo Data Maker)

2) Ability to switch to a prime (no zoom) lens (no need to track and verify focal length setting)

3) Large optical viewfinder for easier framing in daylight.

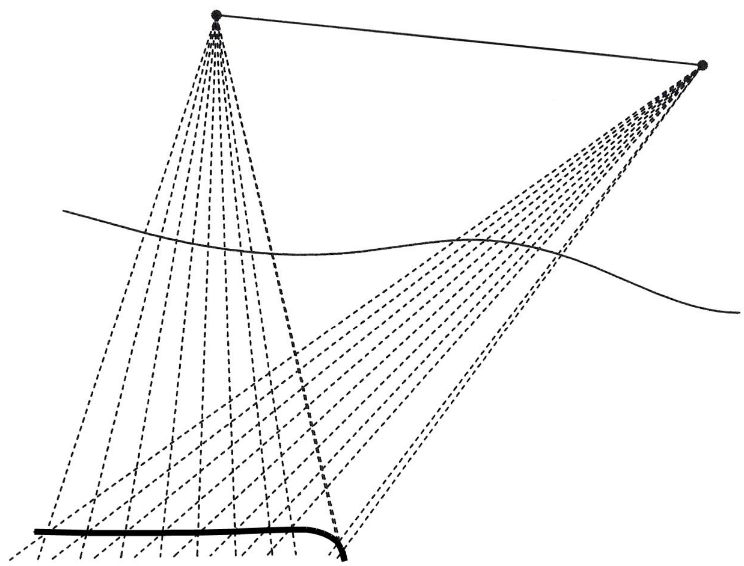
4) High resolution burst mode at several FPS is sometimes more useful than video for motion tracking.

5) High quality still images from the same cameras.

The technique described here uses two digital cameras in video mode to track a PWC over a test course during tests of a prototype reverse thrust bucket.

For these tests, the cameras were set on tripods at the ends of a line approximately parallel to the beach. The distance between them was measured at 135 feet. The cameras are simply used as angle measuring devices, recording the angle from the baseline to the PWC in each frame.

At an HD resolution of 1920 pixels horizontally, and a typical field of view of about 55 degrees, the precision of angular measurement is better than 2 minutes of arc. For an object 300 feet away, this is a position error of only two inches. Even standard definition video, at 640 pixels wide, locates an object at 300 feet to within six inches.



Sample vessel track via a pair of digital video cameras. The boat's position is fixed every 0.2 seconds, except for a 1.4 second gap near the end of the run during which the boat is obscured by a cloud of spray. The cameras are 135 ft apart and the test course is 145 ft from the baseline and 85 ft off the shoreline.

Note that to resolve a digital image to an angular measurement, the relationship between pixel count and angle is not linear. Consider the lens as a pinhole at a distance f from the sensor (focal plane). If alpha is the angle between the center of the field of view and some object, and n is determined by counting the number of pixels from the center of the image to the object (Photoshop's ruler tool makes this easy), then:

alpha = arctan (n/f)

where

f = focal length in pixels
n = pixel count from center
alpha = angle of object from center of field of view

f must be determined by taking calibration photos showing two landmarks with known angular distance between them, one on each side of the camera's centerline.

It is difficult to adjust a camera to place the center of its field of view exactly on a landmark. But with two landmarks and a precisely measured angle between them, and known pixel counts from the image center to the landmarks in the resulting image, it is easy to solve for the focal length in pixels:

$$\arctan(n1/f) + \arctan(n2/f) = \text{alpha}$$

where

n1=number of pixels from center to one landmark
n2=number of pixels from center to other landmark
alpha = measured angle between landmarks
f = focal length in pixels

The equations are readily solved for the desired degree of accuracy by iterative techniques (i.e. trial and error).

Measurement of the angle between the landmarks, for camera calibration purposes, should be done with an instrument that is at least as precise as the angular value of one image pixel, or about 2 minutes of arc for an HD 1920 x 1080 camera. A marine sextant held horizontally does this nicely (and provides a great excuse to drag out the old sextant and actually do something useful with it.)

1944 vintage US Maritime Commission sextant, ideal for horizontal angles due to its extended 72 degree arc. (Is it really a quintant?) It measures angles up to 144 degrees.

When shooting video clips of boats during test runs, it is usually impossible to include the other camera and the test course in the same field of view. But we need to measure the angles between the boat and the baseline of the test course (recall that the baseline is the line between the two cameras) This is done indirectly, by using some other fixed reference in the field of view. Preferably a distant fixed object, but carefully positioned buoys in the test course are adequate as long as the effects of their possible motion during the test sequence are considered. Surveying equipment (or the horizontal sextant) is used to determine the angle between this reference object and the camera at the other end of the baseline.

With the angle between the reference object and the baseline known, it is easy to calculate the angle from any object in the field of view to the baseline.

In practice, it is quicker to count pixels to the edge of the frame than to a landmark, with a recalibration of angle from landmark to image edge before each run in case the camera aim has changed slightly.

Once the angles are calculated for each frame of interest in the test run (typically at 0.5 or 0.2 second intervals for a stopping or turning test lasting several seconds), the track of the boat can be plotted via any CAD software or calculated trigonometrically.

Measuring pixel counts is labor-intensive compared to more automated electronic tracking systems, but the bulk of the gruntwork is done by spreadsheet.

Not only is this method usually sufficiently rigorous for forensic purposes, it is also fully transparent. There can be no claim that a fudged result is being hidden behind a proprietary data acquisition system with unverifiable software code and uncheckable calibrations. A hostile adversary can duplicate every step of the process from the raw footage and the calibration photos.

As video camera resolutions continue to increase, the photometric vessel tracking methodology can be streamlined even further by using a single camera. In smooth water, the motion of a boat is restricted to a horizontal plane. If the height of the camera above the boat is known, then the vertical angle measured downward from horizontal to the boat will determine the distance to the boat. The horizontal angle determines the bearing, and the position of the boat relative to the camera (and any fixed angular reference) can be computed or plotted.

The main advantage of a single camera method is that it eliminates the need for synchronization between cameras.

Accuracy in determining range is a function of the ratio of camera height to range and the focal length of the lens (expressed in pixels).

Example: Consider an HD video camera (1920 x 1080 pixels) positioned 20 ft. above the target, at a horizontal range of 200 ft, with a focal length of 1500 pixels.

Each pixel on the sensor (near the center of the frame) represents 0.0382 degrees or 2.23 minutes of arc. Translated to range precision, each pixel on the image corresponds to an error of 1.3 ft.

This is not nearly as precise as the azimuth measurement, for which each pixel represents about 1.6 inches at a distance of 200 ft. But it is often sufficient for forensic reconstructions, and is likely to improve with more modern hardware - newer DSLR cameras feature a high resolution "burst mode" that can capture high resolution images at frame rates of several per second.

Note however that errors in height of the target due to vessel motions are amplified by the ratio of range to camera height, regardless of the camera's angular resolution. To minimize this error, the best target is the intersection of the bow rake with the undisturbed water surface, and the test course should be configured so that this point is always in view of the camera.

Why focal length in pixels? Isn't focal length usually given in millimeters?

Yes, but in this context the pixel is the preferred unit of distance. Counting pixels between two points in a displayed image is essentially the same as measuring a distance across the focal plane on the camera sensor. But we are really interested in the angular distance, and to compute that we need the distance to the virtual pinhole at the lens. If the sensor pixel is used as the unit of distance on the focal plane, the arithmetic is very much simplified if the pixel is also the unit of distance to the lens. Angle from the center of the sensor to a point n pixels from the center is simply the arc tangent of the number of pixels from center divided by the focal length in pixels.

Remember however that pixel size may change depending on the resolution setting on the camera, and the focal length changes with the zoom setting.

Conclusion

There is little doubt that PWC maneuverability and stopping capabilities can be significantly enhanced by the addition of relatively simple devices. Rudders, reversing buckets, flaps, spoilers, wedges and interceptors all represent mature technology. Reversing buckets are in widespread use on nearly all non-PWC waterjet-propelled vessels. Only electronic logic-controlled throttle reapplication is relatively new - this approach also shows some degree of utility.

The current generation of PWC are beginning to incorporate these features, and at this point the reversing bucket appears to be the most promising.

The more difficult question will be how to assess the effectiveness of these devices. Are the current measures enough? Has the industry held back the most effective solutions for fear of exposure related to older products?

Changing demographics and use patterns present major confounding factors that will likely obscure the actual effects of product safety evolution. Even in the face of these uncertainties, however, one would be reluctant to recommend building a bicycle with no brakes or a fast car that stops as if it were on ice and disconnects the steering whenever the accelerator is released.

Considering the size and age of the current PWC fleet, and the relatively slow replacement rate in recent years, it seems both likely and unfortunate that naval architects with an interest in forensics will continue to be in demand.

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Acknowledgement

The author wishes to thank Christopher D. Barry for compiling much of the information on existing off-throttle steering devices and the list of related patents.

Appendix: List of related patents

5,813,357	Watson		Jet ski steering and braking apparatus (forward extensible flaps)	31-Jul-97	29-Sep-98
5,934,954	Schott	Brunswick	Braking gate for PWCs, w/ hydrodynamic assist	16-Jan-98	10-Aug-99
5,988,091	Willis		Jet ski brake apparatus	23-Nov-98	23-Nov-99

6,174,210	Spade	Bombardier	Waterjet control mechanism (comprising deployable tabs producing downward and rearwards force)	2-Jun-98	16-Jan-01
6,202,584	Takaaki	Yamaha	Steering control for watercraft	2-May-00	20-Mar-01
6,224,436	Westhoff	Bombardier	Reverse gate for water jet apparatus allowing reverse steering similar to auto	24-Dec-99	1-May-01
6,336,833	Rheault	Bombardier	Watercraft having steer responsive throttle (throttle reapplication device)	26-Aug-99	8-Jun-02
6,415,729	Nedderman	Navy	Steering system with variable camber rudders	14-Dec-00	9-Jul-02
6,428,370	Jones	Bombardier	Water jet propulsion system having reverse gate optimized for braking	13-Aug-01	6-Sep-02
6,428,372	Belt	Bombardier	Waterjet propulsion unit with retractable rudder	11-Aug-01	9-Aug-02
6,491,554	Servais	Bombardier	Watercraft with steerable planing surface	11-Jul-00	10-Dec-02
6,523,489	Simard	Bombardier	PWC and off throttle steering system (rudder raised and lowered by pump pressure)	8-May-01	25-Feb-03
6,524,146	Spade	Bombardier	Watercraft having steer responsive throttle	18-Jun-02	25-Feb-03
6,546,888	Bertrand	Bombardier	Removable stabilizing fin for PWC	22-Jun-01	15-Apr-03
6,592,413	Simard	Bombardier	Thrust reversing nozzle assembly for watercraft	31-Aug-01	15-Jul-03
6,675,730	Simard	Bombardier	PWC and off throttle steering system - (rudder raised and lowered by pump pressure)	16-Jul-02	13-Jan-04
6,691,634	Fritchle		Braking and control device for PWC (integrated into lever on steering assembly comprising two plates forming brakes, w/differential application to steer)	21-May-03	17-Feb-04
6,743,062	Jones	Bombardier	Braking system for jet-propelled watercraft (applies reverse gate and then opens throttle with throttle being increased as brake pedal is applied with more force)	28-Nov-00	1-Jun-04
7,018,252	Simard	Bombardier	Watercraft control mechanism (comprising deployable steering vanes of the transom)	4-Sep-02	28-Mar-06
7,168,384	Willis		Brake apparatus (center flap beneath jet nozzle)	13-Jan-06	30-Jan-07

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[2] http://www.oldseadoos.com/

[3] http://inventors.about.com/library/inventors/bljet_ski.htm

[4] From conversation with Phil Taylor of Jetstream, Yuba City, CA, "20 hours of operation per year per boat is probably a high number.")

[5] Yamaha Operator's Manual for the "WaveJammer" PWC, 1987, p. 10-2

[6] Good, Paulo, et. al., "Stopping Distance and Acceleration Performanc of Personal Watercraft," SAE 2005, report 2005-01-1175

[7] National Transportation Safety Board, Safety Study - Personal Watercraft Safety, NTSB/SS-98/01, May 1998

[8] Colavecchio, B. and Moss, W. "Off-Throttle Steering of Jet Pump Propelled Craft," Underwriters Laboratories, inc., for U.S. Coast Guard, 2001

[9] Uffa fox, in the closing chapter of his 1939 book *The Crest of the Wave*, imagines a magic drawing table (roughly the equivalent of a modern CAD system). Yet even there, the height of the sailplan he designs is determined by the size of the electronic display. Those of us old enough to have performed design studies on paper have felt the influence of the edge of the drawing space on our design - but that was when we were students. What's extraordinary about the UL test course is that they actually admit that the test course geometry was limited by the small size of their 8 acre lake
.
[10] SAE International, “Off Throttle Steering Capabilities of Personal Watercraft”, SAE Recommended Practice J2608, September 2003

[11] Good, Paulo et. al. "Off-Throttle Turning Performance of Personal Watercraft for Accident Reconstruction," SAE 2005, report 2005-01-1198.

[12] Review of Sea-Doo GTX 215
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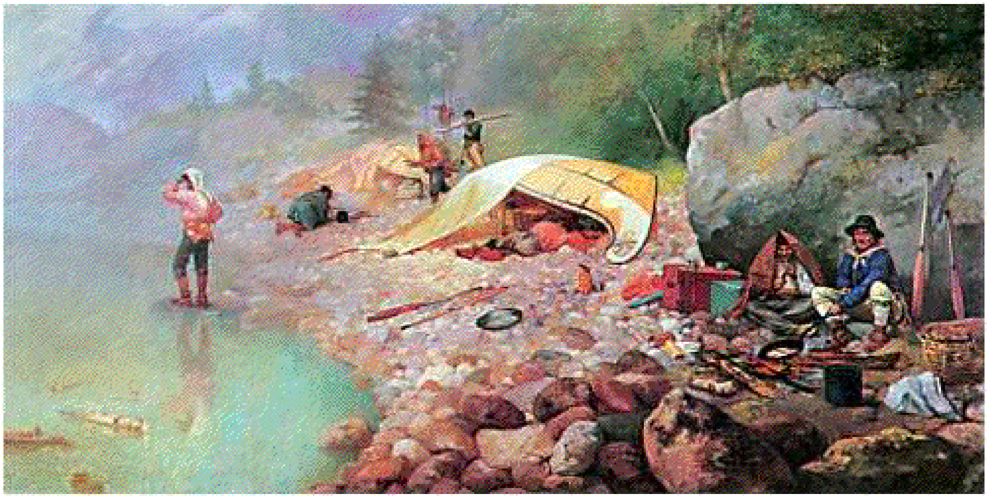
http://www.uscgboating.org/nbsac/MtgMin/html/76th%20NBSAC%20Summary%20Minutes%20-%20Final-3-28.htm

"*Voyageurs at Dawn*" by Frances Hopkins.
http://www.paddling.net/sameboat/archives/sameboat183.html

Youtube Video of iBR
http://www.youtube.com/watch?v=taFKWn3Xiso

Answer to pop quiz:

Traditional North American canoes have the turned-up shear line at the ends so that they lie at a useful angle to provide shelter when overturned on land.



"*Voyageurs at Dawn*" by Frances Hopkins. Can powered PWCs do this?