PWC Operation Study using the Virtual Jet Ski Driving Simulator

Final Report

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November 10, 2006
(revised 11/24/06)

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1. Introduction and Objective

This report describes a study that was conducted by the University of Michigan Virtual Reality Laboratory for the Research Triangle Institute and the United States Coast Guard.

The objective of this project was to study the behavior of PWC (Personal Water Craft) operators when using the Virtual Jet Ski Driving Simulator at the University of Michigan. A total of 24 subjects were asked to ride the virtual Jet Ski and to perform a number of given tasks during these rides. About half of the subjects were novices (had no significant experience in riding a PWC), the other were experienced or expert PWC operators.

The data collected during these virtual rides were examined with respect to indicators that revealed the level of expertise and that could be predictive of how an individual operator may behave on a real PWC.

All data collected or created during this study, as well as selected illustrations are available on a password-protected Web site. The sponsor has been given access to this Web site. In the following, the Web site is being referred to as the PWCStudy Web site.

2. The Virtual Jet Ski Driving Simulator

The "Virtual Jet Ski Driving Simulator" was developed in previous years by the University of Michigan Virtual Reality Laboratory with funding from the Research Triangle Institute in cooperation with the United States Coast Guard.

The simulator allows a user (operator) to drive a Jet Ski (or PWC) through a lake environment that is presented in a fully immersive virtual reality CAVE system. The operator sits on a Jet Ski mockup and controls the ride via handlebar and throttle. While the mockup is stationary (does not move), the environment changes dynamically in response to handlebar and throttle operation, thereby, creating the feeling of PWC-driving in a very convincing way. The virtual reality system provides head-referenced stereo viewing and a realistic, full-scale representation of the environment.

During a virtual ride, a physics-based simulation program continuously calculates the dynamic reaction of the Jet Ski to handlebar and throttle operation. This is performed in real-time through a time-step integration of the equations of motion. Five degrees of freedom are continuously updated (translation in x and y, pitch, roll, and yaw). The physics-based simulation includes the so-called off-throttle-steering-loss, i.e., the fact that steering with the handlebar becomes ineffective if the operator lets go off the throttle. The Jet Ski cannot be steered without the directional force of the propelling jet.

For each individual ride, the simulator creates a log file. This file contains the time history of all relevant data, including handlebar position, throttle position, speed, as well as position and orientation on the virtual lake. The log file can be processed in various ways and allows for a detailed analysis of an operator's driving behavior and reactions in given situations.

3. Study Outline

In consultation with the sponsor, three general scenarios (or driving tasks) were considered for this study.

1) Ask the operator to drive on a straight course and stop the Jet Ski in front of a target. Evaluate the final distance from the target. This test requires familiarity of the run-out behavior of a Jet Ski.

2) Ask the operator to perform the same task on a curved course.

3) Place the operator into a panic situation that may lead to a collision and study the operator's reaction. Stopping the Jet Ski and/or avoiding a collision may require familiarity with the off-throttle-steering-loss.

For these three general scenarios, a multitude of pre-tests were performed to define the details for the virtual setup and for the final test protocol. This was necessary to guide (or force) drivers into comparable driving patterns in order to obtain comparable data. The details and the related rationales are described below under "5.1 Straight Course Tests", "5.2 Curved Course Tests" and "5.3 Collision Tests".

4. Human Subjects and Operator Classification

A total of 24 human subjects were recruited for this test and acted as PWC operators for the Virtual Jet Ski Driving Simulator. The following data were collected from each subject before the test:

- Age and Gender
- Jet Ski Driving Experience
- Completion of a Boating Safety Course (yes/no)
- Snowmobile Experience
- Previous CAVE Experience

Completion of a Boating Safety Course is required in several states before an individual is legally allowed to operate a PWC. These courses often educate the

attendees about the off-throttle-steering-loss typical for most PWCs. Knowing about this particular Jet Ski behavior may be helpful when operating a virtual or real PWC.

Like a PWC, a typical snowmobile is also being operated by only handlebar and throttle (no breaks). Therefore, we added this question. In addition, we asked if the individual had experienced a virtual reality CAVE before. But, ultimately, both questions (snowmobile, CAVE) were not considered and had no impact on the results of this study.

Using the data collected, the subjects were classified as “Novice Drivers” or as “Experienced/Expert Drivers”. Novice drivers had never driven a PWC or had very limited experience (up o 0.5 hours). Experienced drivers had one or two hours of driving experience, expert drivers had 10 hours or more (up to 50 hours) of driving experience. Subjects that had attended a boating safety course were almost all experienced/expert drivers (based on their Jet Ski driving experience). Only one subject had attended a boating safety course, but had never driven a PWC. This subject was classified as novice.

A numerical value EV (Expertise Value) was assigned to each subject. EV represents the number of hours the subject had ridden a PWC. This value was used to sort any of the results by level of expertise.

The spreadsheet Subjects.xls (available on the PWCStudy Web site) shows all data collected from the 24 subjects as well as the Expertise Value EV and the resulting classification. In this and all other spreadsheets, each subject is identified by a subject ID of the form Sxx (e.g., S03 for subject number 3).

For the final analysis, the 24 subjects are divided into two groups. Subjects with an EV of 0.5 or less belong to the group “Novice Drivers” (11 subjects), subjects with an EV of 1.0 or higher belong to the group “Experienced and Expert Drivers” (13 subjects). The dividing EV (1.0 hours of driving experience) was chosen since statistics show that most PWC accidents occur during the first 1 to 1.5 hours of gaining experience in Jet Ski driving, i.e., some amount of expertise seems to build up during this initial driving time.

Since all data are provided as spreadsheets on the PWCStudy Web site, it is easy to analyze the data for any other grouping of the given subject pool.

It should be noted here that the stated number of hours a subject thinks he or she has driven a PWC are highly subjective and, therefore, somewhat unreliable. PWC operators typically don’t carry a stopwatch and don’t keep a log. Observations have shown that novice drivers usually restrict their rides to just a few minutes since they have to recuperate from the unexpected stress or they have to share the PWC with others. Still, they may spend an entire afternoon around the water and, therefore, may recall a driving time that is imprecise.

5. The Driving Tests

The three types of driving tests are described in detail in the following sub-chapters. They should be interpreted in the context of the overall Test Protocol (see Appendix A). The protocol gives each subject various opportunities to become familiar with the simulator, the behavior of the virtual Jet Ski, and the virtual environment created for each test before the test was conducted and recorded in a log file. Great care was taken to adhere strictly to the protocol in order to make the resulting findings comparable. Any deviations or unusual occurrence (subjects and computers are not perfect) were written down and are listed under "Notes" in the spreadsheet Rides_Table.xls.

The spreadsheet Rides_Table.xls (available on the PWCStudy Web site) gives the major results from the individual tests sorted by subject ID. Additional data can be extracted from the log files and other derived data files if so desired.

5.1 Straight Course Tests

For this test, a straight course on the virtual lake was outlined by a set of buoys. At the end of the course, a banner was placed indicating the finish line. The particulars of the straight-line course are as follows:

- Total length of course from start position to finish line: 284 meters
- Begin of buoys: 108 meters from start position
- Length of course marked by boys: 176 meters
- Width of course between left and right buoys: 24 meters
- Total number of buoys: 18 (9 on the left, 9 on the right), including 2 buoys at finish line
- Spacing along straight course: 22 meters between buoys

At the beginning of test, the Jet Ski was placed at a fixed start position and facing the finish line visible at the given distance of 284 meters. The subject was then asked to accelerate with full throttle to maximum speed (about 40 mph), maintain maximum speed as long as it seems appropriate, and then bring the Jet Ski to a stop as close to the finish line as possible. In order to do so, the operator has to let go of the throttle ahead of the finish line end properly estimate the distance that will be covered while the Jet Ski decelerates (run-out behavior of the Jet Ski).

To verify data consistency, we asked each subject to perform this test two times. The spreadsheet Rides_table.xls shows selected results for these two tests (data blocks called "Straight 1" and "Straight 2", respectively). The spreadsheet gives, among others, the total time from start to final stop and the remaining distance to the finish line.

Almost all subjects reached maximum speed in a similar, short time period (4 to 5 seconds). Individual subjects initiated deceleration at different points in time. During deceleration, some subjects accelerated again to get closer to the finish line and, as a result, needed more time. The obvious challenge was to get as close to the finish line in the shortest period of time. Among others, the results allow recognizing "aggressive" and "timid" or "careful" drivers, which may or may not relate to previous PWC driving experience.

To create more comparable driving patterns, different scenarios were investigated before the above protocol was adopted. Forcing a specific speed on the Jet Ski (by program control) to create comparable situations before deceleration starts made the operator uncomfortable and uncertain about the behavior of the Jet Ski. Defining a line from where deceleration should begin confused the operator more than it helped with getting comparable data.

5.2 Curved Course Tests

For this test, a short straight course connected to a curved course on the virtual lake was outlined by a set of buoys prescribing a moderate left turn of constant radius. At the end of the curved course, a banner was placed indicating the finish line. The particulars of this course are as follows:

- Total length of course from start position to finish line: 384 meters
- Length of initial straight course (from start position to begin of buoys): 82 meters
- Length of curved course (marked by buoys): 302 meters measured along centerline
- Radius and extend of curved course (centerline): 192 meters over 90 degrees
- Width of curved course between left and right buoys: 24 meters
- Total number of buoys: 22 (11 on the left, 11 on the right), including 2 buoys at the finish line
- Spacing of buoys: every 9 degrees

At the beginning of the test, the Jet Ski was placed at a fixed start position facing the straight part with a clear view of the marked curved part ahead. In this test, the operator was only asked to stop as close to finish line as possible and to get there in the shortest amount of time (by always staying within the buoys). The speed during navigating this course was left to the operator.

The additional challenge of this test is the fact that the operator has to negotiate a 90 degrees turn while, at the same time, initiate deceleration ahead of the finish line.

The spreadsheet Rides_table.xls shows selected results from this test (in the data block called "Curved"). As expected, there is a larger variation in the time needed

from start to final stop since individual subjects drove at different speeds while trying to negotiate the curved course. As before, “aggressive” versus “timid” driving plays a role in the outcome and may or may not relate to previous PWC driving experience.

5.3 Collision Tests

Designing a test that places the operator into a panic situation and obtaining comparable driving patterns and results was very difficult. Experiments with a pontoon boat that appears around a corner or another Jet Ski crossing the path did not yield comparable results. Driver’s reactions to these situations varied widely and could not be captured in a way that allowed for practical further analysis.

The “old” trick of the pop-up log (used in earlier studies) seemed to work best and was adopted for this test. At any point in time (selected by the tester) and without warning, a log pops out of the water at a fixed distance (25 meters) ahead of the moving Jet Ski. The PWC operator may be able to avoid collision with the log (Avoid) or will collide with the log (Crash). The test is very short (less than 2 seconds) and, therefore, does not allow for much variation in driving patterns. Familiarity with the off-throttle-steering-loss is most important for this test.

Each subject was exposed to three different version of the collision test:

Collision 40mph: For the first collision test, the subject is asked to drive at maximum speed (about 40 mph) on a straight line across the lake. Without warning, the log pops up at 25 meters ahead of the speeding Jet Ski. This test was designed to make every subject crash with the intention to overcome the shock of this first log encounter and prepare for the next two collision scenarios. However, one subject managed to avoid the log while driving at maximum speed.

Collision 30mph: The second collision test was performed at significantly lower speed (30 mph). By now, the subject knows what to expect and can demonstrate his or her ability to avoid the log. While the first test (at 40 mph) resulted in 23 crashes (for 24 subjects), the second test produced only 7 crashes.

Collision 35mph: For the third and last collision test, the operator was asked to drive at 35 mph, thereby, making the test more difficult than the previous one. Amazingly, only 6 crashes were encountered indicating that most subjects learned from the previous collision tests and, as the data also show, reduced their reaction time.

For the three collision tests, the spreadsheet Rides_table.xls shows the outcome (Avoid/Crash), the reaction in handlebar and throttle operation, and the reaction time. The reaction time is measured from the moment the log pops up until the first change in handlebar or throttle position, respectively, is observed (recognizable in the log file). All subjects reacted first by turning the handlebar sharply. Most important is the reaction in throttle operation. Letting the throttle go (down) results in steering loss.

Accelerating (throttle up) improves the capability to steer and helps with avoiding the collision.

In all three collision tests, the subjects were asked to drive on a straight line at the given respective speed. The current speed was always visible through a virtual speedometer projected at the lower left in the virtual environment at a constant distance from the Jet Ski. Most subjects managed this task very well. The actual speed at the moment when the log pops up is listed in the spreadsheets. Only two subjects deviated from the requested speed by a noticeable amount (bold numbers in the spreadsheet). However, because of the mall subject pool, these results were not removed from the analysis.

6. Analysis and Selected Results

The study produced an enormous amount of data (all data files are available on the PWCStudy Web site). This data can be analyzed in a variety of ways. In the following, only some of many possible findings are reported. Since the log files with the time histories of all tests for the 24 subjects have been saved, further analysis can be performed at any time.

The spreadsheet Rides_Analysis.xls (available on the PWCStudy Web site) shows selected results. The subject pool was divided into two groups as follows:

Total Number of Subjects = 24

NO = Novice Drivers, Total = 13

EX = Experienced and Expert Drivers, Total = 11

All values given below are average values for the respective group (NO or EX). The spreadsheet is set up in a way that mean values, standard deviations, and other relevant statistics can be calculate easily if so desired.

6.1 Straight Course Tests

The Straight Course Test was performed twice by each subject. For the findings below, the results from both tests (Straight 1 and Straight 2) have been combined.

General Observation:
NO are more careful (“timid”), take more time. (9% more than EX).
EX drive more efficiently (“aggressive”), reach finish line 2.2 seconds earlier.
Remaining distance to finish line is similar for both NO and EX (a little shorter for EX).

Time from Start to Final Stop:

NO:	26.378 seconds
EX:	24.144 seconds

Remaining Distance to Finish Line:

NO:	16.915 meters
EX:	15.653 meters

6.2 Curved Course Tests

General Observation:
Difference between NO and EX is more pronounced regarding time. NO seem to have more problems negotiating the curved course.
NO are more careful, need 17% more time.
EX drive more efficiently, reach finish line 6 seconds earlier.
Remaining distance to finish line is again similar (a little shorter for EX).

Time from Start to Final Stop:

NO:	41.808 seconds
EX:	35.752 seconds

Remaining Distance to Finish Line:

NO:	16.203 meters
EX:	15.920 meters

6.3 Collision Tests

General Observations – Reaction Times:
When combing all three collision tests, the average reaction time of EX is slightly better than NO. The difference may not be significant; reaction time may be independent from previous PWC driving experience.

Total Average Reaction Time:

NO:	0.874 seconds
EX:	0.792 seconds

General Observations – Crash/Avoid:
EX perform significantly better than NO.
EX improve significantly from collision test at 30 mph to subsequent collision test at 35 mph. No improvement with NO.

Collision at 30 mph:

NO:	45.45% Crash	54.55% Avoid
EX:	15.38% Crash	84.62% Avoid

Collision at 35 mph:

NO:	45.45% Crash	54.55% Avoid
EX:	7.69% Crash	92.31% Avoid

General Observations – Use of Throttle:
Proper use of the throttle (before an imminent crash) requires some sense for the off-throttle-steering-loss. Here, the EX perform significantly better by accelerating in order to make the crash-avoiding turn or by keeping the throttle unchanged (which still enables steering). Letting go of the throttle (and, thereby, being unable to turn) is the intuitive, but incorrect reaction seen by the majority of NO.

Throttle Reaction in Response to Sudden Log Appearance:
(results from Collision 30mph and Collision 35mph combined)

	NO	EX
Let go of throttle (down – incorrect)	59.09%	7.69%
Do not change throttle (none – adequate)	18.18%	42.31%
Accelerate (up – best reaction)	22.73%	50.00%

6.4 Conclusion

The selected results shown above indicate that the Virtual Jet Ski Driving Simulator provides, to some degree, a realistic simulation of real PWC driving. The simulator allows for recognizing the driving skills of PWC operators. Experienced and expert drivers seem to perform better than novice drivers. This is most pronounced in the analysis of the throttle use during a panic situation. In other tests (straight and curved course driving and stopping), the difference is less distinct.

The results need to be examined with care. It seems that many other factors (besides PWC driving experience) influence the driving behavior in a virtual simulator. For example, one novice driver (she had never been on a Jet Ski) managed to avoid the pop-up log at maximum speed due to an unusual short reaction time for this first log encounter. Another pre-test subject (not included in these results) managed all tasks perfectly, had never driven a Jet Ski before, but was a video game expert. Other factors like “timid” versus “aggressive” behavior, being uncomfortable with an unfamiliar virtual environment, or taking the driving tests not seriously may play a role.

This study, although already meaningful, could be refined by developing additional or alternative test scenarios, designing new test protocols, using a larger and carefully screened subject pool, and by further improving the driving simulator.

7. Acknowledgment

We would like to thank the sponsors for funding this challenging, but highly interesting study. Special thanks goes to Dr. Anthony Andrady, Research Triangle Institute, for initiating and advising the study. In addition, we highly appreciate the efforts and contributions from Hagen Buchholz, Lars Schumann, and Scott Hamm, University of Michigan 3D Lab, in preparing and conducting this study. Finally, thanks goes to the 24 human subjects and the additional pre-test volunteers who dared to ride the virtual Jet Ski into dangerous territories.

Appendix A: Test Protocol
(including Data Files under "7. Data Processing")

Test Protocol

PWC Operation Study using the Virtual Jet Ski Driving Simulator
Last Update: 10/18/06 by KPB

1. Welcome and Introduction

Give subject Consent Form, ask subject to read and sign
Explain: Consent Form required by UofM for any human subject study

If subject ask about off-throttle-steering-loss (mentioned in Consent Form), tell subject this will be explained later (after the test).

Create ID for subject (format Sxx starting with S01)
Collect and record data on prepared sheet as follows

- Date
- Subject ID (Sxx)
- Age (must be 18 years or older)
- Gender (M/F)
- Jet Ski Driving Experience
  - None
  - Once (how long)
  - Occasional (number of hours)
  - More (owns or has frequent access to a Jet Ski)
- Boating Safety Course (yes/no)
- Snowmobile Experience
- CAVE Experience

Set up Free-Ride in CAVE

Introduce subject to CAVE
Explain purpose: to protocol and study driving behavior and reactions
Mention sponsor: US Coast Guard
Explain briefly CAVE and Simulator, handlebar and throttle use
(Do not mention off-throttle-steering-loss)

2. Free-Ride

Purpose: familiarize subject with simulator and Jet Ski operation
Start simulator with Jet Ski at home dock

Ask subject to drive Jet Ski out on lake and through channel on other side
Point out: channel is on the right of the lighthouse
Ask subject two times to stop and get a feeling for run-out behavior
This includes: Ask subject to try stopping under bridge; encourage repeated use of throttle

- Log File not needed; will be overwritten by "5. Collision"

3. Straight-Line

Set up Straight-Line Course in CAVE

3.1 Explore Straight-Line Course

Ask subject to explore course and drive to finish line at his/her own pace (this will load all required textures)

- First Straight-Line log file not needed

3.2 First Straight-Line Test (data under **Straight 1**)

Reset (place Jet Ski in start position)

Ask subject to drive as fast as possible to finish line, but stop as close as possible in front of finish line

Encourage subject to use full throttle from start

Wait until Jet Ski comes to a complete stop — Take notes:
Subject stays within buoys: y/n
Stops before/behind finish line

- Second Straight-Line log file: Save as S0xx_Straight1.log

3.3 Second Straight-Line Test (data under **Straight 2**)

Reset (place Jet Ski in start position)

Ask subject to repeat the above

Wait until Jet Ski comes to a complete stop — Take notes:
Subject stays within buoys: y/n
Stops before/behind finish line

- Third Straight-Line log file: Save as S0xx_Straight2.log

4. Curved-Course

Set up Curved-Course in CAVE

4.1 Explore Curved-Course

Ask subject to explore course and drive to finish line at his/her own pace (this will load all required textures)

- First Curved-Course log file not needed

4.2 Curved-Course Test (data under **Curved**)

Reset (place Jet Ski in start position)

Ask subject to drive as fast as possible to finish line, but stop as close as possible in front of finish line

DO NOT encourage subject to use full throttle from start (leave it up to subject)

Wait until Jet Ski comes to a complete stop — Take notes:
Subject stays within buoys: y/n
Stops before/behind finish line

- Second Curved-Course log file: Save as S0xx_Curved1.log

(No repeat of Curved Course)

5. Collision

Set up Free-Ride in CAVE

Ask subject to drive out on lake and turn left

Tell subject that an object will appear and that subject should try to avoid object

Ask subject to always go in the direction of far away bridge (to have sufficient space)

5.1 Collision at full speed (data under **Collision 40mph**)

Ask subject to go full speed (40 mph) and on a straight line

Wait for full-speed straight line driving
Pop up log at 25 m — Take notes:
Crash = full crash with log
Avoid = avoided log, no crash

Allow subject to recover

5.2 Collision at 30 mph (data under **Collision 30mph**)

Ask subject to go 30 mph on a straight line

Wait for 30 mph (approx.) straight line driving
Pop up log at 25 m — Take notes:
Crash = full crash with log
Avoid = avoided log, no crash

Allow subject to recover

5.3 Collision at 35 mph (data under **Collision 35mph**)

Ask subject to go 35 mph on a straight line

Wait for 35 mph (approx.) straight line driving
Pop up log at 25 m — Take notes:
Crash = full crash with log
Avoid = avoided log, no crash

End of Test, ask subject to leave CAVE

- Free-Ride log file (contains 5.1, 5.2, and 5.3 events): Save as S0xx_Free1.log

6. Closing

Provide subject with copy of Consent Form

Answer any remaining questions subject may have, explain off-throttle-steering-loss if asked

Thank subject for cooperation and send subject on his/her way

7. Data Processing

Create Directory called S0xx for the subject-specific files listed below.

Save all relevant log files (save 4 files out of 6) with the following filenames:

for Straight 1:	S0xx_Straight1.log
for Straight 2:	S0xx_Straight2.log
for Curved:	S0xx_Curved1.log
for Collision 40mph/30mph/35mph:	S0xx_Free1.log

Derive additional subject-specific files from the above:

Compressed log files:
- S0xx_Straight1.txt
- S0xx_Straight2.txt
- S0xx_Curved1.txt
- S0xx_Free1.txt

Spreadsheet combining all txt files and graphs:
- S0xx_Graphs.xls

VRML representation (lake map, path, graph; speed, handlebar, throttle; event and collision markers):
- S0xx_Straight1.wrl
- S0xx_Straight2.wrl
- S0xx_Curved1.wrl
- S0xx_Free1.wrl

Note that the above VRML files call on other files that need to be present in directory S0xx (for each of the four log files the individual history of speed (sp), handlebar (hb), and throttle (th), the lake map geometry, the slider, and other auxiliary files). When Data Processing for a subject is completed, the subject's directory S0xx should contain a total of 34 files.