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Pilot Gain and the Workload Buildup Flight Test Technique:

A Closer Investigation of Pilot Inceptor Workload

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Background and Overview

The term "pilot gain" essentially describes the way the pilot acts on the inceptor during flight. It is a key aspect of handling qualities research and related flight tests. Pilots are asked to fly intentionally high or low gain and there are specific tasks associated with high gain flying - e.g. air-to-air refueling - and low gain flying - e.g. a course correction during a ferry flight. Most test organizations have their famous high and low gain pilots and the term "pilot gain" is understood very well on an intuitive level - especially when sitting in the backseat of an aircraft controlled by a high gain pilot. But in spite of all this, there is no generally accepted verbal or mathematic definition of "pilot gain".

Pilot inceptor workload is one way to quantify pilot gain. It is a two-dimensional plot of the pilot's aggressiveness (defined as the stick speed) vs. duty cycle (defined as the percentage of time the pilot moves the stick). It was introduced by the USAF Test Pilot School (TPS) as a comprehensible representation of pilot gain for test pilots and flight test engineers who are trained at the TPS.

This report includes a comprehensive investigation of pilot inceptor workload based on theoretic evaluations, simulator data and open source flight and simulator test data.

Chapter 1 gives a short introduction to the topic of "pilot gain" including pilot gain measures and two-dimensional representations of pilot gain (power spectral density plots and pilot inceptor workload).

Chapter 2 introduces and evaluates four potential one-dimensional forms of the two-dimensional pilot inceptor workload. The analysis is performed based on mathematic considerations and theoretic evaluations of experimental test pilots from the German test center (WTD 61).

Chapter 3 focuses on the relation between the two dimensions of pilot inceptor workload (aggressiveness and duty cycle). The evaluation is based on data gathered within a simulator study with 24 military pilots who applied different flight test techniques. These included the pilot gain calibration runs during which the pilots had to intentionally apply different pilot gain (low, normal and high) during a challenging sum of sines tracking task. Also, three different versions of the workload buildup flight test technique were performed using the same tracking task. In addition, the simulator data was compared with open source information about F-16 flight test data from the USAF TPS project BAT DART.

Chapter 4 validates potential one-dimensional versions of pilot inceptor workload based on the simulator data and evaluates the necessity of a one-dimensional variant of pilot inceptor workload.

Chapter 5 introduces and compares variants of the pilot inceptor workload plot based on stick deflection and acceleration.

Content

Abbreviations and Nomenclature

AFB	Air Force Base
BAT	Boundary Avoidance Tracking
DART	Deterministic Analytical Rating Task
DLR	Deutsches Zentrum für Luft- und Raumfahrt e.V. (German Aerospace Center)
FTT	Flight Test Technique
HOTAS	Hands On Throttle and Stick
HTF	Highest Task Frequency
PIO	Pilot-Induced/Involved/In-the-loop Oscillation
PIW	Pilot Inceptor Workload
PIW1	One-Dimensional Form of PIW
PSD	Power Spectral Density
PT1	Point Tracking pilot model 1
RMS	Root Mean Square
TPS	Test Pilot School
USAF	United States Air Force
WTD 61	Bundeswehr Technical and Airworthiness Center for Aircraft

Nomenclature

δ	stick input
δ_{max}	maximum stick deflection
agg	aggressiveness
dc	duty cycle
K_1	pilot model gain
K_1	noise threshold
K_2	maximum stick deflection
n	number of discrete data points during a test point
R	Regression Coefficient
t1	start time of test point
t_2	end time of test point
T_D	lead compensation time constant
T_e	time delay
T_I	lag compensation time constant
t_n	end time of test point
x_i	binary value representing a data point contributing to the duty cycle

Note: Redundant nomenclature could not be avoided because equations from other authors were quoted in their original form.

Figures

Tables

1. Measuring Pilot Gain

1.1. Pilot Gain

The term "pilot gain" essentially describes the way the pilot acts on the inceptor during flight. Very often the term "pilot gain" is used synonymously with the expression "aggressiveness", a term quite familiar to most pilots. Pilot gain is a key aspect of handling qualities research and related flight tests. Pilots are asked to fly intentionally high or low gain and there are specific tasks associated with high gain flying, e.g. air-to-air refueling, and low gain flying, e.g. a course correction during a ferry flight.

The lower the pilot gain, the more the pilot-vehicle system resembles the stable aircraft dynamics; the higher the pilot gain, the less stable is the pilot-vehicle system. This is why high gain pilots tend to find unfavorable aircraft dynamics a low gain pilot may only experience in an emergency situation. Pilot gain is a matter of task, training, aircraft dynamics and the current stress level, but it is also a matter of individual disposition. In nearly all flight test organizations there is a famous low gain pilot and a famous high gain pilot. Both dispositions have their advantages and disadvantages and none is generally superior to the other.

Even though pilot gain is one of the most important aspects in handling qualities testing and even though it is very well understood on an intuitive level, there is no generally accepted verbal or mathematical definition. There are, however, several suggestions for pilot gain measures. In [10] and [12] potential pilot gain measures were introduced and evaluated.

Based on a special test setup, a validation was performed for 30 potential pilot gain measures [12]. The validity of a potential pilot gain measure was based on its ability to reflect the pilot gain the pilot intended to apply during the test. The validity was quantified by means of a validity index with a range from -1 (monotonically decreasing with pilot gain) and 1 (monotonically increasing value pilot gain). In addition, three significant outliers were identified during the tests. Their different tracking behavior was supported by PSD plots and time histories of their stick inputs. An efficient pilot gain measure had to be able to identify these three outliers with their specific effects. Finally, a pilot gain ranking was derived based on the 20 pilot gain measures which achieved a good validity index. The deviation of individual pilot gain measures from the overall ranking was used as a third parameter for the validation process. Overall, valid 10 pilot gain measures were identified. They are

- Mean Stick Speed
- RMS Stick Speed[1]
- Percentage of High Stick Speeds
- Mean Stick Acceleration
- RMS Stick Acceleration
- Percentage of High Stick Accelerations
- Duty Cycle[2]
- PSD Area HTF – 2 Hz[3]
- PSD Ratio Area (HTF - 2 Hz) vs. Area (0 - 2 Hz)
- PSD Ratio Area (HTF - 2 Hz) vs. Area (0 Hz - HTF)
- Goodness of fit of the PT1 pilot model[4]

More detailed information can be found in [12].

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[1] RMS = Root Mean Square

[2] Duty Cycle was a last-minute addition and not checked for consistency with the pilot gain ranking

[3] PSD = Power Spectral Density, HTF = Highest Task Frequency

[4] The PT1 pilot model is the same model used for the Neal-Smith criterion [8], but without the assumptions of this criterion. Parameter identification is performed instead.

1.2. Power Spectral Density Plots

There are two common two-dimensional pilot gain measures. One possibility is to use Power Spectral Density (PSD) plots of the pilot's stick inputs. These plots give an overview of the frequencies the pilots uses during a tracking task. Figure 5-1 shows an example of a PSD plot.

The plot is based on a sum of sines task. During this type of task the pilot has to track a target with an aircraft-fixed reference. The target's movement is based on a sum of sines with predefined frequencies. In Figure 5-1 the PSD peaks in the area between 0 Hz and the Highest Task Frequency (HTF, 0.7 Hz in the example) are sharp and defined. They reflect the frequencies of the sum of sines task which was used for the target movement.

The PSD peaks in the area beyond the HTF are more scattered and distributed over a frequency range. They are often a result either of high pilot gain or flaws in the aircraft dynamics (or both). They mainly occur when the pilot overshoots the target and then corrects back in both directions for several times. When the aircraft dynamics are kept constant, pilot gain is the main contributing factor for differences in this area.

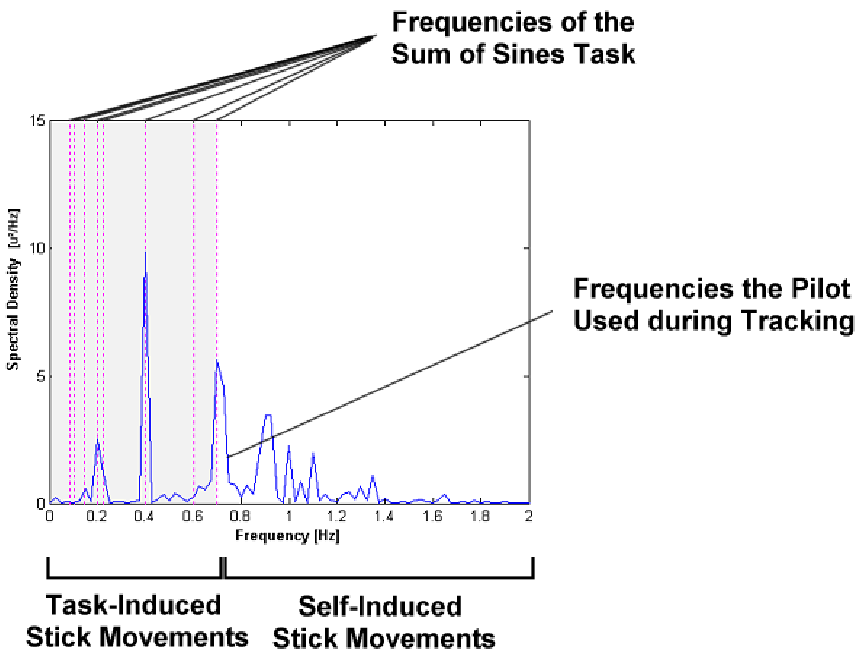


Figure 5-1: Example PSD Plot with PSD Areas

PSD plots can not only be used to identify the pilot gain variation of an individual pilot, they also expose important characteristics of pilots who prefer to fly rather gently (low gain pilots) or aggressively (high gain pilots) [12]. The differences become evident when the PSD plots are separated into two regions: The region above and below the HTF. Because of this effect, the two-dimensional PSD can be reduced to one dimension by regarding the area below the PSD curve. This PSD area reflects the signal power of the pilot's stick inputs within the specified frequency range. Among others this approach was used in [4] as a potential of pilot control activity, even though the frequency ranges were defined in a different way than in [12].[5]

By regarding the signal power (PSD area) or signal power ratios, the pilot gain can be reasonably assessed [12] and the two-dimensional PSD is reduced to a one-dimensional measure.

[5] In [4], four pre-defined frequency regions are assigned for different types of tasks ranging from "Typical open-loop control associated with trimming and flight path modulation" (0.25 – 0.8 rad/s) to "Very high-gain closed-loop control, almost certainly associated with control difficulties" (4.0 – 10.0 rad/s). In [12] only two task-related frequency regions are defined: the region above and below the HTF.

1.3. Pilot Inceptor Workload

Pilot Inceptor Workload (PIW) is the second common two-dimensional pilot gain measure. It originates from the USAF Test Pilot School and consists of two time domain-based measures, duty cycle (or duty factor[6]) and aggressiveness [5], [6], [7]. The idea for PIW arose because of the necessity to measure pilot gain in a way that is readily apparent to pilots and does not require an experienced handling qualities engineer for interpretation (as it is generally the case for PSD plots). The need for a less complex pilot gain measure was also a consequence of the tight schedule at the USAF Test Pilot School.

1.1.1. Duty Cycle

Duty Cycle is defined as "the percentage of time the pilot is changing his input on the stick" [5], [6], [7]. It is closely related to the pilot's effort.

In [19] a mathematic representation of duty cycle is suggested in a continuous form:

$$dc = 100\% \cdot \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} f(t)dt \qquad \text{Eq. 1}$$

$$f(t) = \begin{cases} 0, \left| \frac{d}{dt}\delta(t) \right| < K_1 \ and \ |\delta(t)| < K_2 \\ 1 \end{cases} \qquad \text{Eq. 2}$$

where t_1 is the start and t_2 the end time of the test point, dc is the duty cycle, $\delta(t)$ is the control input. In addition, two thresholds are defined. K_1 is a noise threshold used to avoid that very small inceptor signals (noise, vibrations) are regarded as voluntary stick movements. K_2 is the value for which a duty cycle of 1 is assumed even if the inceptor is held motionless. This is the case for the maximum deflection as it is assumed the pilot would move the inceptor even further if he could.

Because the real world creates continuous signals, but flight test instrumentation only collects discrete data, the definition of the duty cycle is converted to a discrete form in this report:

$$dc = \frac{1}{t_n - t_2} \sum_{i=2}^{n} x_i \qquad \text{Eq. 3}$$

$$x_i = \begin{cases} 0, \left| \frac{\delta_i - \delta_{i-1}}{t_i - t_{i-1}} \right| < thr \ and \ |\delta_i| < \delta_{\max} \\ 1 \end{cases} \qquad \text{Eq. 4}$$

where t_1 is the start and t_n is the end time of the test point, n is the number of discrete data points contained in the test point, δ_i and t_i are the discrete values of the stick deflection and the time, thr is the noise threshold and δ_{max} the maximum stick deflection.

Due to the discrete calculation of the stick speed, x_i contains one element less than δ_i which is why the sum used for the duty cycle calculation begins at i = 2 instead of i = 1.

1.1.2. Aggressiveness

Aggressiveness is defined as "the root-mean squared per-second average of the inceptor measurand (position or force) rate of change" [5], [6]. Aggressiveness adds information about how the pilot moves the stick to the information provided by the duty cycle.

[6] The suggestion to use „duty factor" instead of „duty cycle" was made in [7]. Because most papers refer to "duty cycle", this term is pursued in this report.

In [19] a mathematic representation of Gray's definition for aggressiveness is suggested in a continuous form:

$$agg = 100\% \cdot \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \frac{|\delta(t)|}{\delta_{max}} dt \qquad \text{Eq. 5}$$

where agg is the aggressiveness and the other parameters are in line with the definitions of Equations 1 and 2. The division by δ_{max} is used to normalize the range to ±1 for the inceptor deflection.

The discrete form used in this report is

$$agg = \sqrt{\frac{1}{n-1} \sum_{i=2}^{n} \left(\frac{\delta_i - \delta_{i-1}}{t_i - t_{i-1}} \right)^2} \;. \qquad \text{Eq. 6}$$

In this report, the duty cycle and stick command range between 0 and 1 instead of 0 and 100% like in [19]. Also, the stick deflection is by default in between a value of -1 and 1.

1.1.3. PIW Plot

Figure 1-2 shows the general layout of a PIW plot. As the data point moves away from the plot's origin, the pilot gain is increased. Its maximum is reached when both, duty cycle and aggressiveness, reach their maximum value (upper right corner).

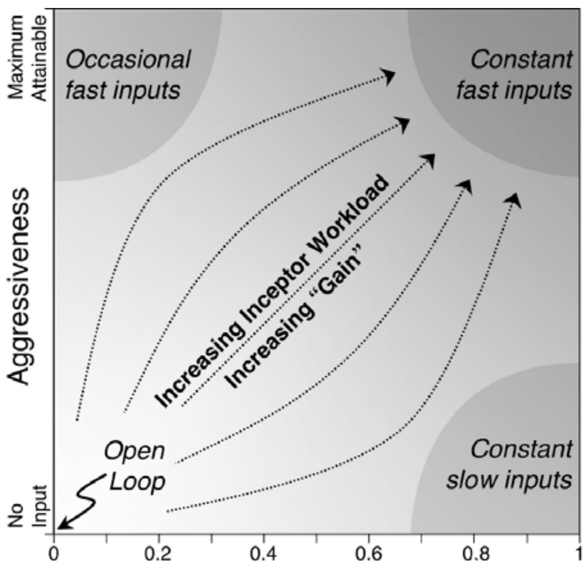


Figure 1-2: Pilot Inceptor Workload Plot [5], [6], [7]

High aggressiveness and low duty cycle (left upper corner in the PIW plot) represent occasional fast inputs, often used in conjunction with lead compensation where the pilot applies an input based on pre-existing knowledge about the aircraft dynamics and waits for the aircraft to settle until he applies the next input. This tracking behavior is associated with momentarily high pilot gain, but a rather open loop strategy.

Low aggressiveness and high duty cycle (right lower corner in the PIW plot) represent a constant, but slow stick movement. The pilot is in the loop, but the pilot gain is rather low.

2. One-Dimensional Forms of Pilot Inceptor Workload (PIW1)

Overall four different one-dimensional forms of PIW (called PIW1) are introduced in this report.[7]

Note that all one-dimensional forms of PIW require a normalized value for the aggressiveness. Chapter 3.5 takes a closer look at potential ways to a potential normalization process.

As a prerequisite for reasonable choices of PIW1, the reduction of a two-dimensional PIW plot to PIW1 should result in a value ranging from 0 for the origin to 1 for the right upper corner with maximum pilot gain.

An interesting aspect is the choice of a value for the critical corners being the upper left und lower right corner. This value could either be zero or nonzero – whether it takes either of these values is a question of philosophy: mathematically there is no possibility to reach a nonzero duty cycle with zero stick speed. The correct mathematic solution would hence be a singularity for the corners. This however very likely creates problems with values close to the corners. Another way of looking at it would be to set the PIW1 value for these corners to zero. However, when converging towards the corner the PIW1 value could get quite low for this solution – close to zero – while there should be a significant difference between a data point close to the origin and a data point with e.g. slow constant stick movements. A third solution is a low but non-zero pilot gain value for the corners. This would, however, also give a mathematically valid solution for the impossible case of a nonzero value on one axis and a zero on the other one.

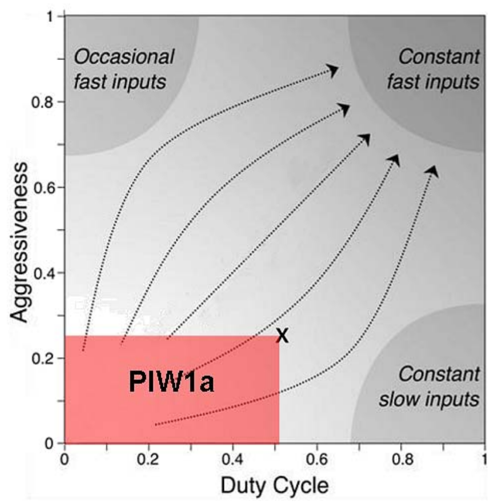
After all there is no perfect solution. However, simulator data has shown that the critical corners are not approached during a closed loop tight control tracking task which is why their importance must not be overestimated.

2.1. Suggestions for PIW1

2.1.1. PIW1a

A simple way to reduce PIW to one dimension is by multiplying both, the values of duty cycle and aggressiveness. Mathematically, the resulting value represents the area of a rectangle with side lengths corresponding to the values of the duty cycle and aggressiveness value (Figure 2-1).

The value at the critical corners is 0.



$$PIW1a = agg \cdot dc \qquad \text{Eq. 7}$$

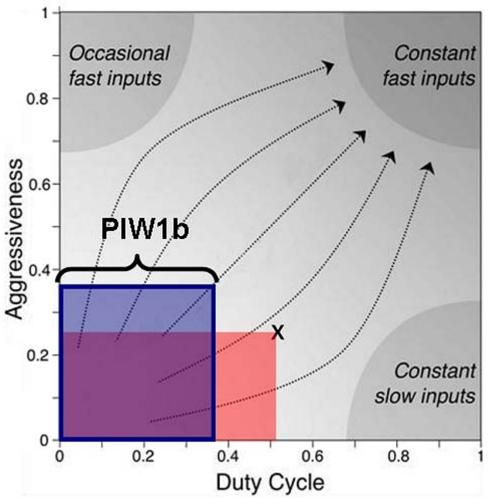
Figure 2-1: Depiction of PIW1a

[7] Most of the information about PIW1 in this report is based on a pre-publication as technical note by the same author [11] which was used as a quick workaround to provide the USAF Test Pilot School with information about the different forms of PIW1.

One main problem of this PIW1 form is the lack of linearity at the diagonal. Intuitively, if the normalized aggressiveness and duty cycle have the same numerical value, it is reasonable that PIW1 has the same value. For example if aggressiveness and duty cycle are both 0.5, PIW1 should be 0.5, too. For PIW1a the resulting value is, however, 0.25 which seems rather unintuitive.

2.1.2. PIW1b

A potential solution for the nonlinear values at the diagonal of the PIW plot is the use of the square root of PIW1a. Mathematically, the resulting value is the side length of a square having the same area as the rectangle used for the calculation of PIW1a (Figure 2-2).



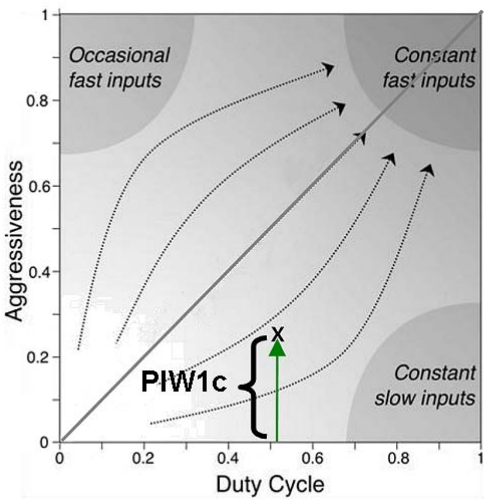
$$PIW1b = \sqrt{agg \cdot dc} \qquad \text{Eq. 8}$$

Figure 2-2: Depiction of PIW1b

The value at the critical corner is 0 and the diagonal has linearly distributed values, meaning that for an aggressiveness and duty cycle of 0.5 the PIW1b value is also 0.5.

2.1.3. PIW1c

A very simple way of reducing the two-dimensional PIW plot to PIW1 is using the minimum of both values, normalized aggressiveness and duty cycle (Figure 2-3).



$$PIW1c = \min(agg, dc) \qquad \text{Eq. 9}$$

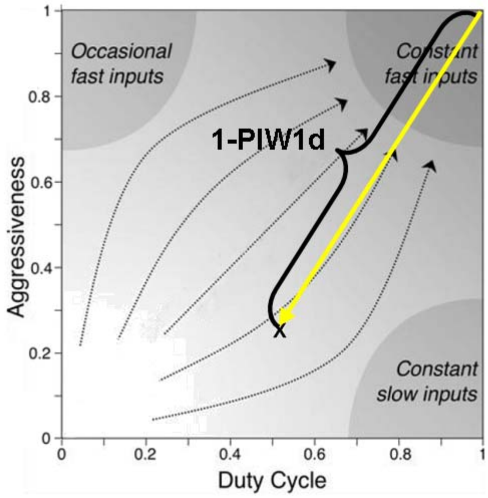
Figure 2-3: Depiction of PIW1c

The value at the critical corner is 0 and the diagonal has linear values.

2.1.4. PIW1d

PIW1d is the mathematically most complicated combination. It intends to directly catch the effect that the pilot gain is higher with closer proximity to the upper right corner with maximum gain.

First of all the data point's distance to the upper right corner is calculated with Pythagoras' theorem. As this approach would result in a PIW1 value which becomes smaller with increasing pilot gain, the distance is subtracted from 1 (Figure 2-4).



$$PIW1d = 1 - \frac{\sqrt{(1-agg)^2 + (1-dc)^2}}{\sqrt{2}} \qquad \text{Eq.10}$$

Figure 2-4: Depiction of PIW1d

The value at the critical corner is nonzero (0.29) and the diagonal has linear values. This version of PIW1 was first introduced in [10] and [13].

2.1.5. Summary

Table 2-1 provides a summary of the different forms of PIW1.

PIW1a is the only form with nonlinear values at the main diagonal of the PIW plot; PIW1d is the only form with nonzero values for the critical corners.

Name	**Equation**	**Value at the Critical Corners**	**Linearity at the Main Diagonal**	**Equation**
PIW1a	$PIW1a = agg \cdot dc$	0	no	Eq. 7
PIW1b	$PIW1b = \sqrt{agg \cdot dc}$	0	yes	Eq. 8
PIW1c	$PIW1c = \min(agg, dc)$	0	yes	Eq. 9
PIW1d	$PIW1d = 1 - \frac{\sqrt{(1-agg)^2 + (1-dc)^2}}{\sqrt{2}}$	0.29	yes	Eq.10

Table 2-1: Summary of Different Forms of PIW1

2.2. Theoretic Analysis of PIW1

2.2.1. Three-Dimensional Representations

One way of comparing the different forms of PIW1 is by creating three-dimensional representations with the two basic dimensions (x-y) being the conventional PIW plot and the third dimension being the PIW1 value.

The idea for the three-dimensional representations arose when one pilot commented that the PIW1 should be like a tablecloth which is held up at the corner with the maximum pilot gain.

This also means he implied a value of zero for the critical corners and all locations in the PIW plot where one of the two parameters is zero. This would exclude PIW1d.

The three-dimensional representations are given in Figure 2-6. It is evident that the pilot's description matches the interpretation of PIW1a even though the diagonal of the PIW plot is the only one without a linear distribution of PIW1.

An interesting effect is that in spite of their mathematic profound difference and their different interpretation of the pilot gain values at the corners, PIW1b and PIW1d create quite similar results for the core of the three-dimensional plots. As it was mentioned before, the values at the corners should not be overestimated as they hardly ever come in play in a closed-loop tight control tracking task. An example for a normal parameter range based on a sum of sines task is given in Chapter 4.

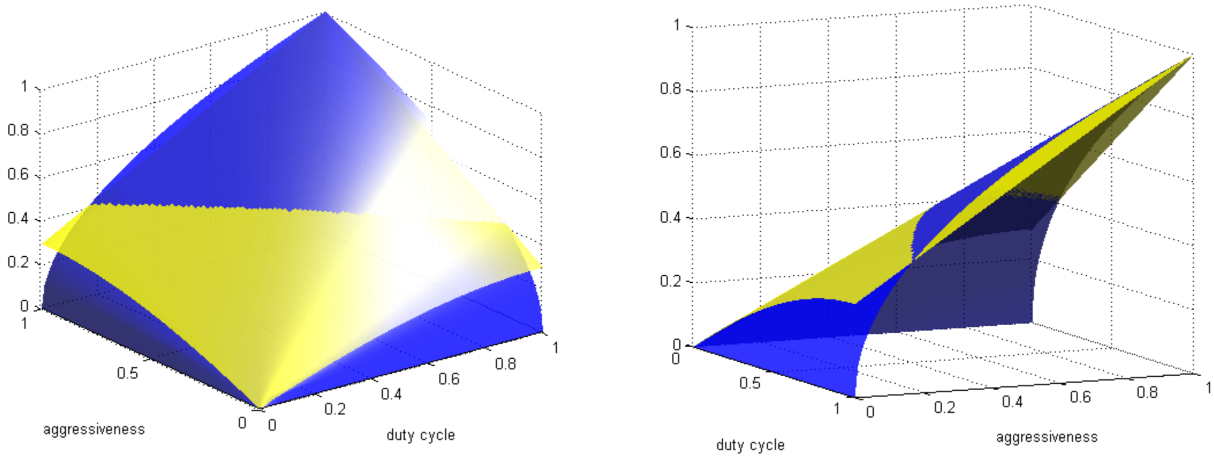


Figure 2-5: Comparison between PIW1b and PIW1d Values

As PIW1b and PIW1d are that similar in the relevant parameter range, the mathematically simpler form should be preferred – in this case this is PIW1b.

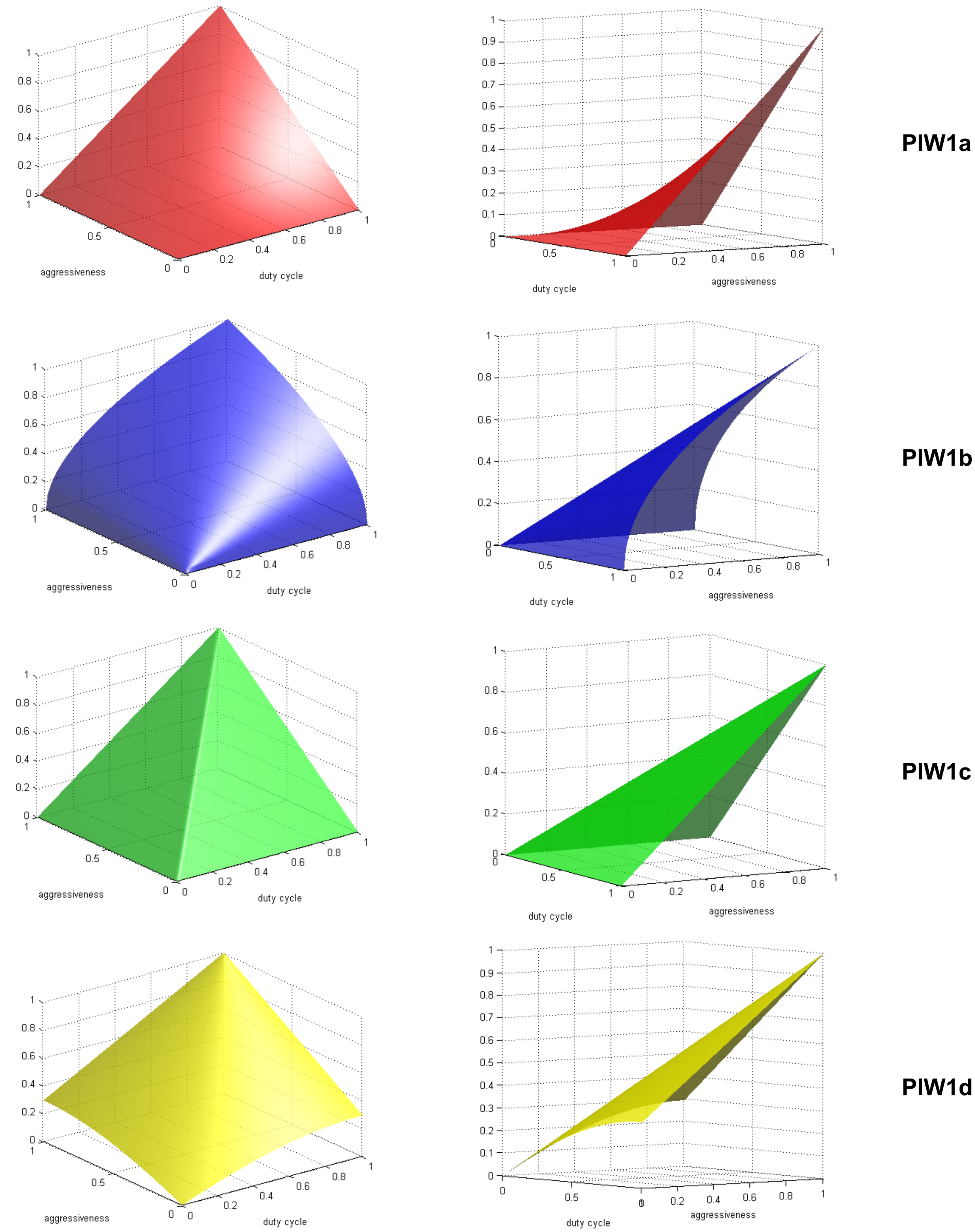


Figure 2-6: Three-Dimensional Representations of Different Forms of PIW1

2.2.2. Isogains

Another way of comparing different forms of PIW1 are "isogains". These are lines with constant values of pilot gain represented by PIW1. The isogains presented in Figure 2-7 show PIW1 values ranging from 0 to 0.9. In all cases, 1 is achieved only at the upper right corner.

PIW1a shows an unequal distribution of the isogains over the PIW plot. An already quite significantly high value of [0.32, 0.32] has to be achieved at the diagonal for the first isogain with PIW1a = 0.1.

The isogains for PIW1b are more reasonably distributed.

As it was already visible in Figure 2-6, it becomes evident that PIW1c has an unsteady derivative at the diagonal. Whenever possible, a mathematically unfavourable effect like this should be avoided.

PIW1d shows parallel sectors because it is based on the data point's distance towards the upper right corner of the PIW plot.

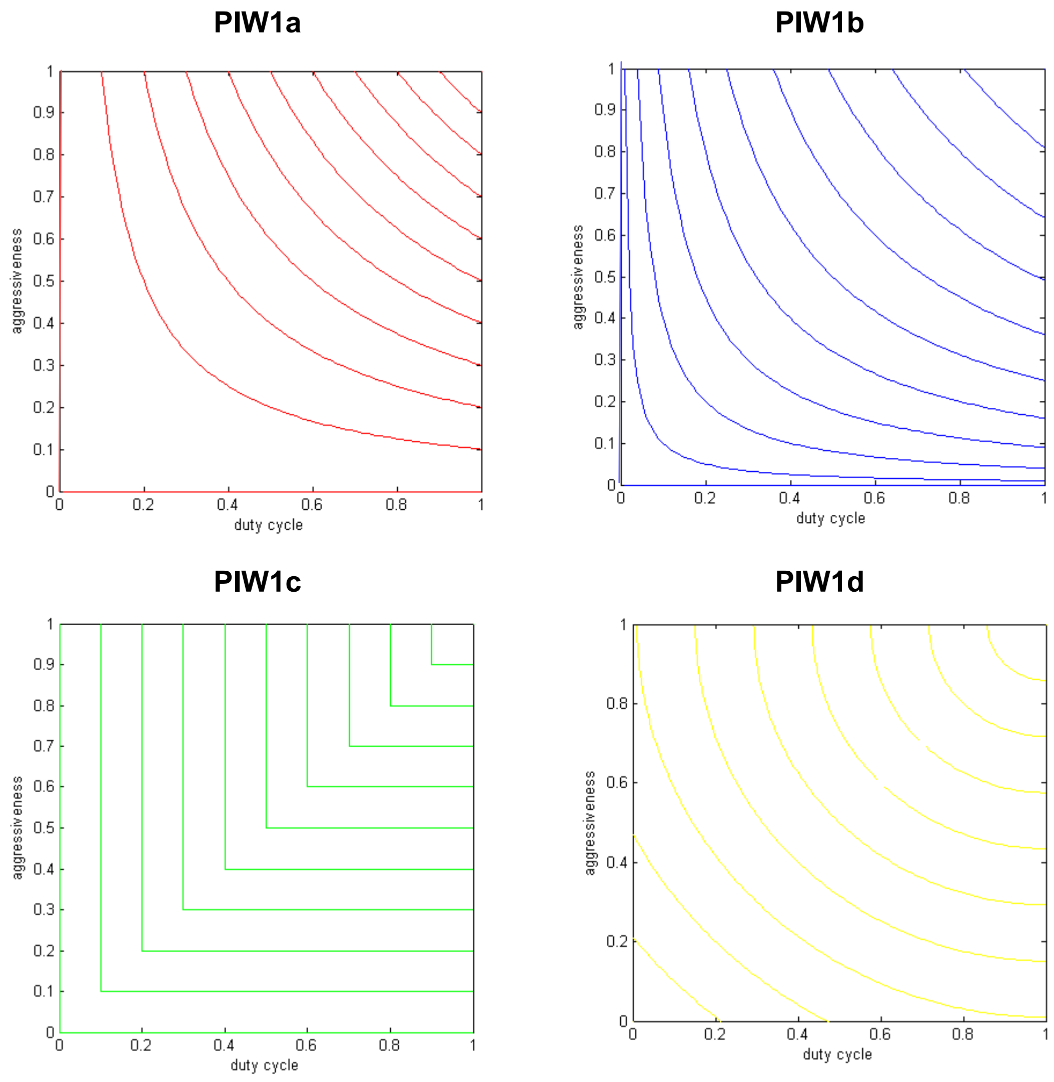


Figure 2-7: Isogains of Different Forms of PIW1

2.3. Comparison of PIW1 with the Assessment of Test Pilots

In order to compare the theoretical considerations about PIW1 with the opinion of experimental test pilots, five test pilots from WTD 61 were consulted and asked to assign one-dimensional values to 12 different test cases. The test cases were provided in the form of PIW plots with a red "X" marking the data point in question and numerical values for duty cycle and aggressiveness.

The pilots were provided with information about PIW and the definition of duty cycle and aggressiveness and they were asked to assign one-dimensional values ranging from 0 for the low left corner to 1 for the upper right corner.

The test cases were chosen to cover a wide variety of questions. They cover PIW1's symmetry towards the diagonal of the PIW1 plot (meaning whether [0.2, 0.5] results in the same PIW1 value as [0.5, 0.2]), the values at and close to the critical corners and the values at the diagonal.

Appendix A shows all test cases and the pilots' assignment of a one-dimensional value. Even though the pilots were specifically asked to assign PIW1 values based on their intuition only, not on self-derived equations, two pilots could not resist to do so anyway. They provided both, data based on their intuition and data based on self-derived equations. The pilots were not informed about the mathematic background of PIW1a-d to avoid a bias towards any of these solutions.

2.4. Test Data

Figure 2-8 presents the results by comparing all forms of PIW1 in three dimensions with the discrete data points assigned by the test pilots. It is readily apparent – and not surprising – that due to the nonlinear distribution of PIW1 at the diagonal of the PIW1 plot, PIW1a produces values which are significantly smaller than the ones assigned by the test pilots. PIW1c and PIW1d provide reasonable results, but the best match appears to be PIW1b.

This is also reflected by the mean deviation of the pilot's assigned data points from the different PIW1 values presented in Table 2-2.

Mean Deviation	
PIWb:	-0.040
PIWd:	0.085
PIWc:	-0.116
PIWa:	-0.200

Mean of Absolute Value of Deviation	
PIWb:	0.113
PIWc:	0.135
PIWd:	0.150
PIWa:	0.203

Table 2-2: Deviation of Different forms of PIW1 from the Assignment of Test Pilots

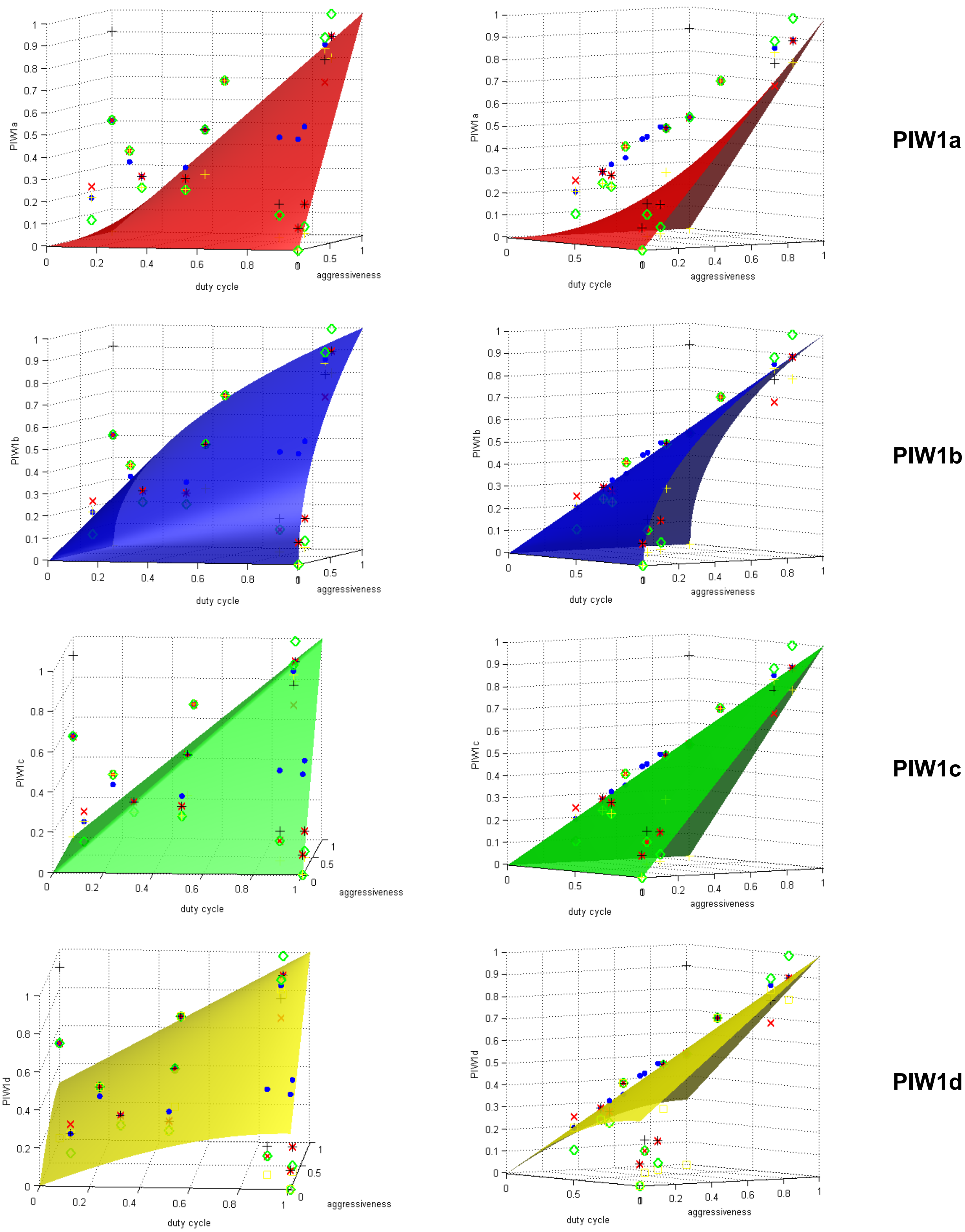


Figure 2-8: Three-Dimensional Representation of Different Forms of PIW1 and the Assignment of PIW1 by Test Pilots

2.4.1. Derived Rules

In addition to the numerical evaluation of the different forms of PIW1, the pilots' assignments were analyzed with respect to the following general rules.

- Aggressiveness and duty cycle are equally important.
- When aggressiveness and duty cycle have the same value, PIW1 should have this value, too.
- When aggressiveness or duty cycle is zero, PIW1 should be zero, too.

The results are shown in Table 2-3.

	Pilot A	Pilot B.1	Pilot B.2	Pilot C	Pilot D	Pilot E.1	Pilot E.2
Aggressiveness and duty cycle are equally important.	√	X	X	X	X	X	X
When aggressiveness and duty cycle have the same value, PIW1 should have this value, too.	√	X	√	X	√	X	X
When aggressiveness or duty cycle is zero, PIW1 should be zero, too.	X	√	X	X	X	√	√

Table 2-3: Important Generalized Aspects of PIW1

Only one pilot considered aggressiveness and duty cycle to be equally important. The data of pilot B.1 for example is based on math[8] and follows the equation PIW1 = aggressiveness² · duty cycle.

In three out of the five cases based on intuition, PIW1 achieved the value of aggressiveness and duty cycle when both had the same value.

Only two pilots considered PIW1 to be zero when either aggressiveness or duty cycle was zero. The other pilots chose nonzero values ranging from 0.1 to 0.9.

2.4.2. Pilots' Comments

The results in Table 2-3 may be surprising, but they become more understandable if the pilots' comments are added to provide a complete picture of the assessment.

In general the pilots commented that the scenario was very abstract and it was hard to make a choice of PIW1 for these theoretical cases. This has to be kept in mind when the results are considered.

One of the most important outcomes is the fact that for most pilots, aggressiveness has a significantly higher priority than duty cycle. This opinion was supported by some pilots' comments that the term "aggressiveness" is generally known to be a regular synonym for "pilot gain" and thus the term is an unfortunate choice for just one component of a two-dimensional representation of pilot gain. One pilot suggested to completely remove the duty cycle in favor of the stick deflection. Some pilots commented on a comparison of apples and oranges and recommended not to try to reduce PIW to one dimension in the first place.

[8] Please note that the data in Appendix A shows a deviation from this rule for the data points [0.5, 0.2] and [0.2, 0.5]. Pilot B very likely inadvertently switched the results of these two cases.

3. Relation between Aggressiveness and Duty Cycle

In [5], [6] and [7] Gray introduced some first results about PIW which will be compared to the results of the simulator study "Pilot Gain and the Workload Buildup Flight Test Technique" in this Chapter. Gray's results used for comparison with the simulator study are specifically

- an almost linear relation between the natural logarithm of aggressiveness (in terms of RMS stick speed) and duty cycle.
- aggressiveness and duty cycle increase as pilot gain is expected to increase
- duty cycle and aggressiveness of the least successful subjects tend to differ significantly from that employed by successful subjects
- duty cycle and aggressiveness tend to increase as the pilot is required to work for better performance

3.1. Data Base

3.1.1. Background

In the frame of the future test pilots' and flight test engineers' education, the USAF Test Pilot School has incorporated student's project called Test Management Project (TMP) in their schedule. In 2006, class 06A performed the TMP "BAT DART". The objective of the BAT DART test program was to determine if the pilot plus aircraft performance on a bounded pitch tracking task could be correlated to Cooper- Harper ratings for longitudinal handling qualities [3]. Gray used the data gathered in the frame of BAT DART in order to create PIW plots in [5], [6] and [7].

In the frame of a PhD thesis at DLR, the simulator study "Pilot Gain and the Workload Buildup Flight Test Technique" was conducted. The objective was to perform an in-depth investigation on pilot gain and the effectivity of the workload buildup flight test technique.

3.1.2. Test Environment

The test environment in the BAT DART project was the USAF Test Pilot School's NF-16D VISTA aircraft. This aircraft has the capability to simulate different aircraft dynamics. The test were performed with the small displacement side stick [3].

Figure 3-1: VISTA Aircraft [3]

The test environment for the simulator study was a simple fixed-base simulator consisting of a seat equipped with a throttle on the left hand side and a joystick plus armrest on the right hand side. Both throttle and joystick are from Thrustmaster ("HOTAS Warthog"). The joystick is sold as a replica of the A-10C stick, which is originally a center stick whereas the simulator used the joystick as a modern side stick. The stick inputs are provided with a resolution of 16 bit. The throttle was not used in the frame of this study.

Figure 3-2: Thrustmaster HOTAS Warthog Hardware and Simulator Setup with Test Pilot

3.1.3. Aircraft Dynamics

In [5], [6] and [7], only two out of four cases are presented: the level 1b and level 3 aircraft dynamics. Level 1a and b differ by their feed forward gain, but not by their short period poles.

Model	Short Period Poles	ω_{sp}	ζ_{sp}
Level 1	-3.15 ± 3.2137j	4.5	0.7
Level 2	-0.72 ± 2.2985j	2.4	0.3
Level 3	-0.31 ± 1.5187j	1.55	0.2

Table 3-1: Aircraft Dynamics used in BAT DART [3]

In the DLR simulator study only one dynamic was used. It was PIO prone when entering tight closed-loop control. The system dynamic is described by the following equation:

$$\frac{q(s)}{\eta(s)} = -1.05 \frac{2.1633\,s + 1.9379}{s^2 + 3.3789\,s + 3.1801}\,. \qquad \text{Eq.11}$$

3.1.4. Tracking Task

The tracking task used in BAT DART was a flight path angle task. It was a sum of sines task using three different sines with a maximum frequency of 0.13 Hz (0.84 rad/s).

Frequency (rad/sec)	Amplitude	Phase
0.21	π/180	0
0.42	-π/180	π/3
0.84	π/180	π(2/3)

Table 3-2: Sum of Sines Task used in BAT DART [3]

The tracking task used in DLR's simulator study was a pitch angle tracking task. It was a sum of sines task using eight different sines with a maximum frequency of 0.7 Hz (4.4 rad/s).

In [3] Dotter stated that "the tracking task was not optimally designed for the simulations used. The result was that during a large percentage of the tracking task execution, the pilot was out of the loop with the aircraft, and the short period response dominated the aircraft dynamics."

The DLR task was described as highly challenging with surprising reversals of the target movement. It was developed in the frame of a simulator study with test pilots [16].

Amplitude [deg]	Frequency [rad/s]
0.64	2/23 · 2π
1.44	2/5 · 2π
1.60	2/9· 2π
2.08	1/7· 2π
1.12	2/19· 2π
2.88	2/10· 2π
0.16	6/10· 2π
0.14	7/10· 2π

Table 3-3: Sum of Sines Task used in DLR's Simulator Study

Figure 3-3 gives a comparison of the flight path angle task used in the frame of BAT DART and the pitch angle tracking task used in the frame of DLR's simulator study. The data for the BAT DART task was extracted from [3] (report is approved for public release) using the open source software "engauge".

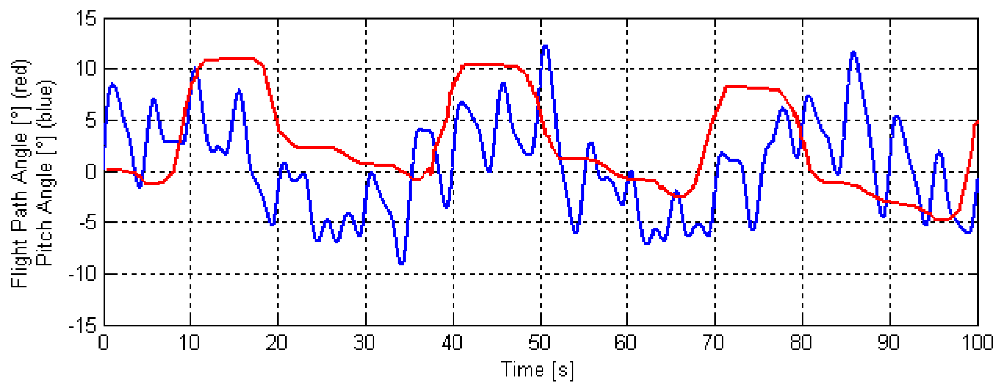


Figure 3-3: Comparison of Tracking Tasks

The difference between both tasks is readily apparent. While the parameter range was similar, the pitch angle task was designed at much higher frequencies.

3.1.5. Flight Test Technique

In [5], [6] and [7] only data gathered with the workload buildup flight test technique was used.

This technique adds boundaries to a tracking task which must not be exceeded and which decrease over time. The boundaries are symmetrical to the target. It is hypothesized that pilot gain increases as the boundary decreases as the task performance standards are increased. In the BAT DART project, the boundary size decreased in intervals of 60 s and each data point represents the time slot with a fixed boundary size.

Table 3-4 lists all test points performed in the DLR simulator study. More detailed information about the test concept can be found in [9]. The relevant test points regarded in this report are test points 5-8.

Test point 5 is called "pilot gain calibration". The test pilot is asked to perform the same tracking task three times, each time in a different manner. First the task is performed with the pilot's natural pilot gain, second with intentionally low gain and third with intentionally high gain. This way three sets of data points – each one containing the tracking data of 40 s – with different intentionally applied pilot gains are created.

Test Point	Description	Classification
1 2 3	Basic Data Psychological Test Tapping Test	Computer-Based Tests
4 5 6 7 8	Familiarization Phase Pilot Gain Calibration (Normal-Low-High Gain) Workload Buildup Flight Test Technique – Levels Workload Buildup Flight Test Technique – Original Workload Buildup Flight Test Technique – Original + Exceedable Boundary	Simulator-Based Tests

Table 3-4: Test Points of DLR's Simulator Study

Test points 6 – 8 cover the workload buildup flight test technique in three different variants.

Test point 6 covers a level-based variant. During this variant the pilot has to track the target while staying inside of the boundaries for a predefined time (45 s). He gets three tries to pass each level, but only successful tries are displayed in this report. After successful completion of a level, the boundary size is decreased and a new level begins [15].

Test point 7 is the original workload buildup flight test technique. The pilot has to track the target while staying inside of the boundaries, but this time the boundaries decrease during the tracking task and the test point has a variable duration based on how long the pilot manages to stay inside of the boundary. The boundary size is kept constant for 10 s and decreases over a time of 2 seconds.

Test point 8 is a variation of the original workload buildup flight test technique. The difference towards test point 7 is given by the fact that the boundary can be temporarily exceeded for 0.5 s. If the pilot returns to the inside of the boundary within this time, the task is continued. [15]

Data points for test points 7 and 8 are calculated for the time with a fixed boundary, i.e. they cover only 10 s of data.

3.1.6. Tracking Display

In the BAT DART project, the head-up display of the VISTA aircraft was used to display the tracking task.

The tracking reference was the flight path marker, the target was represented by a dotted horizontal target line. The boundaries were solid horizontal lines above and below the target line.

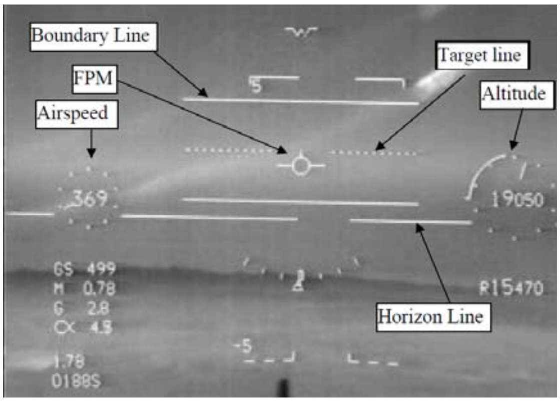


Figure 3-4: BAT DART Head-Up Display [3]

For the simulator study "Pilot Gain and the Workload Buildup Flight Test Technique" a display presented on a monitor was used for the tracking task. The display was based on the DLR in-house software 2indicate.

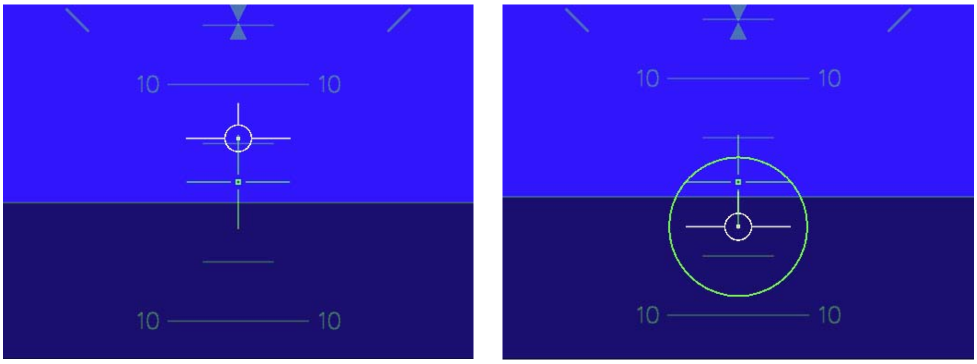


Figure 3-5: Display used for DLR's Simulator Study

Figure 3-5 shows the displays used in the simulator study. The aircraft-fixed reference used for tracking was represented by a gun cross; the target was an aircraft symbol. Figure 3-5 left shows the display without boundary used for test point 5 (pilot gain calibration); Figure 3-5 right shows the display used for the workload buildup flight test technique in test points 6 – 8. The boundary is circular to allow combined roll and pitch tasks in future studies.

3.1.7. Participants

The VISTA flights of the BAT DART project were conducted by seven participants. Their experience is shown in Table 3-5.

Test Pilots

Test Subject	Flight Hours
Test Pilot 1	1300
Test Pilot 2	3000
Test Pilot 3	2000
Test Pilot 4	4000

Non-Pilots

Test Subject	Flight Hours
Test Pilot 5	100
Test Pilot 6	200
Test Pilot 7	0

Table 3-5: Participants of BAT DART Study

The simulator study "Pilot Gain and the Workload Buildup Flight Test Technique" was split into two parts. The simulator study "Pilot Gain and the Workload Buildup Flight Test Technique: Test Pilots" was conducted from March to July 2012. Participants were 8 experimental test pilots from the Bundeswehr Technical and Airworthiness Center for Aircraft (WTD 61) and 4 experimental test pilots from Cassidian.

The simulator study "Pilot Gain and the Workload Buildup Flight Test Technique: Operational Pilots" was conducted from 30th July to 3rd August 2012 at Fighter Wing 73 in Laage which is mainly a Eurofighter training squad. Participants were 7 Eurofighter student pilots, most of which had just finished their training at Sheppard AFB and 5 more experienced pilots who originated either from F-4F or Tornado. A summary of their experience is shown in Table 3-6.

Note that for the experimental test pilots, the assigned category (fighter/bomber/transport pilot) is based on the type of aircraft the pilot flew in the squadron before he became a test pilot. Because of the necessity to cover a wide range of aircraft types, most test pilots also have experience on various other types of aircraft. More detailed information can be found in [9], [12] and [14].

Category	Test Pilot	Flight Hours
Fighter Pilots	1	5900
	2	4000
	3	4000
	4	3400
Bomber Pilot	5	5000
	6	4970
	7	1550
	8	2000
Transport Pilots	9	6700
	10	4000
	11	2950
	12	3600

Category	Operational Pilot	Flight Hours
Fighter Pilots	13	1700
	14	280
Bomber Pilots	15	1500
	16	1250
	17	1000
Young Eurofighter Pilots	18	340
	19	300
	20	450
	21	440
	22	260
	23	300
	24	930

Table 3-6: Participants of DLR's Simulator Study

3.1.8. Outliers

In [12] three outliers were identified in the data base of DLR's simulator flight test.

Their deviations were already apparent during the simulator trials and were supported by PSD plots and time histories.

The pilot with the ID IGOR applied excessive pilot gain during his high gain run.

The pilot with the ID BIER applied higher pilot gain during his low gain test point than during his normal gain test point.

The pilot with the ID ABCD did not vary his pilot gain at all.

The plots in this report thus leave out the following data:

- high gain test point of pilot IGOR
- low gain test point of pilot BIER
- low and high gain test point of pilot ABCD

In all cases it is assumed that the pilots successfully applied their natural pilot gain because the normal gain test point did not require any kind of role playing.

The data of these three pilots is only included in the validity plots in Chapter 4 where they are specifically marked in different colors.

3.1.9. Summary of Different Databases

Table 3-7 summarizes the differences between both databases. It is apparent that the data was gathered under significantly different circumstances.

Aspect	BAT DART	Pilot Gain and the Workload Buildup FTT
Test Environment	VISTA NF-16 D Flight Test	Low Cost Fixed-Base Simulator
Aircraft Dynamics	Level 1 and Level 3	PIO-prone (Level not rated)
Tracking Task	Sum of Sines 3 Sines max. Frequency 0.13 Hz	Sum of Sines 8 Sines max. Frequency 0.70 Hz
Flight Test Technique	Workload Buildup FTT	Pilot Gain Calibration Workload Buildup FTT
Data Points	60 s of data per data point	40 s of data per data point[9] 10 s of data per data point[10]
Tracking Display	head-up display horizontal boundaries	monitor circular boundary
Displayed Data	1 pilot, 1 non-pilot[11]	21 pilots plus 3 outliers

Table 3-7: Summary of Differences between both Databases

[9] pilot gain calibration and level-based workload buildup (test points 5 and 6)

[10] workload buildup in test point 7 and 8

[11] displayed data in this report – the BAT DART database shows the data of more pilots which was, however, well in line with the data of the two pilots which were specifically marked in the associated reports – the other data could not be extracted with a sufficient level of confidence

3.2. Pilot Gain Calibration Data vs. BAT DART

3.2.1. Comparison of both Data Sets

The pilot gain calibration data of DLR's simulator study provides a good database for a closer investigation of PIW since the three test points – low, normal and high gain – cover a wide range of pilot gain for the 24 participants of the simulator study. The data was used to validate different pilot gain measures in [12] and was used to determine the influence of natural pilot gain on the individual pilot gain range in [14].

The intentional variation of pilot gain is a common procedure in handling qualities testing. In spite of this rather unusual approach in comparison with their daily missions, operational pilots were just as successful in varying their pilot gain as the test pilots. The main difference was the fact that they were not familiar with the term "pilot gain". The synonymous expression "aggressiveness" was used instead. Based on the test results, no difference could be identified between the operational pilots' application of different levels of aggressiveness and the test pilots' application of different levels of pilot gain.

A look at the normal gain data (Figure 3-6 left) could leave the impression that a linear relation exists between aggressiveness and duty cycle. However, the linear function would be biased towards the origin of the PIW plot which is not in line with physics: there cannot be a nonzero duty cycle for zero stick speeds. A look at the complete data of the pilot gain calibration reveals an essentially non-linear relation between aggressiveness and duty cycle (Figure 3-6 right).

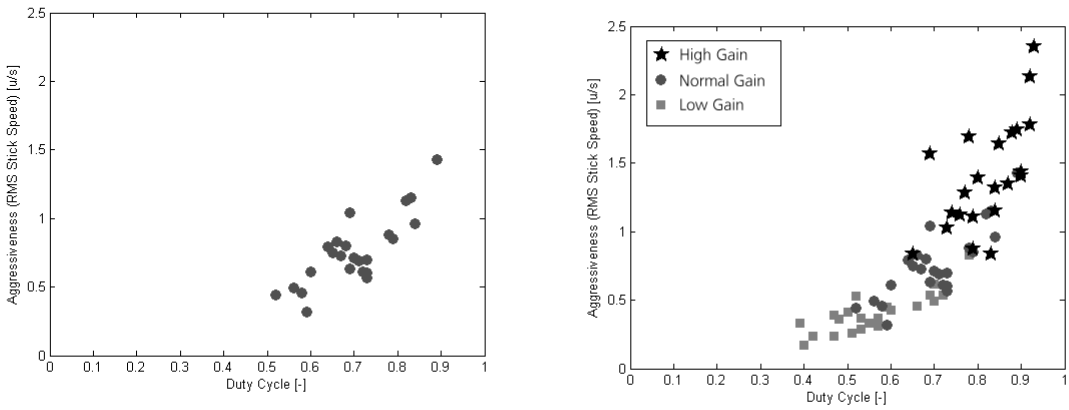


Figure 3-6: PIW Plots for Pilot Gain Calibration Runs (left: normal gain only, right: all data points)

In [5], [6] and [7] Gray uses the natural logarithm of the stick speed in his PIW plots. The data points are then approximately located on a straight line (Figure 3-7 left). The data points were extracted from the plot with the open source tool "engauge" and the graphs were adapted to the full range of duty cycle values (0 to 1) and a larger range of aggressiveness values in order to allow a comparison with the data gathered in DLR's simulator study (Figure 3-7 right).

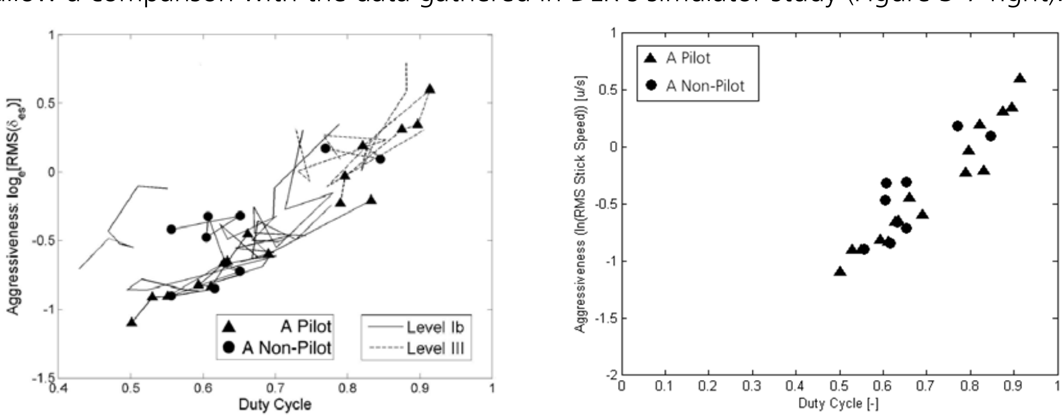


Figure 3-7: PIW Plots with Natural Logarithm (Left Picture from [5], [6] and [7], Right Picture Shows the Same Data with a Different Axis Setting and without the Lines)

Figure 3-8 left shows the data from DLR's simulator study (pilot gain calibration runs) in the form Gray used, i.e. with the natural logarithm of the RMS stick speed. Like in Gray's studies, the result is an approximately linear function. In addition, the data points are highly consistent with Gray's data base (Figure 3-8 right).

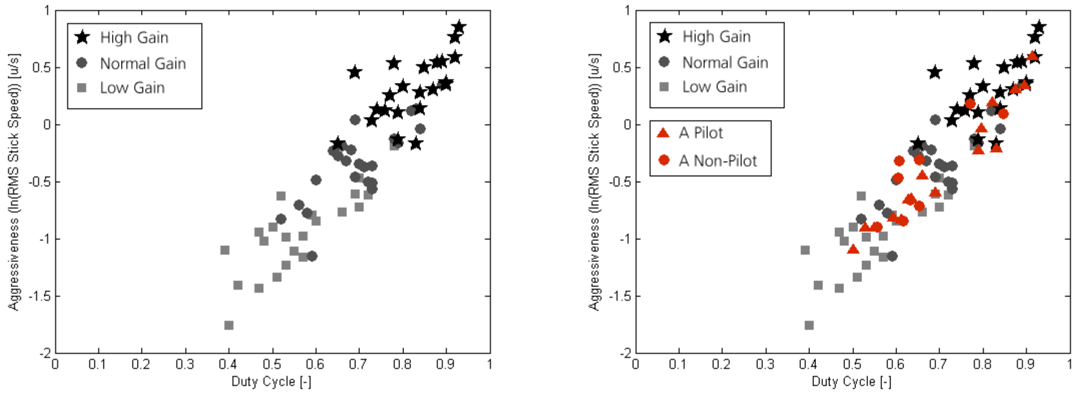


Figure 3-8: PIW Plots for Pilot Gain Calibration Runs (Left: DLR's Simulator Study, Right: Data from DLR and BAT DART)

The fact that both populations of data points do not only show the same quantitative trend but also coincide qualitatively can explicitly not yet be considered a sign that all tests produce exactly the same data points in the PIW plot.

Numerous factors may influence the PIW curve like

- the type of inceptor (sidestick, wheel controller, center stick)
- the inceptor's force characteristics (deflection vs. force curve, magnitude of force)
- other inceptor characteristics (backlash, damping, centering, breakout force)
- the type of control realization in the FCS (rate command, attitude command, C* command, g command, direct law etc.).
- the frequency content and amplitude of the task.

Keeping in mind these influence factors it seems reasonable to assume that the good match of both data sets based on tests which are so fundamentally different could be rather a coincidence than something that gives room for a generalization. A comparison with more data is necessary to decide about the significance of these results.

A great number of handling qualities reports and data bases was screened for more comparative data and internal sources were checked. However, due to a number of restrictions no suitable match for more data points could be found:

- The task has to be a sum of sines task. Step and ramp or pure capture tasks have different characteristics and may not be comparable.
- The task has to be restricted to one axis – otherwise coupling effects and decision processes for the prioritization of the inputs in one axis over the other have to be considered.
- The data has to be usable. Many reports presenting sum of sines tasks are based on military data and use masked or no axis references in order to be in line with military restrictions. In addition, many old reports have a rather poor resolution and thus do not allow an extraction of data from time histories.
- The few reports which could be found with high resolution time histories of single axis sum of sines tracking tasks (e.g. [1]), still could not be used for data extraction with the "engauge" tool because the data points on the x-axis are not equally spaced which leads to a high sensitivity of the calculated stick speed based on the selected time slot (a very small spacing on the x-axis can lead to an excessive local stick speed based on small resolution noise).

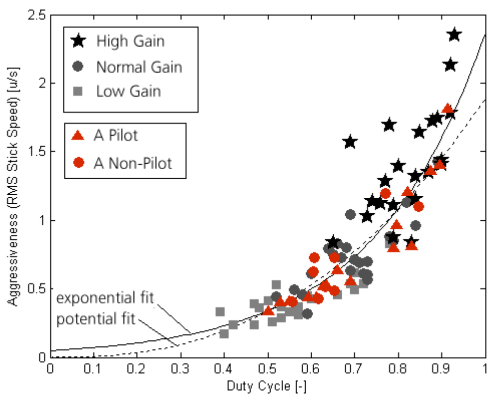
- Most data bases cover only few pilots using their natural pilot gain. The pilot gain range is thus rather limited and a trend in the PIW plot cannot be reflected.

Because of all these restrictions, more tests specifically tailored to further investigate the relation between aggressiveness and duty cycle – namely more pilot gain calibration runs in different scenarios – should be performed in order to clarify whether there is a general trend for aggressiveness vs. duty cycle and whether the generalization is limited to the qualitative trend or whether it can be extended to the quantitative region of the data points as well.

3.2.2. Mathematic Relations

In spite of the good fit of an exponential function one may ask the question if this type of function is the best way to describe the relation between aggressiveness and duty cycle.

A plot of the data points in the original axis (with the RMS stick speed instead of its natural logarithm) allows the consideration of different relations. As Figure 3-9 shows, both an exponential and a potential curve fit create reasonable results. Unlike the exponential function the potential function passes through the origin of the PIW plot. This is well in line with physics – if either aggressiveness or duty cycle is zero, there cannot be a nonzero value for the other parameter. The exponential function, however, creates a better curve fit. This is especially true for the high gain values.



Exponential Function

agg = 0.05·e$^{3.9 \cdot dc}$

Pseudo R² = 0.79

Potential Function

agg = 1.9·dc$^{2.5}$

Pseudo R² = 0.75

Figure 3-9: Exponential and Potential Fit for Database in PIW Plot[12]

In general it is desirable to have a curve fit which does not contradict physics at any location of the criterion plot. However, like for the different versions of PIW1 it should also be considered whether these corners will ever be reached by data points and an aggressiveness or duty cycle value of zero simply cannot be reached in a tight control closed-loop tracking task.

The possibility to reach an approximately linear relation between the natural logarithm of aggressiveness and the duty cycle is quite beneficial for data presentation and a point in favor of the assumption of an exponential function. It must, however, not be forgotten that especially PIW has been developed in order to provide a pilot gain measure which pilots can easily relate to [5], [6] – this may become a problem when the natural logarithm of the RMS stick speed is used.

3.2.3. Increase in Pilot Gain with Increasing Values in PIW Plot

In [5], [6] and [7] which show the results of the BAT DART flight test, Grays results stated that "the results seem to confirm the hypothesis that duty cycle and aggressiveness increase as pilot gain" would be expected to increase."

The results of DLR's simulator study support this statement. Figure 3-10 shows the three distinguishable areas for low, normal and high gain data points. In both representations there is an obvious increase in PIW with intentionally applied pilot gain. Furthermore, the high and low gain

[12] Note that the pseudo R^2 value is typically something used for linear functions only. Appendix B explains the procedure which was used to derive a value for a pseudo R^2 value in Figure 3-9.

data points are clearly separated from each other. The normal gain data points leak into both groups of data points (low and high gain), which is a foreseeable effect due to the pilots' different natural gain. A typical low gain pilot will have his normal gain data point closer to the low gain data points, a high gain pilot will have it rather in the region of high gain data points.

Note that an additional representation of the separation of low, normal and high gain data points is given in Subchapter 5.4.2.

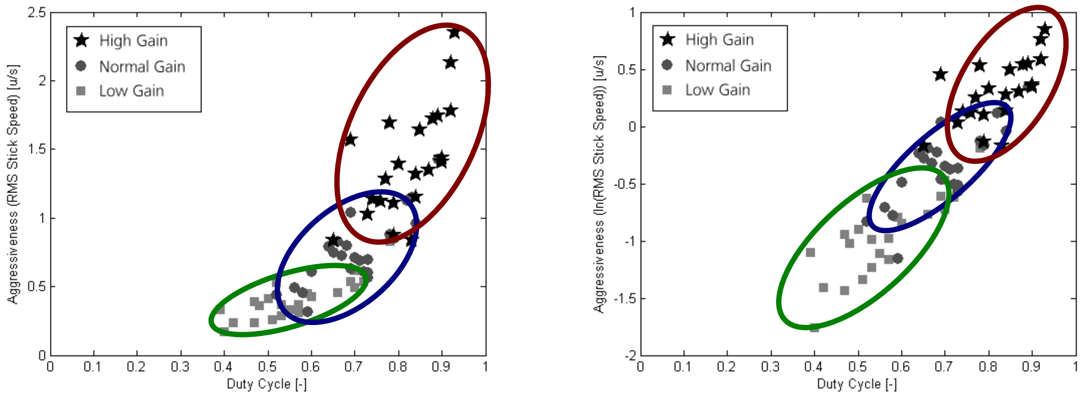


Figure 3-10: PIW Increase with Pilot Gain Increase

Gray's results, specifically the hypothesis that PIW reflects pilot gain, are supported by the results of the simulator study.

3.3. Workload Buildup Data: Level-Based Technique

During the level-based workload buildup, the pilot has to stay inside of the boundaries while tracking the target. The boundary size is kept constant for 45 seconds; the first 5 seconds are used to get the pilot in the loop and 40 seconds are used for data evaluation. After the 45 s the “level is passed” and the pilot can take a short break before he enters the next level with a smaller boundary size [15]. Only successful runs are displayed in this report.

In [5], [6] and [7] Gray’s assumed increase in pilot gain was tied to a decrease in boundary size. Figure 3-11 shows the data points of the level-based workload buildup differentiated by levels. Levels 1-3 were relatively easy and were passed by almost every pilot. Levels 4-6 were already challenging. Levels 7 and above were highly challenging and only mastered by a few pilots. The most successful pilot passed level 11 and failed in level 12. The three second best pilots achieved level 8 and failed in level 9.
Figure 3-11 shows that the pilot gain of levels 1-3 is distributed over a wide range of the PIW plot. The data points are significantly more scattered than the data points of the higher levels. The data points for levels 4-6 appear to have a steeper slope for aggressiveness vs. duty cycle than the data points for level 7+. All three groups of data points have overlapping populations, but a grouping can be identified based on the location of the lower data points of each group. The lowest data points of levels 1-3 are lower than the lowest data points for levels 4-6 and they are lower than the lowest data points of levels 7+. This effect is not surprising: it does not hurt to have a higher pilot gain right from the start, but it will definitely hurt to have a too low pilot gain at higher levels. This is why the distinction between the different groups is most pronounced for the lower data points of each group.

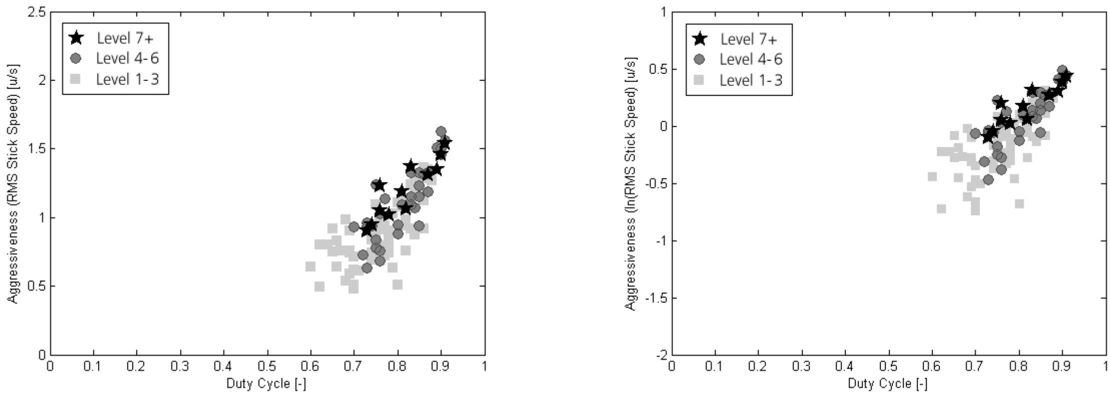


Figure 3-11: PIW for Different Levels of the Workload Buildup

In [5], [6] and [7] it was also stated that “the duty cycle and aggressiveness of the least successful subjects tended to differ significantly from that employed by successful subjects”.

The data points were thus grouped based on the pilots’ success. A good achiever was a pilot who passed level 7 or higher. An average achiever passed at least level 4. The data points of all levels are shown for these pilots in the associated groups in Figure 3-12.

The data of the pilots who passed not more than level 3 are very scattered and located at low to medium PIW values. The data points for the average and good achievers show a clear grouping with different slopes for aggressiveness vs. duty cycle. The average achievers have a steeper slope than the good achievers. Both groups converge in the same area of the plot for higher PIW values, but the more successful pilot started off with higher aggressiveness at lower PIW.

The data points with the highest PIW are clearly achieved only by the good achievers.

One thing that must be kept in mind for the evaluation of the data points for pilots who only achieved level 3 or lower is their background. This group consists of 6 pilots, 4 of which are pure transport pilots who are trained not to fly aggressively and who hardly ever perform tracking tasks like the one in the simulator study. The scattered data points are probably an indication of a lack of an adequate strategy for tracking tasks for this pilot group.

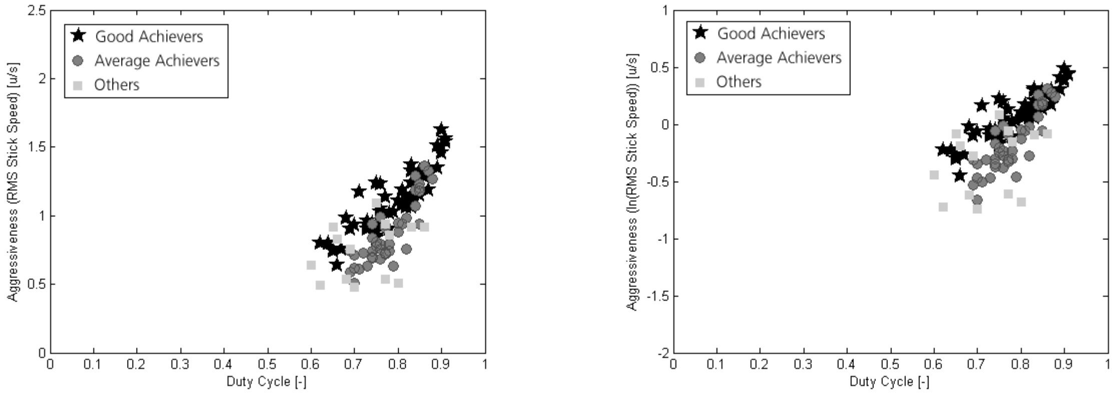


Figure 3-12: PIW of the Level-Based Workload Buildup for Different Achievers

The final question for the level-based workload buildup flight test technique is whether it creates the same general trend (exponential/potential function) as the pilot gain calibration. Based on the fact that the pilot gain calibration was already successfully compared to a variant of the workload buildup flight test technique (BAT DART), it is likely that these data points also match the general trend.

Figure 3-13 confirms this expectation. The data points of the level-based workload buildup flight test technique follow the same trend and show approximately the same scatter. They are mainly located at medium to high gains; however, the pilot gain calibration created some data points with higher pilot gain than the maximum which was achieved with the level-based workload buildup flight test technique. This effect is important for future evaluations of the workload buildup flight test technique and it is not unexpected: at a certain point the use of very high pilot gain does not improve the pilot's performance in the workload buildup flight test technique. Excessively high gain inputs have the potential to create a very quick and large amplitude reaction of the aircraft which can easily result in boundary exceedance. The pilot gain calibration and other techniques allow the pilot to apply aggressive inputs while posing no boundaries to the aircraft reaction. On the other hand it is less intuitive and involves role playing while the pilot gain increase is automatically achieved during the workload buildup flight test technique.

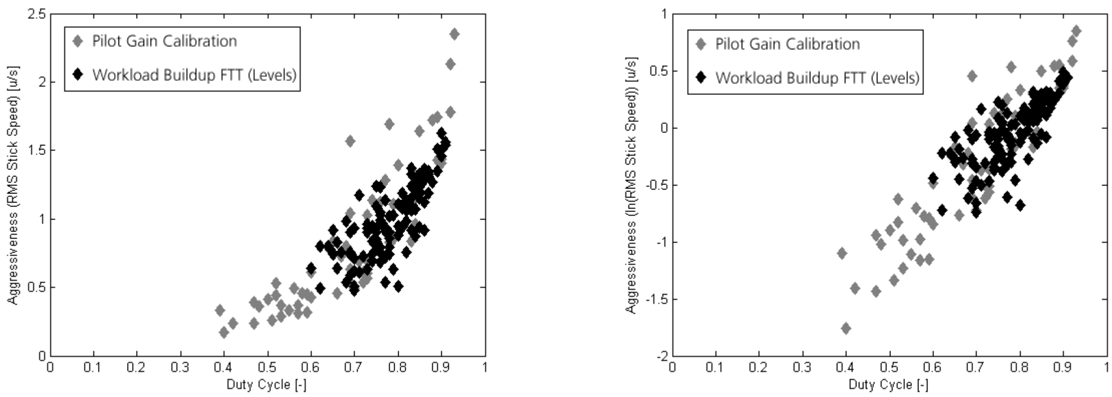


Figure 3-13: Comparison of Pilot Gain Calibration and Level-Based Workload Buildup

3.4. Workload Buildup Data: Continuous Techniques

During the continuous workload buildup, the pilot has to stay inside of the boundaries while tracking the target. The boundary size is kept constant for 10 seconds and then decreased over 2 seconds while the pilot keeps on tracking. The pilot cannot "pass" the test, he can only achieve a good time until he exceeds the boundary.

Each data point displayed in this chapter covers the 10 seconds with a fixed boundary size. Because 10 seconds are a very short time and allow a high influence of local variations in task difficulty, the data points are much more scattered [15]. As a result, no in-depth investigation of different achievers or levels is performed and only a comparison with the general trend is made in this report.

Figure 3-14 shows that the data points of both continuous versions of the workload buildup show the same general trend in the PIW plot as the pilot gain calibration data points. There is no obvious difference between data points of the original technique and the technique where the pilot can temporarily exceed the boundary ("Bdry Ex")[13].

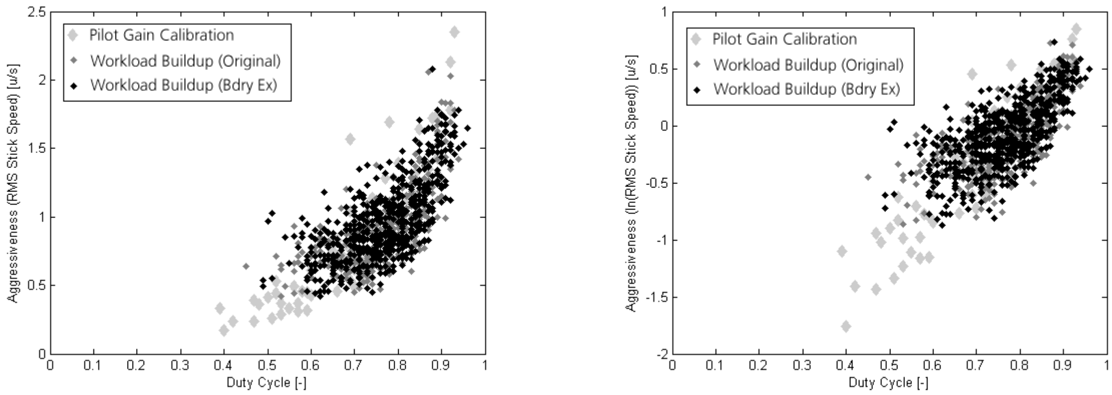


Figure 3-14: Comparison of Pilot Gain Calibration and Continuous Workload Buildup

The data points of the continuous workload buildup – like the data points of the level-based workload buildup – are located at medium to high pilot gain. There are some data points of the pilot gain calibration which represent higher values of PIW.

[13] Even though many data points of the original technique are masked by the "Bdry Ex" data points, the fact that both essentially show the same trend and have the same range in the PIW plot was confirmed by an evaluation of separate plots for both techniques.

3.5. Normalization of Aggressiveness for PIW1

The calculation of PIW1 - a one-dimensional form of PIW - as it was introduced in Chapter 2.1, requires a normalized value for aggressiveness which is in the same range as the duty cycle (0 to 1). In [5], [6] and [7] "no effort has been made to normalize this measure of aggressiveness". As it was already demonstrated in this chapter, there is a close mathematic relation between aggressiveness and duty cycle. This relation can be used for normalization.

3.5.1. Exponential Relation

The exponential relation between aggressiveness and duty cycle is given in Figure 3-9 by

$$\text{agg} = 0.05 \cdot e^{3.9 \cdot \text{dc}} . \qquad \text{Eq.12}$$

The aggressiveness value can thus be normalized using the inverse function:

$$\text{aggs}_{\text{norm}} = \frac{\ln\left(\frac{\text{agg}}{0.05}\right)}{3.9} . \qquad \text{Eq.13}$$

3.5.2. Potential Relation

The potential relation between aggressiveness and duty cycle is given in Figure 3-9 by

$$\text{agg} = 1.9 \cdot \text{dc}^{2.5} . \qquad \text{Eq.14}$$

The aggressiveness value can thus be normalized using the inverse function:

$$\text{agg}_{\text{norm}} = \left(\frac{\text{agg}}{1.9}\right)^{\frac{1}{2.5}} . \qquad \text{Eq.15}$$

3.5.3. Comparison and Limitations of Normalisation

Figure 3-15 shows the data points for both normalizations – based on an exponential (left) and a potential (right) function. For a better comparison a diagonal is depicted on which ideally all data points would be located if there was no scatter and the functions were a perfect representation for the data points.

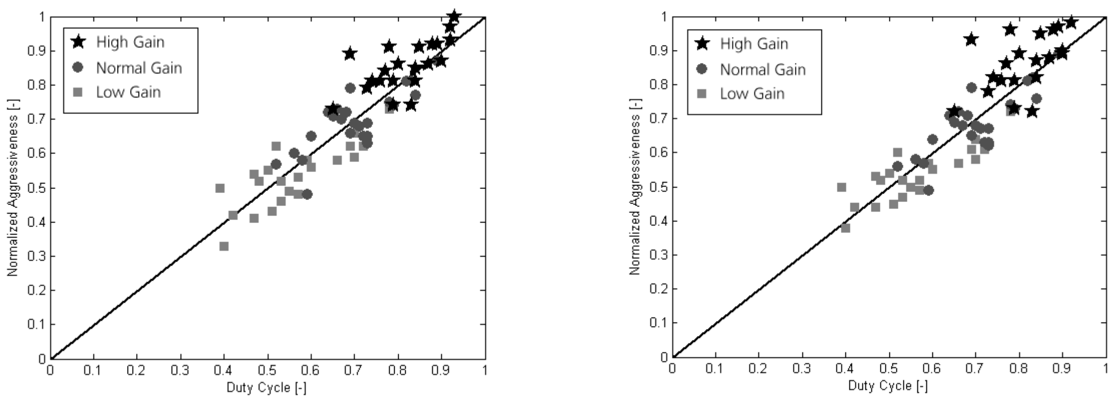


Figure 3-15: Normalized Aggressiveness (Left: Exponential, Right: Potential Function)

The left graph based on the exponential function appears to be more linear while the right graph still has a slight convex curve which is a result of the poor fit for high gain data points (see Figure

3-9). But also the left graph shows a slight shift to the left of the depicted diagonal. Especially for data points which are above a duty cycle of 0.9, the ratio aggressiveness vs. duty cycle is higher than 1.

In the left graph, one data point reaches the maximum aggressiveness of 1; in the right graph two data points even exceed this value (1 < normalized aggressiveness < 1.1). This is an inevitable result of the scatter around the regression lines. In the latter case, the aggressiveness value should be corrected to 1 and marked in order to show that this value would actually be higher.

The question which remains at this point is: is a calculation for PIW1 still necessary?

To answer this question one must consider why there is a need for a one-dimensional form of PIW in the first place. A pilot gain measure is useful when different results of handling qualities flight tests have to be explained. In this case a definite parameter is needed which can be compared between two pilots without giving any room for interpretation. This could be – amongst others – PIW1.

On the one hand one could question the need for PIW1 because this chapter has shown that aggressiveness and duty cycle are closely connected by a monotonically increasing mathematic function, meaning that the increase of one parameter is tied to an increase of the other parameter. As a consequence, instead of calculating PIW1 one could simply use just one of the two parameters in order to determine the differences in pilot gain. As both parameters passed the validation in [12], this is a legitimate approach.

On the other hand this approach would not fully cover the information contained in PIW because the scatter between both parameters is not regarded. In Figure 3-15 there are for example quite a few data points with the same duty cycle but different aggressiveness.

The scatter is, however, reasonably small with a sample standard deviation of 0.07 for the exponential function and 0.08 for the potential function.

In general, every variant of PIW1 will inevitably reduce the information content previously contained in a two-dimensional plot.

4. Validity of PIW1

In [12] an approach for the validation of potential pilot gain measures was introduced which is based on the idea that a pilot gain measure should reflect the pilot gain which the pilot intended to apply. It thus has to be either monotonically increasing or decreasing with pilot gain. Based on this idea a validity index was developed which is 1 for monotonically increasing and -1 for monotonically decreasing pilot gain measures. A value of 0 implies no relation with pilot gain whatsoever.

The known outliers (see Chapter 3.1.8) were also included in the calculation of the validity index in [12] – as a consequence, a validity index of 1 could not be reached and the threshold for a valid pilot gain measure was set to 0.8.

The ability of a pilot gain measure to detect the known outliers based on their specific characteristic was chosen as a second criterion to determine valid pilot gain measures.

Finally, a pilot gain ranking was created by sorting the pilots from low to high gain based on their normal control strategy. Significant deviations of rankings for individual pilots could lead to an exclusion of the potential pilot gain measure. This third criterion is not applied in this report.

4.1. Validation of PIW1 Based on Exponential Fit for Aggressiveness

Figure 4-1 shows the validity plots of PIW1a-d based on the exponential fit used for the normalization of aggressiveness. It shows the data point of all 24 pilots during the pilot gain calibration, grouped based on the intentionally applied pilot gain. The three known outliers are marked in yellow, red and green.

Because of its relatively low values for low pilot gain (see Figure 2-7), PIW1a creates values which are lower than the results of the other variants. PIW1b clearly creates the highest values (with the exception of outlier IGOR which is higher for PIW1c) and the most consistent trend for all data points.

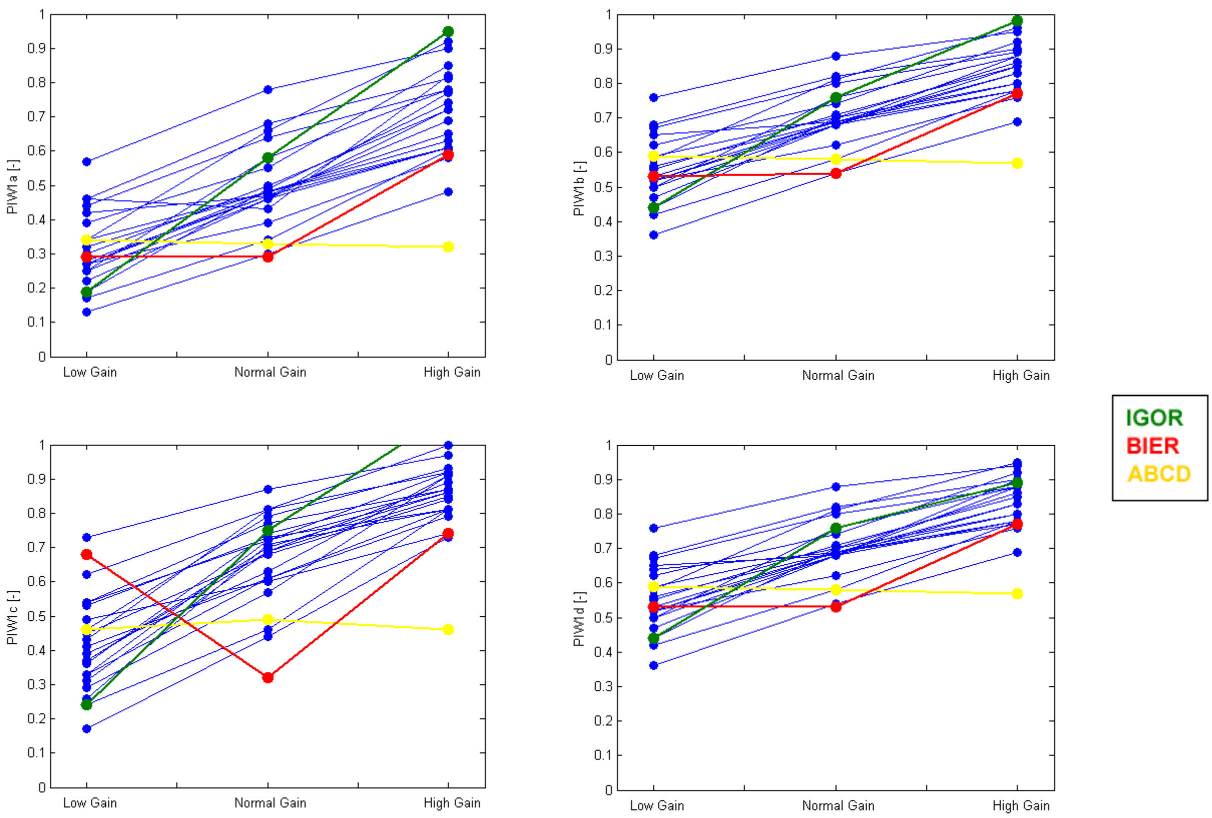


Figure 4-1: Validity Plots of PIW1 Variants Based on Exponential Fit for Aggressiveness

The validity index is 0.92 for all four variants of PIW1. When the outliers are excluded from the analysis, a perfect validity index of 1 is reached by all of variants of PIW1.

Outlier detection is achieved when the following patterns are visible:

Pilot ABCD: all three data points have about the same value

Pilot BIER: the low gain data point has a higher value than the normal gain data point

Pilot IGOR: the high gain data point is excessively high

More information about the outliers can be found in [12].

Only PIW1c correctly detects all outliers. PIW1a, b and d do not create excessively high values for pilot IGOR. While it is at least the highest data point for PIW1a and b, it is not excessively high. PIW1a, b and d also fail to detect the wrong application of the low gain test point of pilot BIER. It has essentially the same value as the normal gain data point.

In summary, all versions of PIW1 are suitable and have an excellent validity index. In terms of outlier detection PIW1c clearly excels, which is curious because it is mathematically the simplest representation (Chapter 2.1.3). PIW1b and PIW1d clearly present the most consistent data with an approximately linear increase in PIW1 with increasing pilot gain.

4.2. Validation of PIW1 Based on Potential Fit for Aggressiveness

Figure 4-2 shows the validity plots of PIW1a-d based on the potential fit used for the normalization of aggressiveness. It shows the data point of all 24 pilots during the pilot gain calibration, grouped based on the intentionally applied pilot gain. The three known outliers are marked in yellow, red and green.

For this normalization of aggressiveness it becomes more obvious that PIW1a creates values which are lower than the results of the other variants.

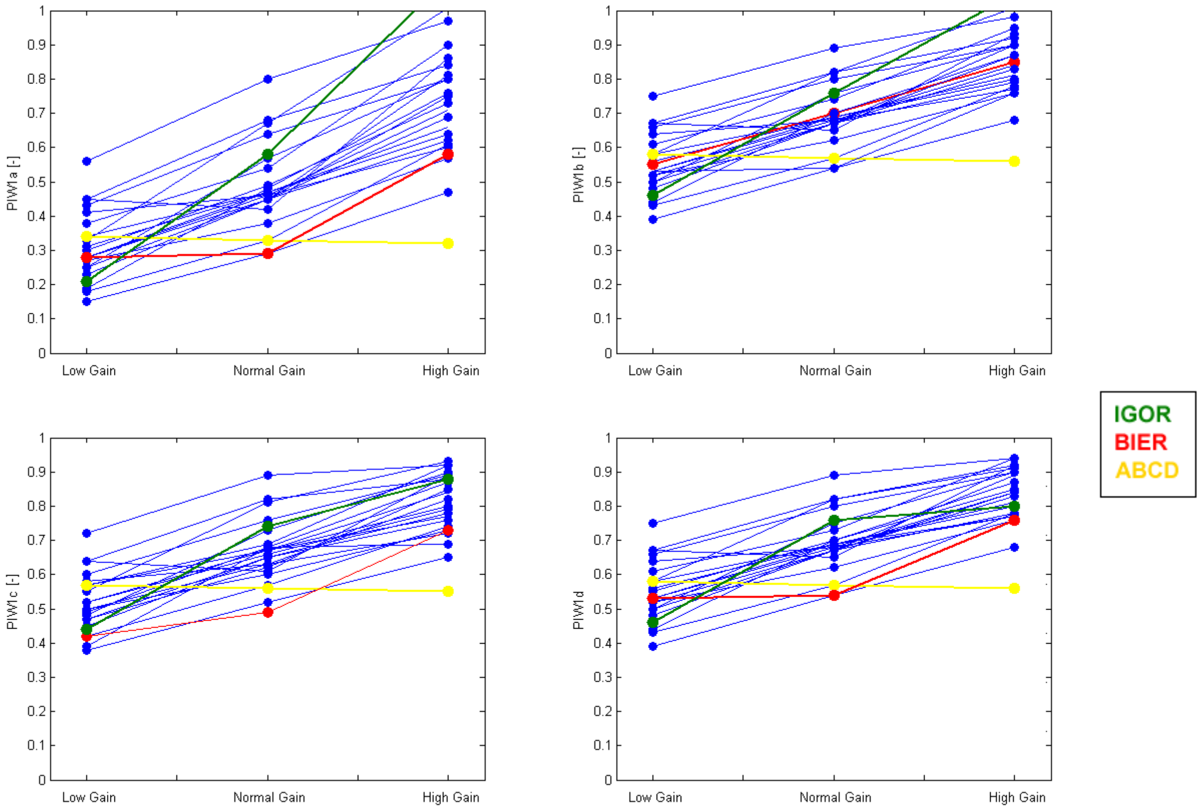


Figure 4-2: Validity Plots of PIW1 Variants Based on Potential Fit for Aggressiveness

The validity index is 0.92 for all four variants of PIW1. When the outliers are excluded from the analysis, a perfect validity index of 1 is reached by all of variants of PIW1.

No version of PIW1 correctly detects all outliers. All fail to recognize the outlier of pilot BIER who applied higher pilot gain at his low gain test point than at his normal gain test point. PIW1a and b show excessively high values for the high gain data point of IGOR, PIW1c and d fail to detect this. All variants of PIW1 correctly detect that pilot ABCD kept his pilot gain constant.

In summary, all versions of PIW1 are suitable and have an excellent validity index. In terms of outlier detection PIW1a and b are slighly ahead of the other variants, but the difference is only based on the detection of the excessively high data point.

4.3. Separation of Data Points from the Workload Builup

In Figure 3-11 and Figure 3-12 it was shown that the groups of data points for more and less successful pilots and for more and less challenging levels of the workload buildup flight test technique have different trends in the PIW plot. These differences should also be present in the one-dimensional representation of PIW in order to conserve the information contained in the two-dimensional plot.

4.3.1. Grouping based on the Pilots' Achievements

Figure 4-3 shows the mean value and SSD of the data points from the groups based on the pilots' achievements as they were defined in Subchapter 3.3. PIW1 is based on the exponential fit for aggressiveness in these plots. The results based on the potential fit are similar and can be found in Appendix C. An increasing PIW1 for better achievers is visible in all plots. This is well in line with the results in Subchapter 3.3. However, the different ratio of aggressiveness vs. duty cycle which is present in Figure 3-11 is no longer represented by PIW1.

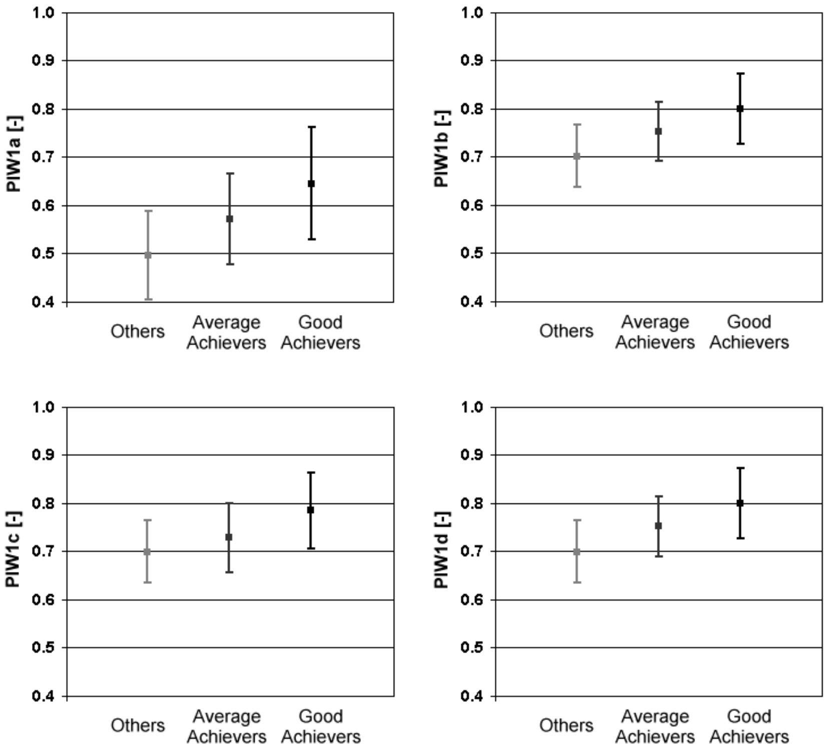


Figure 4-3: PIW1 Variants based on Exponential Fit Grouped by the Pilots' Achievements

The same basic trend can be seen in Figure 4-4. It shows the mean and SSD of the PIW1 variants grouped by levels. PIW1 is based on the exponential fit for aggressiveness in these plots. An increasing PIW1 for higher and thus more challenging levels is visible in all plots. This is again well in line with the results in Subchapter 3.3. As for Figure 4-3, the different ratio of aggressiveness vs. duty cycle which is present in Figure 3-12 is no longer represented by PIW1.

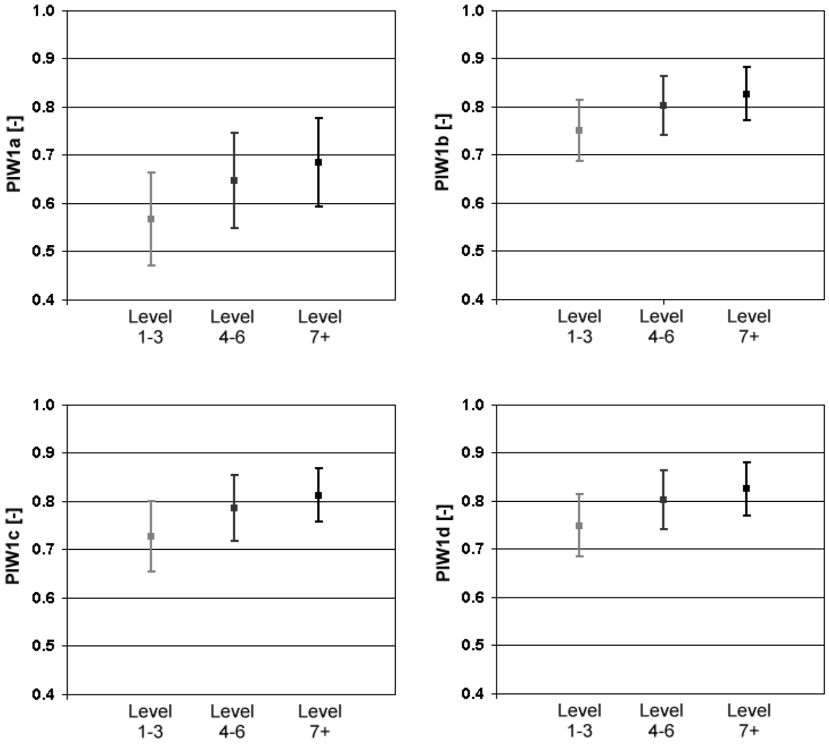


Figure 4-4: PIW1 Variants based on Exponential Fit Grouped by Levels

4.4. Discussion

All presented variants of PIW1 are suitable to represent pilot gain.

Table 4-1 gives an overview of the validation data for PIW1 variants and the two components of PIW, the RMS stick speed and the duty cycle. The best results are achieved by the RMS stick speed and PIW1c for an exponential fit. Because the most simple approach should always be preferred if it proofs to be valid, based on these results there is no need to calculate PIW1 since the RMS stick speed alone is already an excellent representation of pilot gain. All other measures but PIW1c (based on an exponential fit) mask one or two outliers while being mathematically more complex at the same time.

Pilot Gain Measure	Validity Index (incl. Outliers)	Validity Index (excl. Outliers)	Outlier Detection
RMS Stick Speed	0.92	1.00	3/3
Duty Cycle	0.83	0.92	1/3
PIW1a – exponential	0.92	1.00	1/3
PIW1b – exponential	0.92	1.00	1/3
PIW1c – exponential	0.92	1.00	3/3
PIW1d – exponential	0.92	1.00	1/3
PIW1a – potential	0.92	1.00	2/3
PIW1b – potential	0.92	1.00	2/3
PIW1c – potential	0.92	1.00	1/3
PIW1d – potential	0.92	1.00	1/3

Table 4-1: Comparison of Validity of Selected Pilot Gain Measures

The different grouping of more and less successful pilots and more and less challenging levels in the workload buildup flight test technique is reflected by one-dimensional versions of PIW1. However, the aspect of a different slope for aggressiveness vs. duty cycle which is clearly visible in the two-dimensional PIW plot gets lost.

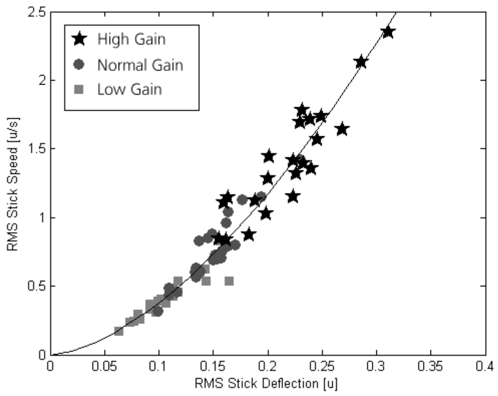
5. Variations of PIW with Stick Deflection and Acceleration

One of the participants in the study about one-dimensional measures in Chapter 2.3 found the duty cycle to be so much less important than the stick speed that he suggested to remove duty cycle completely and replace it by the stick deflection instead. There have also been other suggestions to evaluate whether the stick deflection or acceleration can be used instead of stick speed. In [19] it was suggested to use the product of stick speed and stick deflection for aggressiveness.

All these variants are closer investigated in the following subchapters.

5.1. Stick Speed vs. Stick Deflection

Figure 5-1 presents the RMS stick speed vs. the RMS stick deflection, i.e. a variant of PIW with no consideration of the duty cycle. There is a strong relation between both parameters which is amongst others reflected in the high pseudo R² of 0.94. The relation is potential; an exponential function is clearly unfit.



Potential Function
speed = 16.137·deflection$^{1.6282}$
Pseudo R² = 0.94

Figure 5-1: RMS Stick Speed vs. RMS Stick Deflection

Stick speed and stick deflection are clearly related as one is the derivative of the other. There is, however, no straight forward way to determine a mathematic relationship between these two parameters as the RMS value of the stick speed and deflection over the test point is a function of the pilots' input frequencies and their corresponding amplitudes and as both depend on each individual pilot and his control strategy, the task and the aircraft reaction at different frequencies.

Because of this a pilot model was used to see if the relation can be explained on a control system-related basis. The model is based on the model, but not the assumptions, of Neal and Smith [8]. The pilot's input is based on the following equation:

$$F_1(s) = K_1 e^{-T_{e1}s} \frac{T_D s + 1}{T_I s + 1}. \qquad \text{Eq.16}$$

Three parameter sets were used as a baseline. The parameter sets are based on parameter identification performed with the DLR in-house tool Fitlab [17].

In order to demonstrate the effect of increasing pilot gain, for the purpose of this report the pilot model gain K_1 was varied and the other parameters were kept at the originally identified values.

- The parameter set ETNN-NG is the parameter set of the pilot with the ID ETNN for the pilot gain calibration data point performed with normal gain. This pilot achieved the best overall performance.
- The parameter set PFAR-LG is the parameter set of the pilot with the ID PFAR for the pilot gain calibration data point performed in an intentionally low gain manner. PFAR was already fairly low gain at his normal gain data point and could further lower his pilot gain for the low gain data point. Furthermore, he is a fighter pilot which gives him an advantage over low gain transport pilots as he is familiar with tracking tasks.

- The parameter set TEST-HG is the parameter set of the pilot with the ID TEST for the pilot gain calibration data point performed in an intentionally high gain manner. TEST was one of the highest gain pilots.

The three parameter sets were used to cover essentially different tracking strategies with the pilot model.

Figure 5-2 left shows the data points of the simulator study and compares them with the results of the three pilot models with a variation of the pilot model gain parameter K_1.

It is evident that the pilot model based on the highest pilot gain (TEST-HG) presents the best fit for all data points – even the ones performed in a low gain manner. This is quite surprising, not only because low and high gain pilots are known to have significantly different tracking strategies, e.g. in terms of the relevant frequency range, but also because the goodness of fit of a pilot model decreases with increasing pilot gain ([12], [14]). In Figure 5-2 left such a deviation could only be assumed for the two highest gain data points, the higher one of them being the high gain data point of pilot TEST (i.e. the data point the model is based on). Because of this it is even more remarkable that the data of this parameter set fits the data points best. It should also be mentioned that the only low gain data point located at the line of the PFAR-LG pilot model is not the associated data point of PFAR.

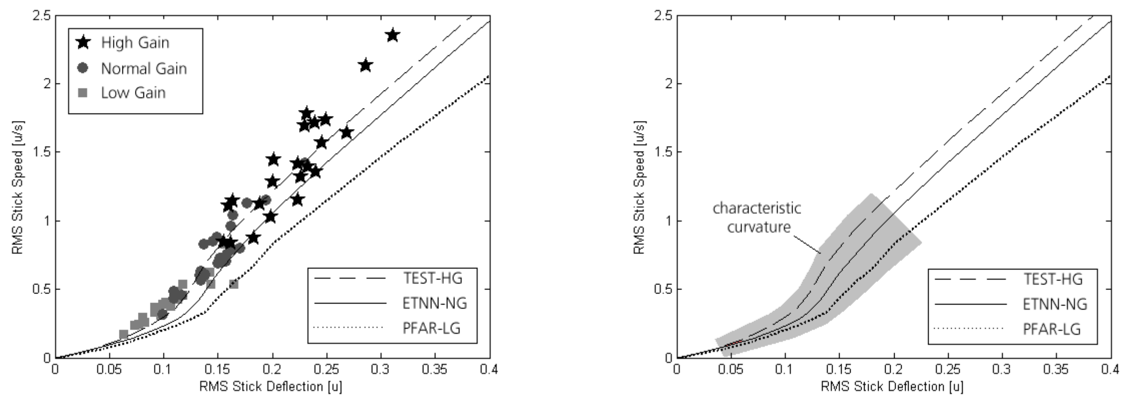


Figure 5-2: Comparison of Pilot Model Results and Simulator Study

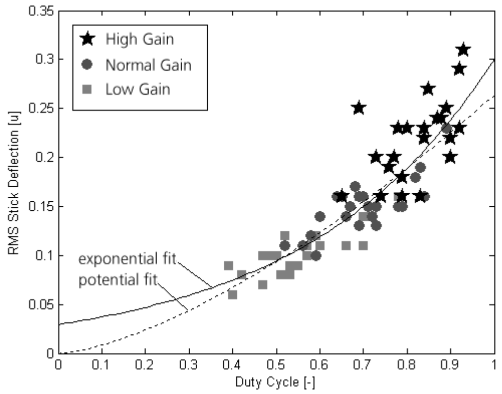
All three pilot model results have a characteristic curvature (Figure 5-2 right) which is not reflected in the real pilots' data.

In summary, a close relation between stick deflection and stick speed can be explained by pilot models, but only to a certain extend. The models show a significant curvature which is not representative for the real pilots' data and only the highest gain model (TEST-HG) creates a reasonable fit for the data while at the same time it does not cover the data point it is based on.

Because of the high correlation between stick deflection and stick speed a PIW plot using both parameters rather provides redundant information instead of adding significant background.

5.2. Stick Deflection vs. Duty Cycle

Figure 5-3 presents a PIW plot using the RMS stick deflection instead of the RMS stick speed as a measure of aggressiveness. Because of the similarity of the RMS stick speed and deflection, it is not a surprise that a PIW plot of the RMS stick deflection vs. duty cycle creates a similar picture as the regular PIW plot. Again the exponential curve fit works better for data points with higher pilot gain.



Exponential Function

$aggdef = 0.0295 \cdot e^{2.3 \cdot dc}$

Pseudo R^2 = 0.78

Potential Function

$aggdef = 0.264 \cdot dc^{1.5}$

Pseudo R^2 = 0.76

Figure 5-3: PIW Plot with RMS Stick Deflection instead of RMS Stick Speed

In [18] the mean instead of the RMS stick deflection was used for the PIW plot. Figure 5-4 presents a comparison of the data gained in the DLR simulator study and the results from [18] which used three different aircraft models and the workload buildup flight test technique. The trends are not at all similar. While the data from [18] shows no significant trend for the mean stick deflection-based aggressiveness vs. duty cycle plots, the data from the DLR simulator study shows a clear trend similar to the RMS stick deflection. A few points from the Level 3 model in [18] coincide with the population from DLR's simulator study, but the trend is essentially different with no apparent link between an increase in mean stick deflection and duty cycle. It seems that in 18] there is a wide range of duty cycle values which is related to the same mean value of the stick deflection.

No background information about the simulator setup in [18] is given in this report; it can be found in the referenced paper. Because [18] focuses on adaptive model follower algorithms, a lot of the background information which could explain the differences is not available. It should also be noted that based on the information in the paper it is unknown whether one data point resembles the complete test point or whether data points are calculated for each boundary size of the test point.

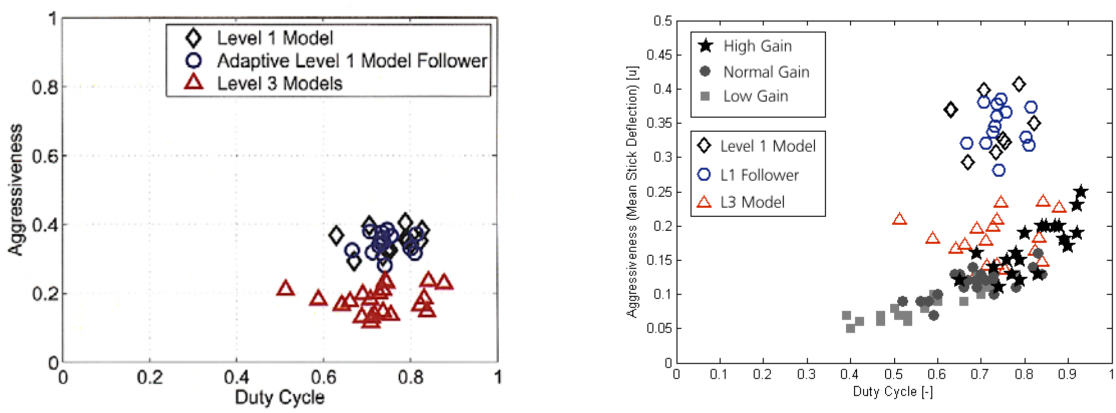
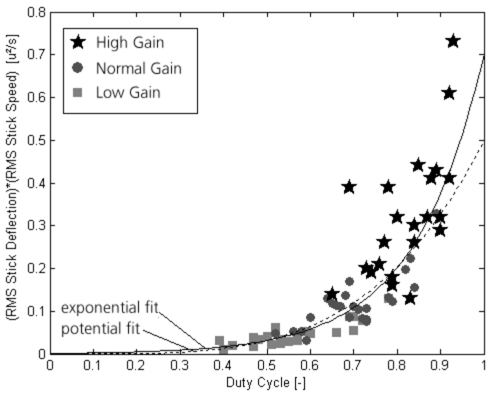


Figure 5-4: PIW Plots with Mean Stick Deflection instead of RMS Stick Speed (left: original plot from [18]; right: adapted plot including data from DLR simulator study)

5.3. Stick Deflection * Stick Speed vs. Duty Cycle

In [19] it is hypothesized that the product of (RMS stick deflection) * (RMS stick speed) will probably give "a truer representation" of pilot (inceptor) workload.

Figure 5-5 presents a PIW plot using the product of RMS stick speed x RMS stick deflection instead of the RMS stick speed as a measure of aggressiveness. The plot has a similar shape than the other variants with a slightly stronger curvature. As for the other variants an exponential fit is more suitable for data points with high PIW than a potential fit.



<u>Exponential Function</u>

$aggprod = 0.0014 \cdot e^{6.2 \cdot dc}$

Pseudo $R^2 = 0.74$

<u>Potential Function</u>

$aggdef = 0.498 \cdot dc^{4.0}$

Pseudo $R^2 = 0.68$

Figure 5-5: PIW Plot with RMS Stick Deflection x RMS Stick Speed vs. Duty Cycle

5.4. Comparison of Different PIW Variants based on Stick Deflection

5.4.1. General Discussion

Figure 5-6 presents a comparison of the three variants of PIW. The fourth variant – RMS stick speed vs. RMS stick deflection – is omitted because both measures are redundant.

It is evident that the version with stick deflection has the smallest curvature, the product of RMS stick speed and RMS stick deflection has the strongest curvature of the variants. In all cases the exponential fit is better than the potential fit. Low and high gain data points are well separated in all plots. Basically all plots appear to be suitable representations of PIW.

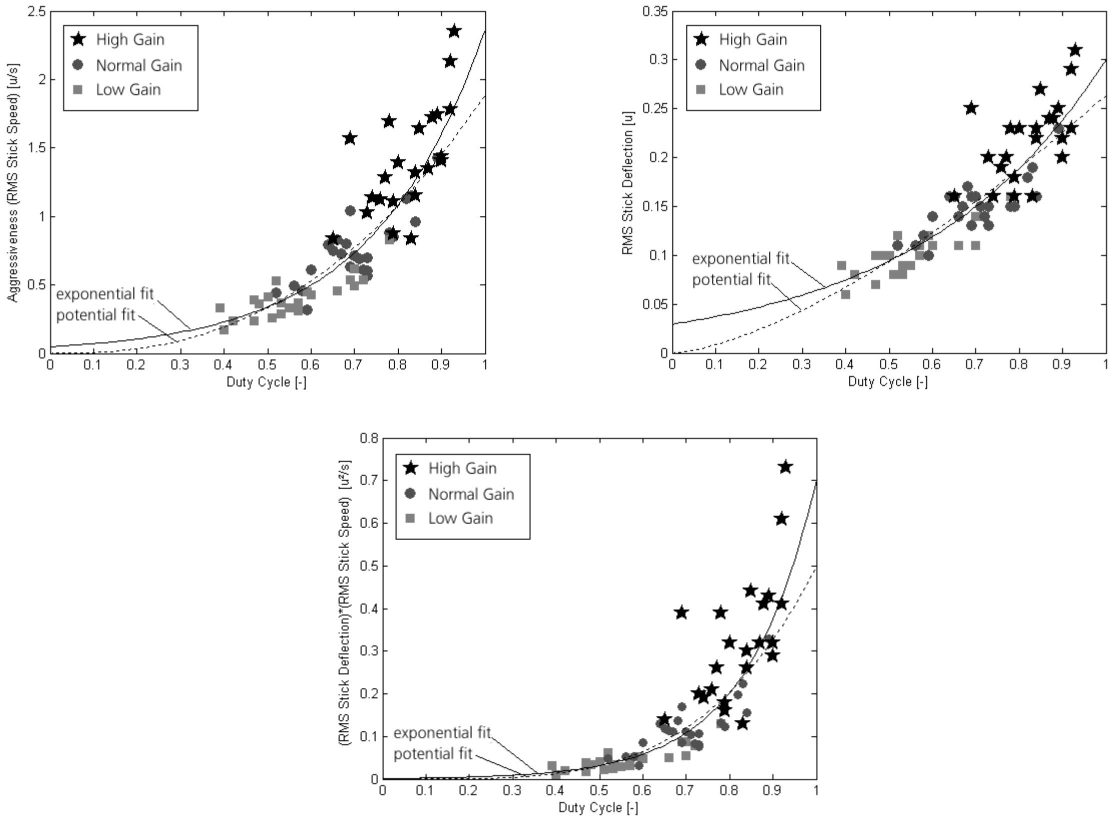


Figure 5-6: Comparison of Different PIW Variants with Stick Deflection

5.4.2. Separation of Low, Normal and High Gain Data Points

Because the x-axis remains the same in the three variants presented above, a direct comparison of the parameters used for “aggressiveness” has the potential to provide more information about the separation of low, normal and high gain data points.

Figure 5-7 shows the mean value and plus/minus one sample standard deviation of the parameter values used for aggressiveness grouped by parameter and applied pilot gain. Because the parameters have different value ranges, they were normalized to the mean value of the normal gain data points.

As Figure 5-7 shows, there is a clear separation between low and high gain data points for all three variants. The overlap for the normal gain range of one sample standard deviation is larger for the product of the RMS stick speed with RMS stick deflection, which would make it slightly less suitable than the other variants. Also the value range grows most significantly for this variant, having a much larger range for the high gain data points than for the normal and high gain data points. In general, however, all variants appear to be suitable for PIW.

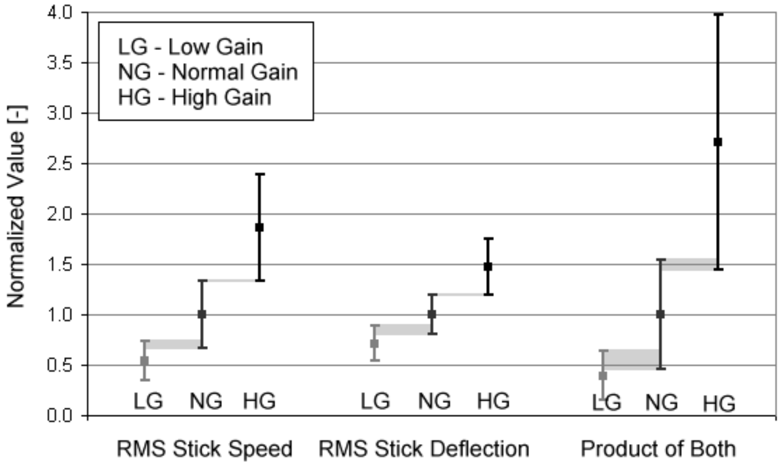
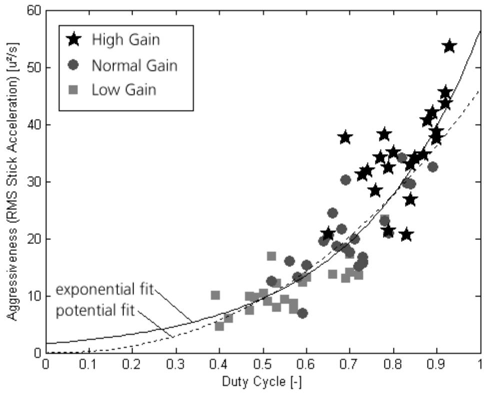


Figure 5-7: Separation of Low, Normal and High Gain Data Points

5.5. Stick Acceleration vs. Duty Cycle

Figure 5-8 presents another possible variant of PIW, using the RMS stick acceleration instead of the RMS stick speed. Like for the other evaluated parameters, an exponential function creates a better fit for high PIW values than the potential function.



Exponential Function
aggacc = $1.6103 \cdot e^{3.5589 \cdot dc}$
Pseudo R^2 = 0.78

Potential Function
aggacc = $46.207 \cdot dc^{2.2903}$
Pseudo R^2 = 0.76

Figure 5-8: Stick Acceleration vs. Duty Cycle

Figure 5-9 depicts the separation of low, normal and high gain data points for the RMS stick acceleration. The result is neither significantly better nor worse than the results for the other variants presented in Figure 5-7.

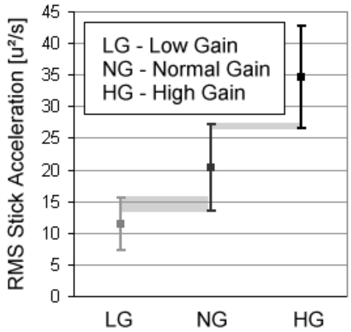


Figure 5-9: Separation of Low, Normal and High Gain Data Points (RMS Stick Acceleration)

Because the stick acceleration involves the calculation of the second derivative of the stick deflection, i.e. a more complex mathematical process, but at the same time the information contained in the PIW plot is not improved, it is a valid variant of PIW, but there is no reason to prefer it.

6. Conclusions and Limitations

6.1. One-dimensional Representations of PIW

Four different one-dimensional representations of PIW – PIW1 - are introduced and evaluated in this report. Based on the different mathematic backgrounds the variants of PIW1 have different characteristics regarding a linear distribution of data points at the diagonal from very low to very high data points and resulting values for data points which have a value of zero for one of the two dimensions. A comparison with an evaluation of test pilots shows that many pilots regard the aggressiveness – represented by the stick speed – as a much more important parameter than the duty cycle. Consequently, their evaluation often included a stronger weighting of aggressiveness than duty cycle. This was not reflected by either of the PIW1 variants.

6.2. Relation between Aggressiveness and Duty Cycle

Data of DLR's simulator study "Pilot Gain and the Workload Buildup Flight Test Technique" and openly available data from the USAF TPS study BAT DART was analyzed in order to evaluate the relation between duty cycle and aggressiveness.

An exponential or potential function can be used to create a link between both dimensions of PIW. The exponential function creates a better fit for high gain data points, but it does not pass through the origin of the PIW plot which is in contradiction with physics. The potential function creates a poor fit for high gain data points, but passes through the origin of the PIW plot.

While Gray preferred the use of the natural logarithm in [5], [6] and [7], this mathematic alteration of the data may contradict the very idea of PIW, which is being closely related to a test pilots' reality. Because the natural logarithm is rather abstract, a representation of the original data without the natural logarithm or other alterations should be preferred in PIW plots.

The data points of DLR's simulator study and BAT DART create quantitatively and qualitatively the same trends. Because of the high number of influence factors, more studies are needed in order to evaluate whether this is a coincidence or a general effect which is essentially the same for different test setups.

The data of the "pilot gain calibration" runs of DLR's simulator study shows a clear separation of low and high gain data points in the PIW plots, supporting Gray's hypothesis that PIW is a suitable representation of pilot gain.

Different test techniques used in DLR's simulator study show essentially the same trends for aggressiveness vs. duty cycle. The high gain test points of the "pilot gain calibration" overall create the highest pilot gain because there are no boundaries which restrict the pilots' inputs. On the other hand it is less intuitive and involves role playing while the pilot gain increase is automatically achieved during the workload buildup flight test technique.

6.3. Validity of PIW1 and Recommendations

A normalization of aggressiveness to a range between 0 and 1 can be performed based on the identified exponential or potential function. Based on the normalized values, the different variants of PIW1 can be calculated.

Even though all PIW1 variants achieved very good validity indices and a good separation of low and high gain data points, outlier detection was rather poor. Also, PIW1 did not add any more information to the data contained in the RMS stick speed alone.

While PIW is a very intuitive representation of pilot gain, PIW1 removes the direct link between the represented data and flight test and introduces a considerable amount of abstraction. No benefit of PIW1 over the use of the RMS stick speed as a stand-alone parameter could be identified. It is thus recommended to use the two-dimensional representation of PIW whenever possible and to use the RMS stick speed when a one-dimensional parameter is needed.

6.4. Variations of PIW with Stick Deflection and Acceleration

Several variations of PIW plots with stick deflection and stick acceleration were evaluated. These were specifically:

- RMS stick speed vs. RMS stick deflection
- RMS stick deflection vs. duty cycle
- RMS stick speed * RMS stick deflection vs. duty cycle
- RMS stick acceleration vs. duty cycle.

All representations proved to be suitable.

Because of their physical connection, stick speed and deflection are closely related by a potential function. The plot with these two parameters thus provides redundant information rather than adding extra information.

All other plots show an exponential or potential relation between the two alternative dimensions of PIW. Low and high gain data points are well separated.

Based on this result, the use of the original version of PIW using the RMS stick speed vs. duty cycle is recommended. RMS stick acceleration and RMS stick speed * RMS stick deflection are mathematically more complex, but do not add any new information. The RMS stick deflection is mathematically less complex than the RMS stick speed but achieved worse ratings in terms of validity in [12]. In addition, a pilot holding the stick at its maximum position throughout the test point would achieve the maximum value for PIW while not being in the loop at all.

The original version of PIW as it was presented in [5], [6] and [7] is, hence, the best choice.

Summary and Outlook

This report takes a closer look at Pilot Inceptor Workload (PIW) as a representation for pilot gain.

Four different one-dimensional variants of PIW called PIW1 were introduced and evaluated based on their mathematic characteristics, comments and evaluations of experimental test pilots and data gathered in the frame of a simulator study. In summary, no benefit of PIW1 over the use of the RMS stick speed as a stand-alone parameter could be identified. It is thus recommended to use the two-dimensional representation of PIW whenever possible and to use the RMS stick speed when a one-dimensional parameter is needed.

The relation between aggressiveness and duty cycle seems to be of either exponential or potential nature with relatively small scatter. While the potential function is well in line with physics, the exponential function does not pass through the origin of the PIW plot, but has a much better fit for high gain data points. The trend is consistent for different test techniques used in the DLR simulator study and for F-16 in-flight data from the BAT DART project of the USAF TPS.

PIW proved to be a suitable representation of pilot gain and shows a clear separation of low and high gain data points.

Different variants of PIW based on the stick deflection and stick acceleration were evaluated. While all of them create reasonable results, the original version of PIW based on the RMS stick speed vs. duty cycle is recommended because it is mathematically simpler than most of the variants and because RMS stick speed is a more reliable representation of pilot gain than the RMS stick deflection.

It was shown that the data of DLR's simulator study and the data extracted from reports about the BAT DART project presented a perfect match in the PIW plot. However, numerous factors have the potential to influence the relation of aggressiveness vs. duty cycle, including

- the type of inceptor (sidestick, wheel controller, center stick)
- the inceptor's force characteristics (deflection vs. force curve, magnitude of force)
- other inceptor characteristics (backlash, damping, centering, breakout force)
- the type of control realization in the FCS (rate command, attitude command, C* command, g command, direct law etc.).
- the frequency content and amplitude of the task.

It is thus recommended to support the results of this report by further studies in the simulator and in flight in order to evaluate whether the good match of data points from these two fundamentally different data bases is a coincidence or gives room for generalization.

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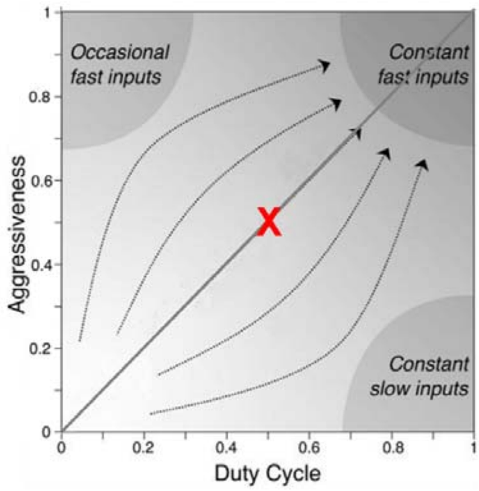
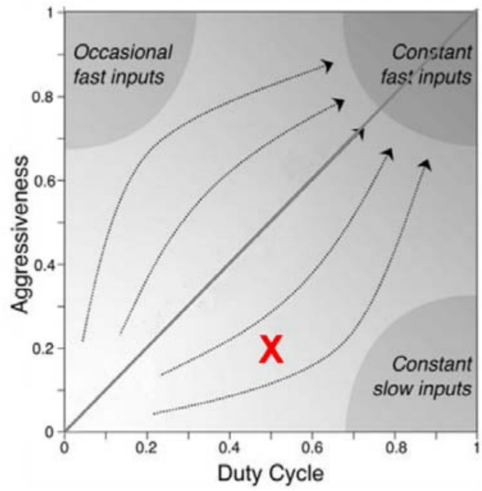
Appendix A: PIW1 Test Cases and Results

12 test cases were presented to 5 experimental test pilots from WTD 61. The data point's location in the graph (marked with a red "X") and the associated numerical data was provided together with a briefing about PIW and the restriction to limit PIW1 to values between 0 for the lower left corner and 1 for the upper right corner. dc = duty cycle, agg = aggressiveness (normalized)

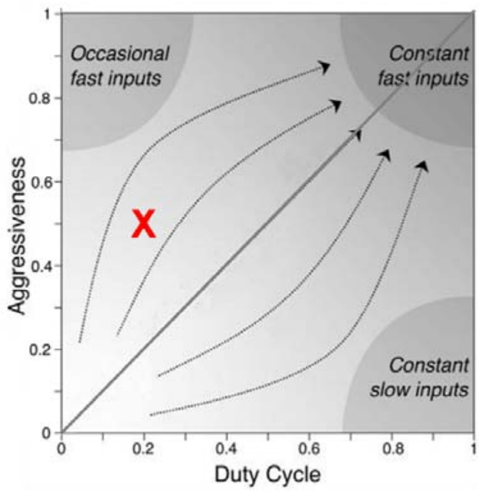
Test Case 1: dc = 0.5, agg = 0.5



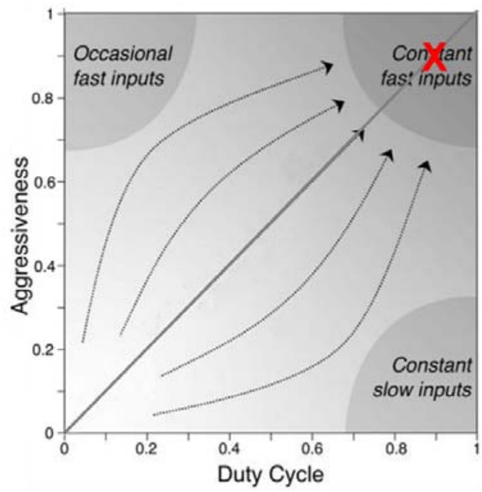
Test Case 2: dc = 0.5, agg = 0.2



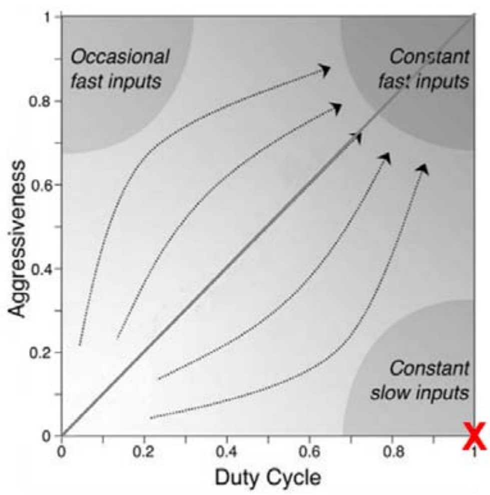
Test Case 3: dc = 0.2, agg = 0.5



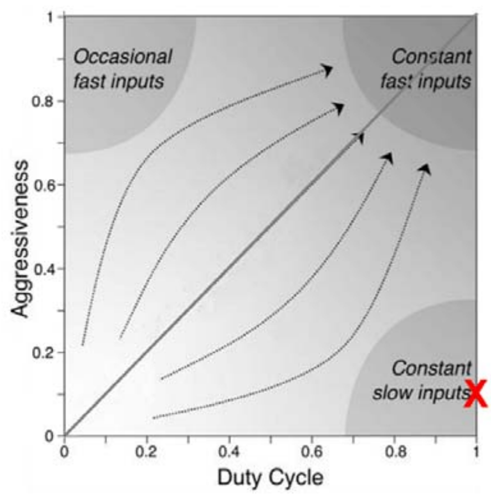
Test Case 4: dc = 0.9, agg = 0.9



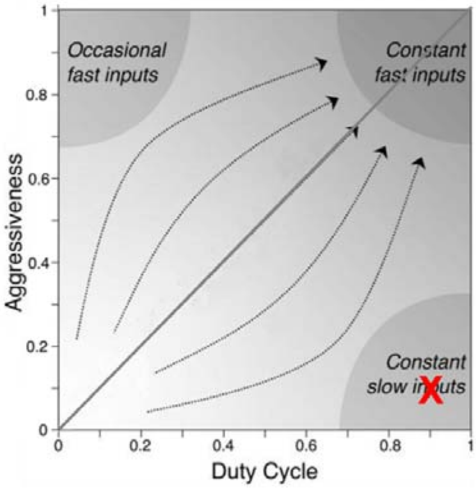
Test Case 5: dc = 1.0, agg = 0.0



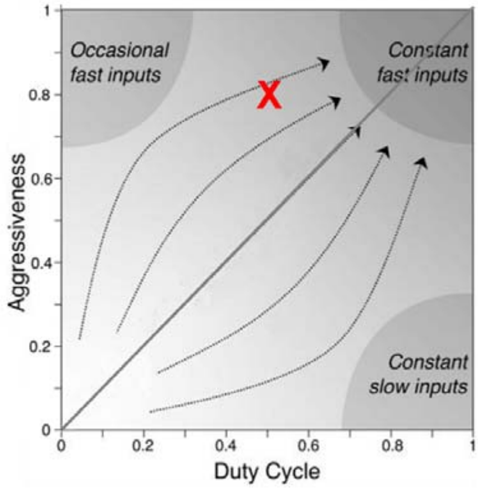
Test Case 6: dc = 1.0, agg = 0.1



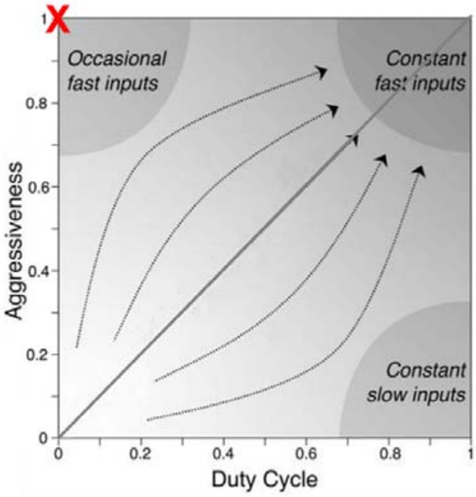
Test Case 7: dc = 0.9, agg = 0.1



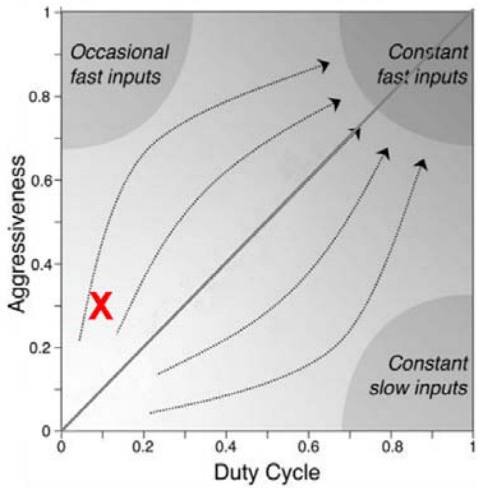
Test Case 8: dc = 0.5, agg = 0.8



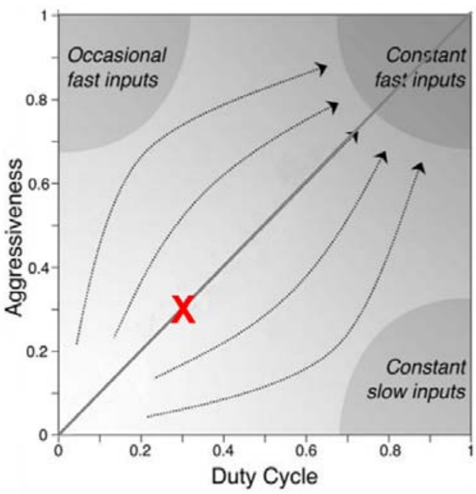
Test Case 9: dc = 0.0, agg = 1.0



Test Case 10: dc = 0.1, agg = 0.3



Test Case 11: dc = 0.3, agg = 0.3



Test Case 12: dc = 0.9, agg = 0.8

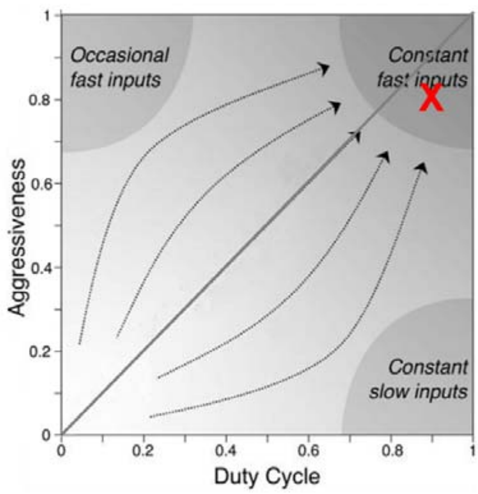


Table A-1 shows the test values (dc, agg), the pilot's evaluation of PIW1 for the test cases and the mathematical value for the four PIW1 forms which are introduced in this report. In those cases where there are two values provided by one pilot, the first one is based on math, the second one on the pilot's gut-feeling.

dc	agg	PIW1 (Pilots)							PIW1 (Math)			
		Pilot A	Pilot B.1	Pilot B.2	Pilot C	Pilot D	Pilot E.1	Pilot E.2	PIW1a	PIW1b	PIW1c	PIW1d
0.5	0.5	0.5	0.125	0.5	0.5	0.5	0.25	0.3	0.25	0.50	0.50	0.50
0.5	0.2	0.35	0.05	0.3	0.25	0.3	0.15	0.25	0.10	0.32	0.20	0.33
0.2	0.5	0.35	0.02	0.4	0.4	0.4	0.18	0.4	0.10	0.32	0.20	0.33
0.9	0.9	0.9	0.73	0.9	1	0.9	0.8	0.8	0.81	0.90	0.90	0.90
1	0	0.5	0	0.1	0	0.1	0	0	0.00	0.00	0.00	0.29
1	0.1	0.55	0.01	0.2	0.1	0.2	0.05	0.07	0.10	0.32	0.10	0.36
0.9	0.1	0.5	0.009	0.15	0.15	0.2	0.04	0.05	0.09	0.30	0.10	0.36
0.5	0.8	0.7	0.32	0.7	0.7	0.7	0.35	0.7	0.40	0.63	0.50	0.62
0	1	0.5	0	0.5	0.5	0.9	0	0	0.00	0.00	0.00	0.29
0.1	0.3	0.2	0.009	0.25	0.1	0.2	0.07	0.2	0.03	0.17	0.10	0.19
0.3	0.3	0.3	0.027	0.3	0.25	0.3	0.2	0.25	0.09	0.30	0.30	0.30
0.9	0.8	0.87	0.58	0.7	0.9	0.8	0.75	0.85	0.72	0.85	0.80	0.84

Table A-1: Pilot's Results (PIW1 Determination for 12 Test Cases)

Appendix B: Calculation of R^2 for Nonlinear Relations

The regression coefficient R^2 is typically associated with linear regressions. It can be extended to nonlinear functions, but different variants exist which is why the variant used in this report is introduced in this appendix.
The equation used for the calculation of R^2 is

$$R^2 = 1 - \frac{SSE}{SSY} = 1 - \frac{\sum \left(Y_i - \hat{Y}_i\right)^2}{\sum \left(Y_i - \overline{Y}\right)^2}$$

This equation is equal to the parameter R_1^2 in [2].

SSY is a measure of the variation in the Y_i values about their mean value $\overline{Y}$.
SSE is a measure of the variation in the values of Y_i or the uncertainty in predicting Y, when a regression model containing the variable X_i employed. [2]

Y_i are the data points on the y axis, in this case the aggressiveness (RMS stick speed).
$\hat{Y}_i$ are the aggressiveness values according to the regression.

The associated data can be found on the next pages.

Appendix C: PIW1 Plots for Potential Fit (Grouping Based on Pilots' Achievements and Levels)

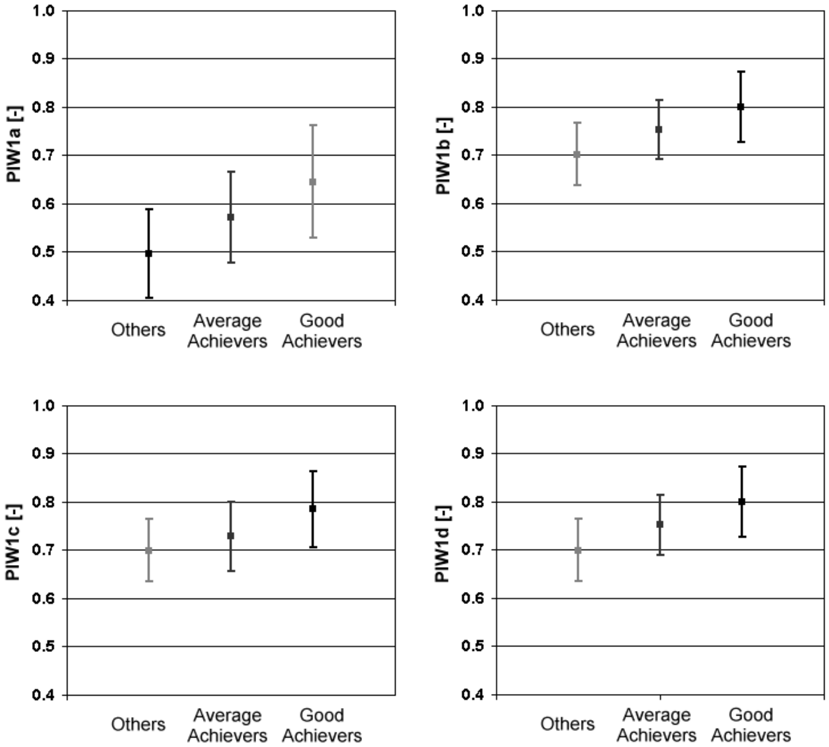


Figure A - 1: PIW1 Variants based on Potential Fit Grouped by the Pilots' Achievements

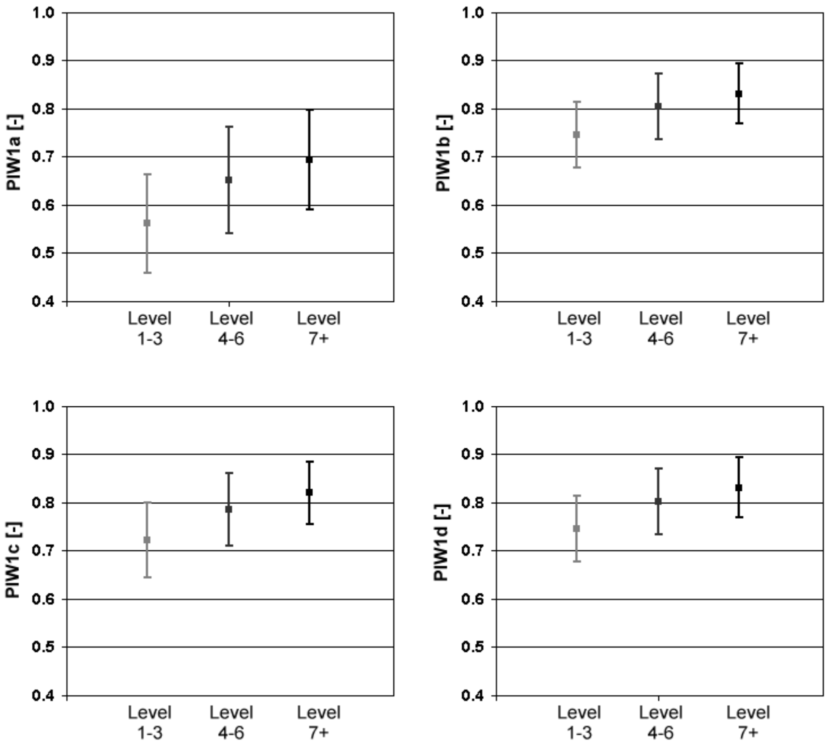


Figure A - 2: PIW1 Variants based on Potential Fit Grouped by Levels