Using a Designed Experiment to Determine Flight Duration of a Model Rocket

or

"Taking the 'random' out of random duration"

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1.0 Abstract:

Measurements of total time of flight for an Estes HiJax™ model rocket employing B and C rocket motors, various parachute diameters, and various payload weights were made. This data is useful to competitors flying in precision duration competition (which includes predicted duration, random duration, and set duration competitions). A table was constructed detailing the motor size, parachute diameter and payload mass necessary to obtain each target duration in 5 second increments between 30 and 120 seconds. This table will be useful as a "field chart" when flying one of the precision duration events.

The investigation was conducted using a pair of two-level, two-factor designed experiments. Replicates of each process condition were made, and measurements of the error associated with each condition were obtained. A mathematical model was obtained which described the influence of the variables and the precision of the duration. As expected, motor thrust had the most influence on total flight duration. Payload mass (in grams) and parachute diameter (in inches) had nearly equal and opposite influences on duration.

After the tests were conducted, it was determined that rocket motors more than approximately one year old gave flight times significantly shorter than more recently-made rocket motors. This may be due to an aging effect of the propellant which lowers the total impulse. However, the reason for this phenomenon was not persued since it was outside the scope of this study.

The rocket employed in the study was an Estes HiJax™, a model which was readily available, used plastic fins, and required no painting. Use of this model removed the variable of surface finish from the flight tests. Two confirmation runs were made to test the model equation obtained from this study. Flight times were obtained which agreed within 12% of times predicted by the model . The model equation presumed use of Estes rocket motors, a level flying field, zero or light wind conditions, no thermals and several other minor conditions detailed in the report. Duplication of the results by other competitors would be problematic unless the stated assumptions of this report were maintained.

2.0 Introduction

2.1 Goal of the Experiment

The purpose of this investigation was to calibrate an Estes HiJax™ model rocket for the NAR precision duration competition, and present rocket configuration data useful to competitors flying in that event. The contestant closest to the target or predicted flight time wins the competition, therefore, knowledge of rocket configuration vs. total flight duration is valuable to the contestant. The rocket is configured using a B6-4 or C6-5 Estes model rocket motor, an appropriate size parachute and appropriate payload mass to obtain a total flight time as close as possible to the target or predicted flight time.

2.1.1 Applicability of Results

It is sincerely hoped that an NAR competitor can use this report to build a parachute, choose an appropriate motor and payload weight, and fly an Estes HiJax™ in a precision duration competition within 10% of the target duration time. This degree of precision will probably place the contestant within the top 5% of competitors, and may result in an award of first through fourth place resulting in higher competition points.

2.2 Overview of Precision Duration Competition

Precision duration comprises three competitions: predicted duration, random duration, and set duration. In predicted duration, competitors must accurately predict total flight duration of their model. In random duration, the Contest Director randomly picks a target duration between 30 and 120 seconds immediately before a contest begins. In set duration, a target duration is chosen well in advance of the contest such that all competitors know the target duration in advance. In all three events, competitor's flights must be their first flight of the day (no practice launches are allowed). Most contestants use a combination of past experience, guesswork and luck to configure their models with the proper motor and parachute that will provide total flight duration close to the target duration. To be successful in this competition, the effects of motor total impulse, payload mass and parachute size on flight duration needed to be quantified.

3.0 Approach:

3.1 The Test Vehicle:

The test vehicle for this study was an Estes HiJax™, chosen for its availability, low-cost, durability, and payload capacity. The HiJax™ also had plastic fins and requires no finishing or painting, therefore, the variables of surface finish and painting were removed from the experimental design. Three HiJax™ models were purchased. Two weighed 57 grams without parachute, wadding, or rocket motor. The third vehicle weighed 54 grams, and was brought up to 57 grams with additional clay weight in the nose. The HiJax™ models were purchased and built as stock kits, with one modification: the 1/8" elastic shock cord was replaced with a ¼" elastic cord about 18" long. One HiJax™ (vehicle #1) landed in a tree early in the program and was lost. The author of this report built all the test vehicles. Each test vehicle was numbered and flight duration data included the vehicle number used for that run.

3.2 Identifying the Variables to Study:

A fishbone diagram was constructed to investigate the total number of variables involved in the flight duration of a model rocket. This diagram is presented in Figure 1. From this diagram three variables, payload weight, motor total impulse, and parachute diameter were chosen for study. A designed experiment was proposed to investigate the effects of the three variables on total flight duration. The flight duration of interest was between 30 and 120 seconds, according to the NAR rules for this competition. A more detailed explanation of variables is given in section 6.2.

3.3 Parachutes

The stock Estes parachute in the HiJax™ kit was replaced with an octagonal parachute made from dry cleaner bag material (polyethylene film). Shroud lines were 30 pound Kevlar fishing line secured with small squares of masking tape. Each shroud line was 1.5 times the diameter of the parachute. The author fabricated and packed all the parachutes used for this study. Three sets of octagonal parachutes (9 total) of 12, 18 and 24 inch diameter (measured flat to flat) were constructed to support this study. All parachutes were fitted with snap swivel hooks to facilitate changing from one rocket to another.

3.4 Rocket Motors

Estes model rocket motors types B6-4 and C6-5 were used exclusively in this study. Initially, A8-3 and B6-4 motors were chosen for this study. However, it became obvious after a few flights that the A8-3 motors were far too weak to give a thirty second duration. The motors were changed to B6-4's and C6-5's, which gave flight results encompassing the 30 to 120 second range of interest. No attempt was made to obtain rocket motors from the same manufacturing lot, although it may (and did, as explained later) account for some performance differences. It was my intention to develop a flight duration model that was robust enough to account for differences between motor propellant lots, since contestants flying in precision duration competitions would not necessarily have access to the same motor lots used during this study.

3.5 Test Procedure

Flight duration was timed using a stopwatch and data was recorded on datasheets. Flights were conducted from an Estes Porta Pad launcher and launch controller, which are available in almost any Estes starter kit. Launches were conducted vertically on flat terrain and all flights were conducted on calm or relatively calm days, either in the morning or evening when thermal activity was at a minimum.

There were 32 flights in this study, and 9 were rejected because of insufficient motor total impulse (A8-3's, as previously mentioned), parachute entanglements, lost sight of rocket, or other reasons. Any flight that could not obviously return unbiased data (for instance, incomplete parachute opening or noticeable launch rod tip-off) was rejected on the spot.

4.0 Equipment Used:

4.1 Construction Equipment

No special construction equipment was required for the Estes HiJax™ models or for the launch equipment.

4.2 Launch Equipment

Rockets were launched from the "Porta-pad" launch equipment found in most Estes model rocket starter sets. A digital stopwatch was used to measure time. Data was recorded manually on data sheets attached to a clipboard. Payload masses of 14 and 28 grams were constructed by filling 18-mm diameter paper body tubes with fine sand, and sealing the ends with balsa wood and glue.

4.3.1 Data Analysis

Results were analyzed using Microsoft Excel with the add-in program DOE KISS by Digital Computations, Inc., and Air Academy Associates. This program was available to the author at his place of employment.

5.0 Data Collected:

The pertinent data analyzed from this experiment is shown in Table 1. Data recorded for each flight included trial number, ambient temperature, an estimate of wind speed and direction, motor type, motor date serial number, test vehicle number, parachute diameter and number, payload mass, comments on launch and recovery, and flight duration achieved.

6.0 Discussion of Designed Experiments

6.1 Overview

A designed experiment is a well thought out series of trial runs where the experimental variables are the only things purposefully changed. Every effort was made to ensure other variables remained constant. The experimental scheme was set up as a matrix, which made analysis easy and resulted in a mathematical equation which describes the output (in this case, flight duration) in terms of the inputs (rocket motor, parachute diameter, and payload mass).

6.2 Identification of Variables

System variables were identified and presented in a fishbone diagram (Figure 1). The number, type and relationship of the variables to each other and the rocket duration can be visualized, and the most promising variables can be studied. Every attempt was made to keep the other variables constant. For this experiment, variables were identified and dealt with as shown in Tables 1 through 4.

Table 2. List of Materials Variables for Precision Duration Experiment

Materials	**How Influence of This Variable Will Be Minimized During the Experiment**
Parachute Material	Held constant. Used dry cleaner bag material for each parachute.
Type of Rocket Motor	Purposely varied during the experiment, but use Estes B6-4 or C6-5 only
Variation in Rocket Motor Total Impulse	1. Randomization of experimental runs 2. Ran replicate experiments, use average results.
Variation in Rocket Motor Delay Charge	1. Randomization of experimental runs. 2. Ran replicate experiments, use average results.
Rocket Construction Material	Use Estes HiJax kit only

6.3 Experimental Setup

Experiments were set up as a matrix as shown in Figure 2. This went against the traditional “vary-one-thing-at-a-time” approach, but it was more effective since matrix algebra could be used to analyze the results, determine the overall error involved, which variables interacted with one another, and which variables were more important. For this experiment, two matrices, each with a center point and four corner points, were constructed. The matrices included the variables of parachute size and payload mass. Two matrices were necessary because there was one distinct, non-continuous variable, namely the total impulse of the rocket motors. Rocket motors sized between a B and a C were not commercially available during the test period.

No attempt was made to use rocket motors with specific date or lot codes. Each rocket motor was randomly chosen as long as it was the proper type (B6-4 or C6-5) for the experiment. Parachutes (as long as they were the proper diameter) and test vehicles were also randomly chosen for each flight. Parachutes showed wear and after several flights they were retired and replaced with identical versions.

Table 3: List of Methods Variables for Precision Duration Experiment

Methods	How Influence of This Variable Will Be Minimized During the Experiment
Folding/Loading Parachute	Author packed all parachutes in this study using same technique.
Weathercocking of Rocket During Boost	1. Avoided launches on windy days. 2. Launched straight up only. 3. Data from weathercocked flights was invalidated.
Thermalling of Rocket During Descent	1. Launch in morning or early evening when thermal activity was low. 2. Invalidate test data from flights with thermalling recovery (there were none).
Incomplete Parachute Deployment	Invalidate test data from runs where parachute did not fully deploy
Launch Angle	All flights launched straight up.
Atmospheric Conditions: Temperature, Pressure and Humidity	Temperture measured for each flight. These conditions allowed to vary, as would be in a real contest.
Flatness of Terrain	All flights from same launch area, no hills.

Table 4: List of Measurement Variables for Precision Duration Experiment

Measurements	How Influence of This Variable Will Be Minimized During the Experiment
Accuracy of Timers	Used newly purchased digital stopwatch.
Parachute Diameter	1. Purposely varied during the experiment: 12, 18 or 24 inches. 2. Measured on fabric cutting board with one-inch grid.
Shroud Line Length	Held constant at 1.5 times chute diameter
Shroud Line Number	All parachutes were octagonal and used 8 shroud lines.
Rocket Weight	All rockets weighed on gram scale to ± 1 gram.

Table 5: List of Design Variables for Precision Duration Experiment

Design Variables	How Influence of This Variable Will Be Minimized During the Experiment
Overall Rocket Weight	Used Estes HiJax, 57 gram total weight, for each run.
Overall Rocket Drag	Estes HiJax Used for each run. Does not require painting or finishing.
Frontal Area	Held constant by rocket design.

6.4 Reduction in Systematic Errors

As explained in the next section, by using designed experiments, two types of error common to experiments are minimized.

6.4.1 Experimental Error

Experimental error is the type of error formed by random outcome of a particular event. Despite the best efforts of holding all the variables in an experiment constant, random chance will still cause some variation in the outcome. Designed experiments deal with experimental error by running duplicate experiments and averaging the results. Naturally, if three or more runs can be made at the same conditions there will be more confidence in the outcome. However, in this experiment it was too expensive to make more than two runs at each condition.

6.4.2 Experimental Bias

Experimental bias occurs when a variable outside the control of the experimenter becomes a factor in the results. For instance, ambient temperature effects during the course of an experiment may be a predominant factor, and an unsuspecting experimenter running trials in "logical order" during the course of the day may see his or her results skewed by this factor. Designed experiments minimize experimental bias by running the tests in random order. Each set of experiments was randomized by drawing numbered slips of paper out of a box. The flights were run in the order drawn.

6.5 Data Analysis

Table 1 shows all 32 flights in the experiment, which includes two confirmation runs. As previously mentioned, the runs were made in random order to reduce experimental bias. Early runs used A8-3 motors, however, these proved too weak to obtain the desired 30 second minimum duration. Flights using the A8-3 motor are shown on Table 1 for completeness but were not used in calculations. All flights in the shaded areas of the Table 1 were not used in calculations because of one problem or another, such as incomplete parachute deployment or weathercocking during boost.

A Microsoft Excel add-in program called DOE KISS was used to calculate results of the designed experiment and produce some of the charts in this report. The program analyzed each matrix (one for B and one for C rocket motors) separately. As shown in Figure 2, each matrix had four corner points and one center point. After the matrix test flights were flown, several additional test flights (runs 28, 29 and 30) were flown along the "edges" of the matrices. The program included these test flights in the results.

6.6 Results and Discussion

B6-4 powered flights were useful in the range of 30 to a maximum duration time of 55 seconds. Using C6-5 motors, durations between 40 and the 120 second maximum time for precision duration were achieved.

The plot of duration vs. payload mass for B6-4 powered flights was highly curved while it is nearly a straight line for C6-5 motors (see Figures 3 and 4). This meant that the equation describing the duration for B6-4 motors had squared terms, like a parabola. The equation developed by DOE KISS for B6-4 motors is:

$$\textbf{(1)} \quad \textbf{Duration} = 22.5 + 10.46(X1) - 9.67(X2) - 3.81(X1)(X2) - 2.5(X1)^2 + 11.14(X2)^2$$

For C6-5 motor duration, the equation lacks squared terms since the plot of duration vs. payload mass is nearly a straight line. The equation for C6-5 motor duration is as follows:

(2) Duration = 73.56 + 25.38(X1) – 23.96(X2) – 11.26(X1)(X2)

The variables X1 and X2 represent the coded variables for parachute diameter and payload mass, respectively. These variables were coded as follows:

(3) X1 = (parachute diameter in inches – 18)/6

(4) X2 = (payload mass in grams – 14)/14

The variables were coded to give a values of –1 and 1 at the low and high values in the experiment, respectively. For example, the low value of parachute size was 12 inches, and when 12 is used in equation 3 above, X1 equals –1.

The coefficient before each term in equations 1 and 2 gives the relative importance of the variables. The variables were ranked by coefficients according to Table 6 below:

Table 6: The Variables of the Model Equations Ranked in Descending Order of Importance

B6-4 Motor Flights		C6-5 Motor Flights	
Variable	**Coefficients**	**Variable**	**Coefficients**
$(\text{Payload mass})^2$	11.14	Parachute Diameter	25.38
Parachute Diameter	10.46	Payload Mass	-23.96
Payload mass	-9.67	Parachute X Payload	-11.26
Payload X parachute	-3.81		
$(\text{Parachute Dia.})^2$	-2.50		

For B6-4 motors, the most important variable was payload mass followed by parachute diameter. For C6-5 motors, the two variables were nearly identically important. Notice that the coefficients for the interaction term Payload X Parachute were relatively small in each equation. Therefore, it can be concluded that the variables interacted only moderately at most.

Please note that the equations above will only be valid for conditions used in this report, which have been stated previously.

DOE KISS also gave a value of adjusted r^2 for each equation. This value was useful for determining how much of the scatter in the data can be explained by the equation. If all the data was fit perfectly by the model equation, then the r2 would be 1.00. The r2 for the B6-4 equation was 0.72 and for the C6-5 equation was 0.92. The C6-5 equation fit the data very well, but the B6-4 equation fit the data only moderately well due to the high amount of curvature in the data.

Another feature of DOE KISS was its ability to select the optimum (least error fit) set of variables for any desired outcome. This feature was used to make a field chart of duration, parachute diameter, and payload mass, as shown in Table 7. This chart is useful for competitors in the random duration event, where they may not have access to a computer or calculator to figure out the optimum configuration for their rocket.

Two confirmation runs were made at target durations of 50 and 90 seconds. The actual durations for these runs were 55.0 and 79.3 seconds, resulting in errors of 10% and 12%, respectively. The flight with the 12% error also experienced some weathercocking, which may have been responsible for the lower than expected duration. These errors were larger than what was expected but would probably place a competitor in the upper quartile of all results.

Table 7: A Field Table for Configuring an Estes HiJax ™ For Any Flight Duration Between 30 and 120 Seconds

Target Time (Seconds)	Rocket Motor (Estes)	Parachute Diameter (inches)	Payload (grams)
30	B6-4	18	7.5
35	B6-4	18	5
40	B6-4	18	1.5
45	B6-4	21	2.5
50	B6-4	24	2
55	B6-4	18	0
60	C6-5	18	26
65	C6-5	18	22.5
70	C6-5	24	27
75	C6-5	18	13
80	C6-5	18	10.5
85	C6-5	24	20
90	C6-5	24	18
95	C6-5	24	15.5
100	C6-5	24	13.5
105	C6-5	24	11.5
110	C6-5	24	9.5
115	C6-5	24	7.5
120	C6-5	24	5.5

While attempting to reconcile some of the scatter in the duration data, it was noticed that, for similarly configured rockets, the older motor always gave shorter durations. A typical date code on a motor may be 16C3, which stands for 16 March, 1998. The first and last numbers are the day and month, respectively. 1998 is designated as C, 1997 as B, 1996 as A, and so on.

A summary of all duration flights involving replicate runs where one motor was older than another is shown in Figure 5. Notice that there are 9 pairs of runs where the motors were different ages. Of these 9 pairs, every one showed a decrease in duration. The probability that this decrease is due to random error during the test runs is 0.5 to the 9^{th} power, or 0.2%. Therefore, this effect is most probably real.

There are not enough points on Figure 5 to draw the general shape of the propellant age vs. duration line, however, it appears that the duration decreases rapidly until approximately the one year mark, and then a more gradual decrease occurs. So to obtain the maximum consistency, use motor either of the same date code or older motors. To obtain the maximum duration, use the most newly manufactured motors.

The reason for the dependency on duration and motor age could not be determined from the test data in this report. It is expected, however, that the propellant may be degrading slightly, resulting in lower altitudes and shorter flight durations.

7.0 Conclusions Drawn

7.1 A designed experiment was successfully used to determine how to configure an Estes HiJax™ for any target duration in the precision duration events.

7.2 An equation describing the expected duration for any configuration was obtained.

7.3 For B6-4 powered flights, payload mass was the most influential variable on duration. For C6-5 powered flights, parachute size and payload mass had equal and opposite effects.

7.4 Parachute size and payload mass exhibited weak interaction effects and are nearly independent of one another.

7.5 A field chart describing the motor, parachute diameter, and payload mass for any duration between 30 and 120 seconds was constructed and tested with resulting errors of 10% and 12%.

7.6 Flight duration of the model varied with age of the motors in the study. Older motors gave shorter duration flights. The reason for this could not be determined from the data in this experiment, however, it is likely that the boost propellant grain degrades slightly with time. It is recommended that rocket motors of minimum age be used for competition purposes, since the propellant grain in those motors would show the least amount of degradation. For precision duration purposes, it is recommended that rocket motors of about one year old be used since beyond this age the boost grain appears to change very little and this will result in more consistent flight durations.

8.0 Future Work:

8.1 Several more confirmation runs will be flown to further confirm the model. One of the confirmation flights weathercocked slightly and may have increased the error in the results.

8.2 Further investigation of motor age vs. flight duration may be worthwhile.

9.0 Total Cost

Total cost for this project was as follows:

Estes HiJax™ model rockets	3 @ $12.99 each	$38.97
Model Rocket Motors	32 @ $1.50 each	$48.00
Stopwatch	1 @ $5.99	$5.99
Batteries for Launcher	1 pkg. @ $2.29	$2.29
3/8" Elastic Shock Cord	1 @ $0.79 each	$0.79
Kevlar shroud line	On-hand	gratis
Dry cleaner bags	On-hand	gratis
Launch system	On-hand	gratis
Launch supplies	On-hand	gratis
Presentation supplies	Various Items	$10
Sub total		$106.04
MD state tax	5% of subtotal	5.30
Grand Total		**$111.34**

Designed Experiment for Predicted Duration

Summary of All Data

Run	Motor	Parachute	Payload	Duration	Date	Time	Motor Code	Chute No.	Vehicle	Temp	Wind	Boost	Chute
1	A8-3	12	0	9.19	9/26/1998	09:45:00	2B12	2	2	65	0	OK	OK
2	A8-3	12	28	4.14	9/26/1998	09:45:00	2B12	1	1	65	0	OK	OK
3	C6-5	12	0	No data	9/26/1998	09:55:00	16C3	1	1	65	0		
3A	C6-5	12	0	65.44	9/26/1998	10:15:00	16C3	1	1	65	0	OK	OK
4	B6-4	18	14	21.34	9/26/1998	10:25:00	28B2	1	1	75	LV	OK	OK
5	C6-5	12	28	41.75	9/26/1998	10:40:00	16C3	2	2	75	LV	OK	OK
6	A8-3	24	0	12.78	9/26/1998	10:45:00	2B12	2	2	75	LV	OK	OK
7	C6-5	24	28	64.09	9/26/1998	10:55:00	26A2	2	2	75	LV	OK	OK
8	A8-3	24	28	6.88	9/26/1998	11:04:00	2B12	2	2	75	LV	OK	BAD
9	This run number was not used												
10	B6-4	24	28	31.03	10/3/1998	08:05:00	17C4	1	1	42	2 W	OK	OK
11	B6-4	12	0	19.5	10/3/1998	08:10:00	17C4	1	2	42	2 W	OK	BAD
11A	B6-4	12	0	26.78	10/3/1998	08:15:00	17C4	1	2	42	2 W	OK	OK
12	C6-5	24	0	137.16	10/3/1998	08:20:00	2B12	1	1	42	2 W	OK	OK
13	B6-4	12	28	14.15	10/3/1998	08:35:00	2B12	2	2	42	2 W	OK	OK
14	B6-4	24	0	42.72	10/3/1998	08:45:00	2B12	2	2	42	2 W	OK	OK
15	C6-5	12	28	38.19	10/3/1998	08:55:00	16C3	2	2	42	2 W	OK	OK
16	B6-4	24	28	25.19	10/17/1998	17:30:00	16C3	2	2	60	0	OK	OK
17	B6-4	24	0	67.45	10/17/1998	17:32:00	16C3	3	3	60	0	OK	OK
18	B6-4	12	0	26.31	10/17/1998	17:40:00	17C4	3	3	60	0	OK	OK
19	C6-5	12	0	56.43	10/17/1998	17:45:00	2B12	3	3	60	0	OK	OK
20	C6-5	24	28	72.34	10/17/1998	17:50:00	2B12	2	3	60	0	OK	OK
21	B6-4	12	28	15.5	10/17/1998	18:10:00	17C4	1	2	58	0	OK	OK
22	C6-5	24	0	110.09	10/17/1998	18:17:00	16C3	3	3	58	0	BAD	OK
23	C6-5	24	0	131.25	10/17/1998	18:25:00	2B12	3	3	58	0	OK	OK
24	B6-4	18	14	14.16	11/7/1998	10:02:00	16C3	1	2	54	5 W	SLW	BAD
25	B6-4	18	14	23.66	11/7/1998	10:12:00	16C3	1	2	53	5 W	OK	OK
26	C6-5	18	14	60.97	11/7/1998	10:20:00		1	3	52	10 W	OK	OK
27	C6-5	18	14	86.15	11/30/1998	10:20:00	16C3	2	3	58	0	OK	OK
28	C6-5	12	14	47.97	11/30/1998	10:30:00	17C4	3	2	59	0	OK	OK
29	C6-5	18	0	100	11/30/1998	10:40:00	17C4	2	3	60	0	OK	OK
30	B6-4	18	0	43.31	11/30/1998	11:03:00	17C4	2	3	61	0	OK	OK