Monte Carlo Analysis of Model Rocket Trajectories Using a Deterministic Baseline

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1. INTRODUCTION:

This project uses pedagogical[1] Monte Carlo methods in OpenRocket simulation software to analyze the safety of model rocket launches given a landing field of 152.4 m square.[2] OpenRocket requires the choice of a constant wind direction, so the field's space is optimized by choosing a direction of 45 degrees, i.e., from corner to corner. This gives the rocket the largest distance to travel prior to violating the field boundary, since the rocket is launched from the center of the field.[3] The field itself defines the north and east axes throughout the project, i.e., north is vertical and east is horizontal. This means that the northern and eastern distances in the simulation will be equivalent given the wind direction, so only one will be graphed throughout the project. If the northern or eastern distance exceeds 76.2 m at the time of landing, then the rocket has violated the field parameter. A safe launch is defined by the constraint of a maximum allowable probability of its landing taking place outside the specified field (violation probability). A probability analysis will be conducted on the resulting data from the Monte Carlo simulation to determine, within a specified confidence bound, whether the maximum violation probability is allowable. The objective of this project, then, is to determine a safe maximum value of average wind speed at normal turbulence for which the maximum violation probability is allowable. The project methodology used a deterministic wind sweep to ascertain a plausible baseline for Monte Carlo methods; these methods were then used to produce the repeated randomized trajectories necessary for probability analysis. The subsequent sections 2-7 will outline the specifications of the rocket, the deterministic and Monte Carlo processes used, the resulting data of both processes, and the safety evaluation of that data.

2. ROCKET CONFIGURATION:

The table below shows key specifications of the rocket and launch guide used throughout this project:

[1] Throughout the project, there are a number of significant simulation limitations that cannot be overlooked in actual practice. Such limitations make these simulations subject to a significant degree of real world uncertainty. However, the main goal of the project is to practice using and applying the methods in general for learning purposes. The limitations are mentioned throughout and could have easily been accounted for had OpenRocket's simulation been compatible, and, therefore, do not detract significantly from the learning value of the project.

[2] This value was chosen because it is the recommended minimum field size outlined in the rocket's instruction manual.

[3] Naturally these initial specifications are circumstantial limitations; they must be respected in reality if the simulations throughout the project are to have any substantial bearing on the practical safety of the actual rocket launch.

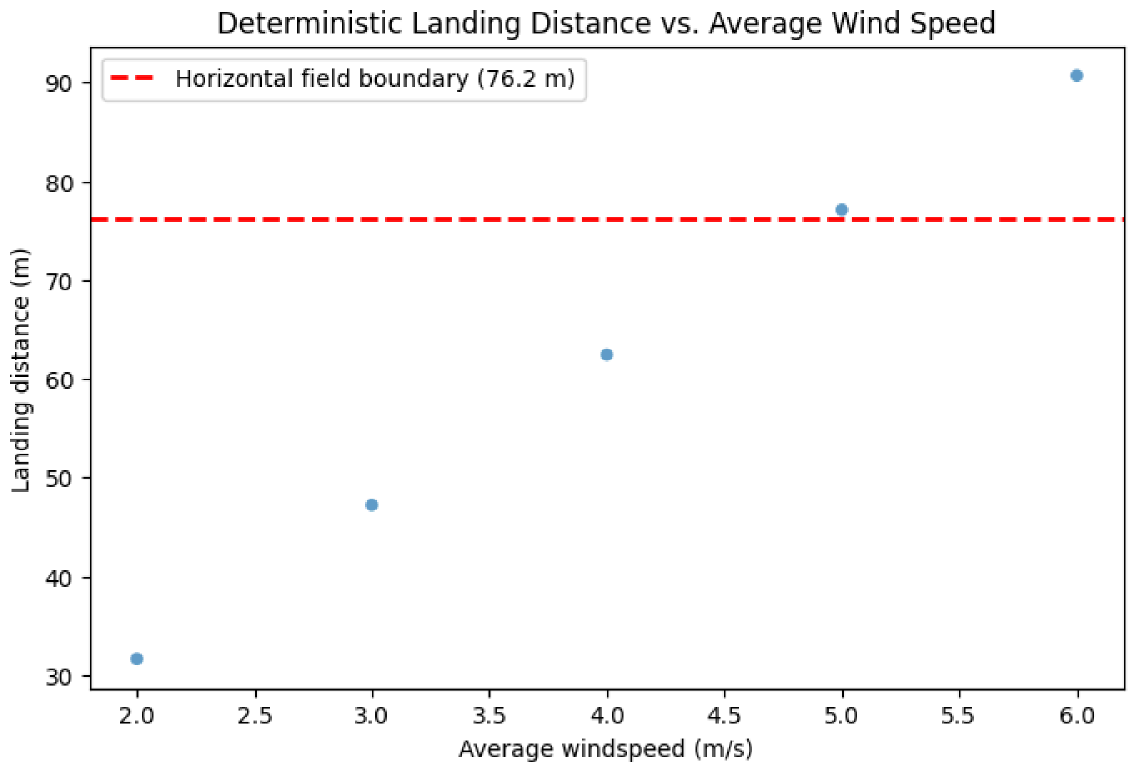
Manufacturer	Estes
Model	Big Bertha
Length	60.4 cm
Body tube outer diameter	4.16 cm
Mass with no motors	68.4 g
Mass with motors	91.5 g
Motor designation	C6-5
Static margin at liftoff	3.35 cal
Launch guide type	Rod
Launch guide length	100 cm
Recovery device type	Parachute
Parachute diameter	30.5 cm
Shock cord length	60 cm

3. DETERMINISTIC WIND SWEEP METHODOLOGY:

   There are a number of serious limitations of the OpenRocket software used in this experiment. A primary one is that any Monte Carlo analysis requires the results of each OpenRocket simulation to be individually and manually exported to a CSV file. This puts a limit on the number of runs that can be done realistically. It also means that it is not realistic to run Monte Carlo simulations for a range of average wind speeds, as this could mean thousands of manual runs and exports. Therefore, a single value for the average wind speed to be used in Monte Carlo had to be selected. This value needed to be reasonably close to the true maximum safe value, but selected with reasonable assurance that the chosen value would not exceed the true maximum value, in order to avoid costly reruns. To achieve that goal, this sweep determined the effect of different wind speeds with no turbulence. The results provided a range of baselines for potential selection in the Monte Carlo simulation (graph of results and selection process detailed in section 4). Wind speeds from 2 to 6 m/s, in increments of 1 m/s, were used for testing. These simulations were exported and then processed to graph the landing distances using Python.

4. DETERMINISTIC WIND SWEEP RESULTS:

The figure below shows the landing distance for each average wind speed from 2 to 6 m/s. The first three trajectories stay within the field boundaries; the highest viable wind speed value, i.e., 4 m/s was selected as the best option for stochastic analysis after testing further values between 4 and 5 m/s (not graphed to avoid clutter since the relationship is clearly linear).

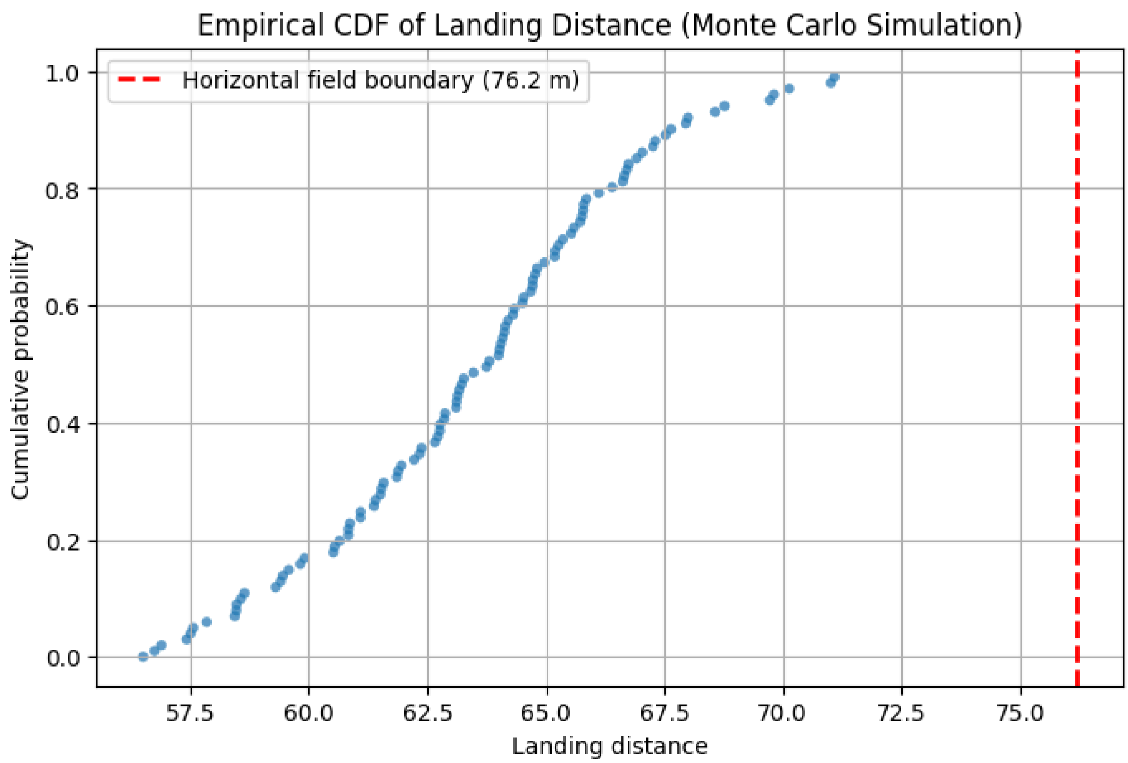


5. MONTE CARLO SIMULATION METHODOLOGY:

The Monte Carlo simulation was necessary to account for the real world fluctuations in wind speed given a typical turbulence intensity. One hundred-one runs were performed as a compromise between accuracy and the expense of manual simulations. The results of these runs were batch-processed using Python (NumPy, Pandas, Matplotlib) to automate the extraction of the horizontal landing distances from each simulation and aggregate them into the graph of an empirical cumulative distribution function (CDF). An average wind speed of 4 m/s was used throughout as the maximum safe estimate. Lower values did not need to be tested because 4 m/s represented the highest risk wind speed. This risk is highest because of the monotonic increase of horizontal drift from the deterministic sweep, where 4 m/s clearly results in drift that is closer to the boundary than the drift produced by lower wind speeds. As for turbulence intensity, there is a range of plausible values, so OpenRocket's automatic recommendation of 10 percent turbulence intensity was chosen. This Monte Carlo simulation was limited to the variability incorporated into OpenRocket's software. This variability includes wind speed only. Therefore, other common variables, such as rocket mass, fin shape, drag coefficient, launch angle, etc. were unable to be taken into account or factored into the final safety calculations.

6. MONTE CARLO SIMULATION RESULTS:

The figure below shows the empirical cumulative distribution function of landing distances for the Monte Carlo simulation. All simulation trajectories landed within the field boundaries. The maximum landing distance was 71.088 m.



7. SAFETY EVALUATION:

The goal of this evaluation is to estimate the launches' true probability of a landing violation, given the information collected from the Monte Carlo simulation. The empirical estimate of the probability is the number of landing violations, k, divided by the number of runs, N, i.e., k/N. In this case, that probability is equivalent to zero, since there were no violations. However, this is not the true violation probability, since only 101 runs were simulated where an extremely large number of runs is required to ascertain a sufficiently accurate estimate. Therefore, it is necessary to use a confidence bound to obtain an estimate of the true probability using a different method, namely, the rule of three. This rule sets such a bound by determining what value of the violation probability would make it unreasonably rare to observe zero violations, and then rules out all probabilities above that one. In this case, the typical 95 percent confidence bound is used, which corresponds to a rule where the upper bound of the violation probability (p) is given by $p = 3/N$. In this case $3/N = 3/101$, implying that $p \lesssim 0.03$ with 95 percent confidence. With this confidence, approximately 3 percent is low enough for a maximum probability under the circumstances, since the rocket is quite weak and will not be launched near buildings, cars, or any other valuable material subject to potential damages.[4]

8. CONCLUSIONS:

According to this simulation, the Estes *Big Bertha* is safe to launch at a maximum wind speed of 4 m/s near 10 percent turbulence intensity, given a central launch from a 152.4 m square field with a corner-to-corner crosswind. “Safe”, in this case, corresponds to an individual launch’s violation probability being less than approximately 3 percent with 95 percent confidence, according to the rule of three. The main limitation of this simulation is OpenRocket’s inability to account for realistic variance in many variables additional to wind speed. These include categories such as wind direction, rocket specifications, and turbulence intensity. However, the goal of this project is a pedagogical Monte Carlo application, and since only one variable is required to understand the core concept, these additional realistic variables detract only from the realism of the simulation, rather than damage understanding of the process. But in order to account for the absence of these variables practically, the rocket will be launched in a larger field under little to no wind to ensure that unexpected variance does not result in an unsafe launch. In short, this project demonstrates a structured methodology for analyzing launch safety under uncertainty by combining deterministic tests, Monte Carlo techniques, and the rule of three to arrive at a sufficiently confident allowable maximum violation probability.

[4] The acceptability of this probability bound is slightly arbitrary given the circumstances. There are no official regulations to be observed as in many real-world projects. However, this bound seems reasonable given that the rocket will be launched only several times and is capable of very little to no harm.