PHYSICS
INTERNAL ASSESMENT
MAY 2025

"Investigating the effect of change in mass of the toy aircraft on the distance required for it to take-off."

Word Count- 2854

INTRODUCTION-

Since my childhood, I have always been fascinated by aircrafts and airports. The lengths of airport runways always intrigued me since they would stretch up to 2-3 kilometers and are used just for a single take-off at a time.

I also was intrigued by the difference between distances a general commercial plane required to take-off and a fighter aircraft. To help me understand this better, I decided to further study the factors affecting the take-off distance of an aircraft (mainly mass) fueled by my interest in Aerospace engineering and Physics. As a result, I chose to analyze how the change in mass of a toy aircraft affects its takeoff distance.

For the experiment I will be utilizing a scaled down 3D-Remote Controlled model of the Sukhoi Su-30. Sukhoi Su-30 is a twin turbo engine aircraft developed in the Soviet Union in Russia's Sukhoi Aviation Corporation.[1] As a child I drew interest in this aircraft as it was one of the very few Mach 1.7 fighter aircrafts in the Indian Air Force Fleet.

Since commercial aircraft are not readily available for experimentation, I decided to use a motorized toy aircraft that mimics the larger aircraft.

RESEARCH QUESTION-

"How does the change in mass (g) of the toy aircraft affect its take-off distance (m) keeping the thrust (N) of the aircraft constant?"

To specifically find out the effect of change in mass and focus on the research question, other factors that affect take-off distance need to be kept constant.

[1] "Sukhoi Su-30." *Wikipedia*, 7 Mar. 2024, en.wikipedia.org/wiki/Sukhoi_Su-30. Accessed 2 Jan. 2025.

BACKGROUND INFORMATION-

There are four types of forces that always act on an aircraft in motion.

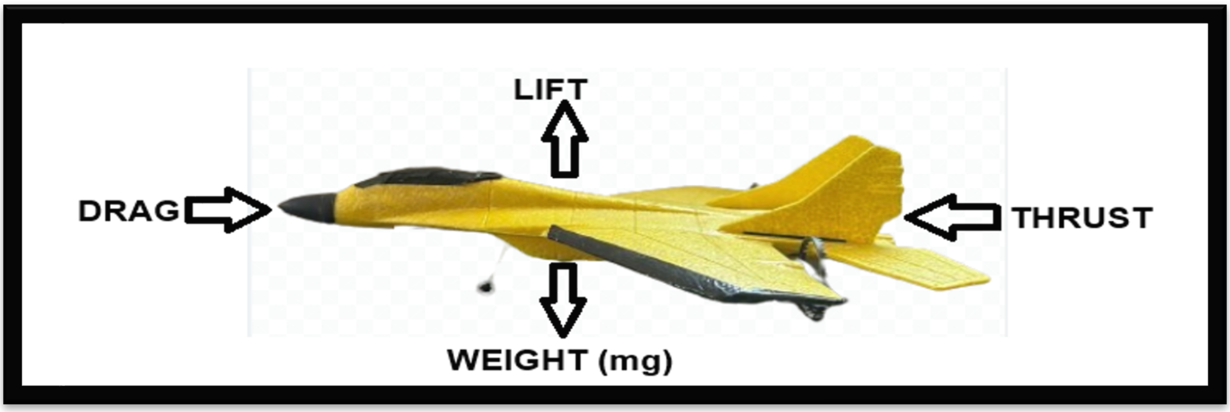

Image 1- Forces acting on an aircraft[2]

The force that causes the aircraft to move forward is thrust.

The force that opposes thrust force is called drag. It usually occurs due to air resistance.

Lift is the force that is generated when any solid object is moving through a fluid (in this case air).[3] This force helps the plane to gain altitude.

The force that opposes lift force is the weight. (mass × gravitational constant of earth)

When an aircraft is required to take off the thrust force should be more than the drag force and the lift force should be more than the weight.

$$\text{Lift} = 0.5 \times \rho \times V^2 \times S \times Cl$$

Formula to calculate lift [4]

ρ - Density of air

V - Velocity at which the air particles collide with the wing.

S - Wingspan of the aircraft

Cl - Coefficient of lift

According to this equation, thrust is directly proportional to the lift and hence to reach sufficient take-off velocity, thrust is required to be applied for a certain time, which in turn varies the distance for takeoff.

So, when an aircraft accelerates from rest while taking off the thrust begins to increase. There is an instance where the aircraft reaches take-off speed due to the thrust being applied for a certain amount of time. At this instance the lift force of the aircraft is more than the weight of the plane, causing the aircraft to take off. This concept is the foundation of the lift/drag ratio that measures the efficiency of aircraft.

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[2] Made using paint software. Microsoft. *Paint*. Microsoft, 2023.

[3] "Lift_(Force)." *Www.chemeurope.com*, www.chemeurope.com/en/encyclopedia/Lift_%28force%29.html#:~:text=The%20lift%20force%2C%20lifting%20force. Accessed 3 Feb. 2024.

[4] Benson, Tom. "The Lift Equation." *Www.grc.nasa.gov*, NASA, http://www.grc.nasa.gov/www/k12/VirtualAero/BottleRocket/airplane/lifteq.html. Accessed 3 Feb. 2024.

HYPOTHESIS-

I hypothesize that by increasing the mass of the plane, the distance required to take off will also increase.

Since the mass of the aircraft is more, the lift force required to overcome the weight will also increase.

To increase the lift force required for take-off the engines will have to provide thrust for a longer period. This longer period will result in an increased distance required for the aircraft to take-off.

VARIABLES-

Independent Variable	Value	Reason
Additional mass added to aircraft	2g / 5g / 10g / 15g / 20g	To measure the effect of mass.

Dependant Variable		Reason
Distance required to take off. (m)	To be measured	The mass will affect the take-off distance of the plane aiding the study.

Controlled Variable	Reason to control	Method of control
Physical properties of the toy aircraft	The initial mass of the aircraft needs to be the same for all trials. Wingspan of the aircraft also needs to remain constant to maintain the lift.	Using the same aircraft for all trials.
Thrust (N)	The thrust provided by the motors of the plane needs to remain constant to make sure that each trial is only affected by the mass and not by any change in thrust.	Using the same motors and propellors for each trial.
Battery Voltage (V)	The voltage of the battery that provides electricity to the motors needs to remain constant to maintain the same value of thrust for each trial.	Using fresh battery for each mass trial.
Density of air (g/m^3)	The density of air needs to remain constant throughout the experiment to minimise the effect of density on the lift, drag and thrust.	By air conditioning the room of experimentation to a certain temperature.

METHODOLOGY-

Experimental Setup-

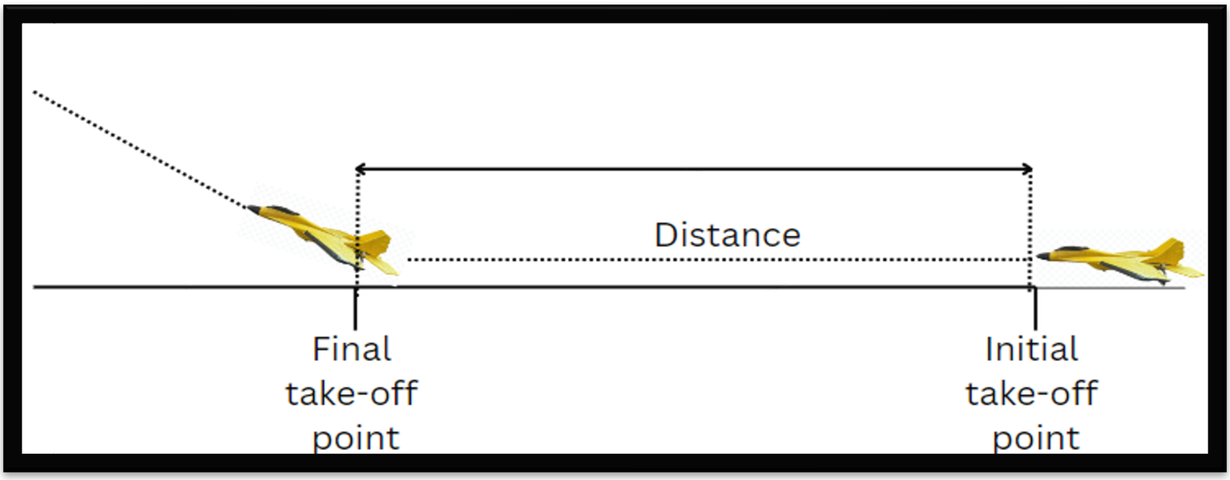

Image 2- Experimental Setup[5]

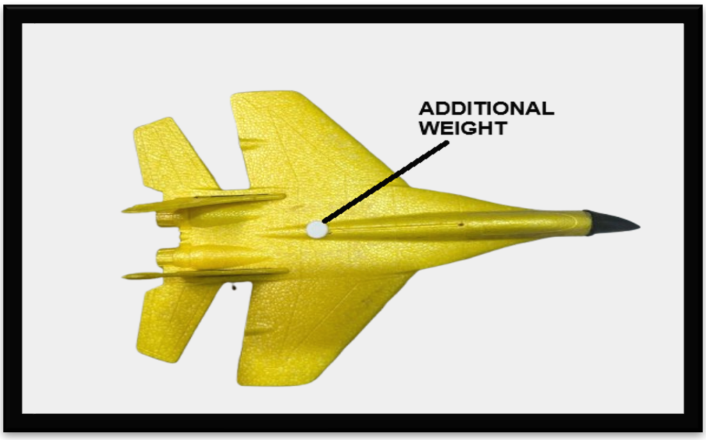

Image 3- Placement of additional mass using sticky adhesive.

MATERIALS-

1) Toy aircraft
2) Mass of 2g, 5g, 10g, 15g, 20g
3) Battery
4) Camera (for recording videos used for tracker software)
5) Markers (to mark initial and final points)
6) Sticky Adhesive

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[5] Made using paint software. Microsoft. *Paint*. Microsoft, 2023.

APPARATUS-

1) Multimeter
2) Tracker Software [6]

RESEARCH DESIGN-

Firstly, check the voltage of the battery that goes in the aircraft using a voltmeter and make sure it remains constant for all trials.

Then, connect the battery and place the aircraft at the marked initial takeoff point. (Align front wheel with point)

Place the mass (2g, 5g ,10g ,15g, 20g) on the aircraft at a defined point right in between the tail of the aircraft and fix it using the sticky adhesive (weight of sticky-adhesive is considered in uncertainties of the weights).

Launch the aircraft. (record the take-off for tracker software using video camera)

Mark the point at which both rear wheels of the aircraft leave the surface of the earth as final take-off point using the video.

Measure the distance between initial and final take-off point.

Repeat step 1-5 in order to get 5 trials data values

Change the mass of the aircraft (2g, 5g ,10g ,15g , 20g) and repeat the procedure to obtain 5 trial data for each mass.

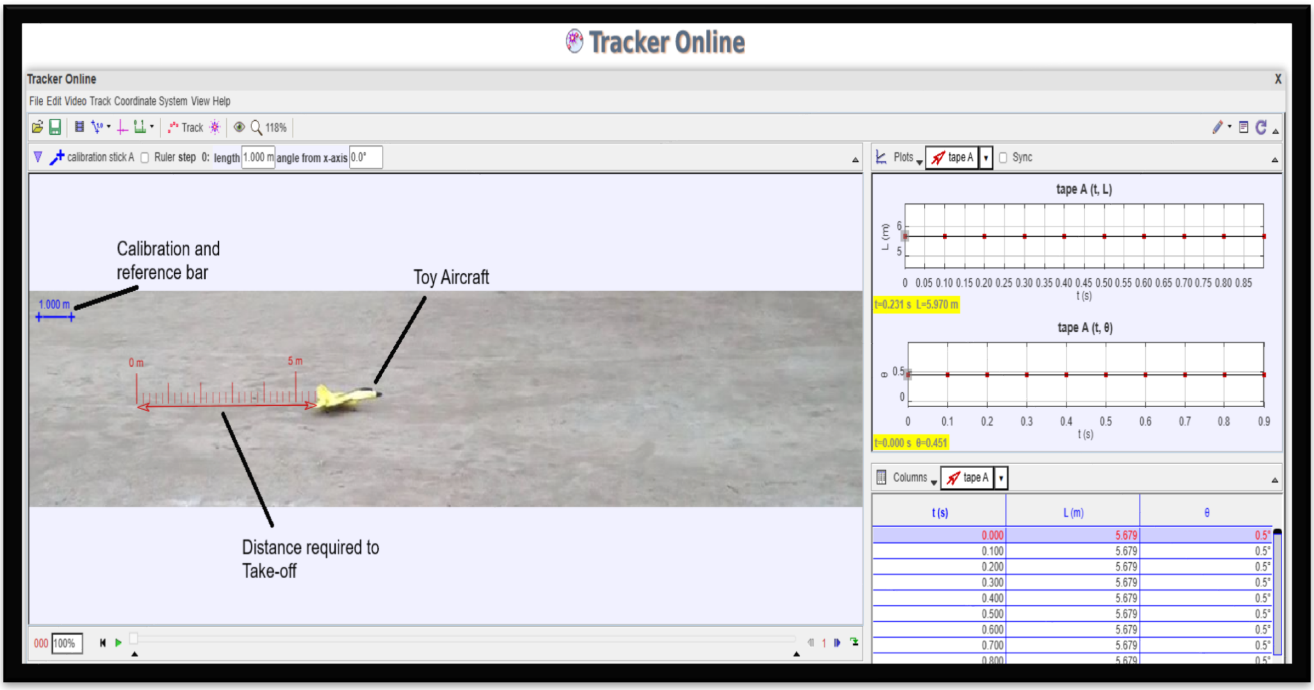


Image 4- Calculation done on Tracker Software

[6] Brown, Douglas. "Tracker Video Analysis and modelling Tool Online." *Physlets.org*, physlets.org/tracker/trackerJS/. Accessed 3 Feb 2024.

SAFETY, ETHICS AND ENVIRONMENT-

Aircrafts can cause physical injury, so flying in open spaces, where animals and people are not present is a safety precaution. Spaces near power lines should be avoided.

Batteries are fire hazards so each battery should be inspected before using.

Disturbing birds and nests will result in ethical violation.

Use sustainable materials for materials such as bamboo pulp thermocol for the aircraft.

DATA COLLECTION-

-Quantitative Raw Data

Table 1-Raw data of experiment conducted for different additional masses attached to aircraft

Additional mass attached to aircraft (g) (±0.01g)	Distance taken to Take-Off from the ground (m) ($\pm1\times10^{-5}$m)				
	TRIAL 1	TRIAL 2	TRIAL 3	TRIAL 4	TRIAL 5
0.00	4.1340	4.2310	4.1200	4.1100	4.5000
2.00	5.6790	5.4230	5.4430	5.8760	5.2330
5.00	6.7380	6.5290	6.8920	6.6620	6.7220
10.0	9.2380	9.5340	9.6730	9.2330	9.2550
15.0	12.345	12.369	12.443	12.565	12.223
20.0	15.664	15.974	15.354	15.321	15.634

-Quantitative Processed Data

Table 2- Processed data of experiment conducted for different additional masses attached to aircraft

Additional mass attached to aircraft (g) (±0.01g)	Average take-off distance with error (m) ($\pm1\times10^{-5}$m)	Error in take-off distance (m)
0.00	4.2190	± 0.1950
2.00	5.5308	± 0.3215
5.00	6.7086	± 0.1815
10.0	9.3866	± 0.2200
15.0	12.385	± 0.1710
20.0	15.589	± 0.3265

-Sample Calculation

Additional mass attached to aircraft (g) (±0.01g)	TRIAL 1	TRIAL 2	TRIAL 3	TRIAL 4	TRIAL 5
5g	6.7380	6.5290	6.8920	6.6620	6.7220

$$\text{Average Take off Distance} = \frac{\text{Trial 1}+\text{Trial 2}+\text{Trial 3}+\text{Trial 4}+\text{Trial 5}}{5}$$

$$= \frac{6.738+6.529+6.892+6.662+6.722}{5}$$

$$= 6.7086 \text{ meters}$$

$$\text{Error in take-off distance} = \frac{\max-\min}{2}$$

$$= \frac{6.892-6.529}{2}$$

$$= \frac{0.363}{2}$$

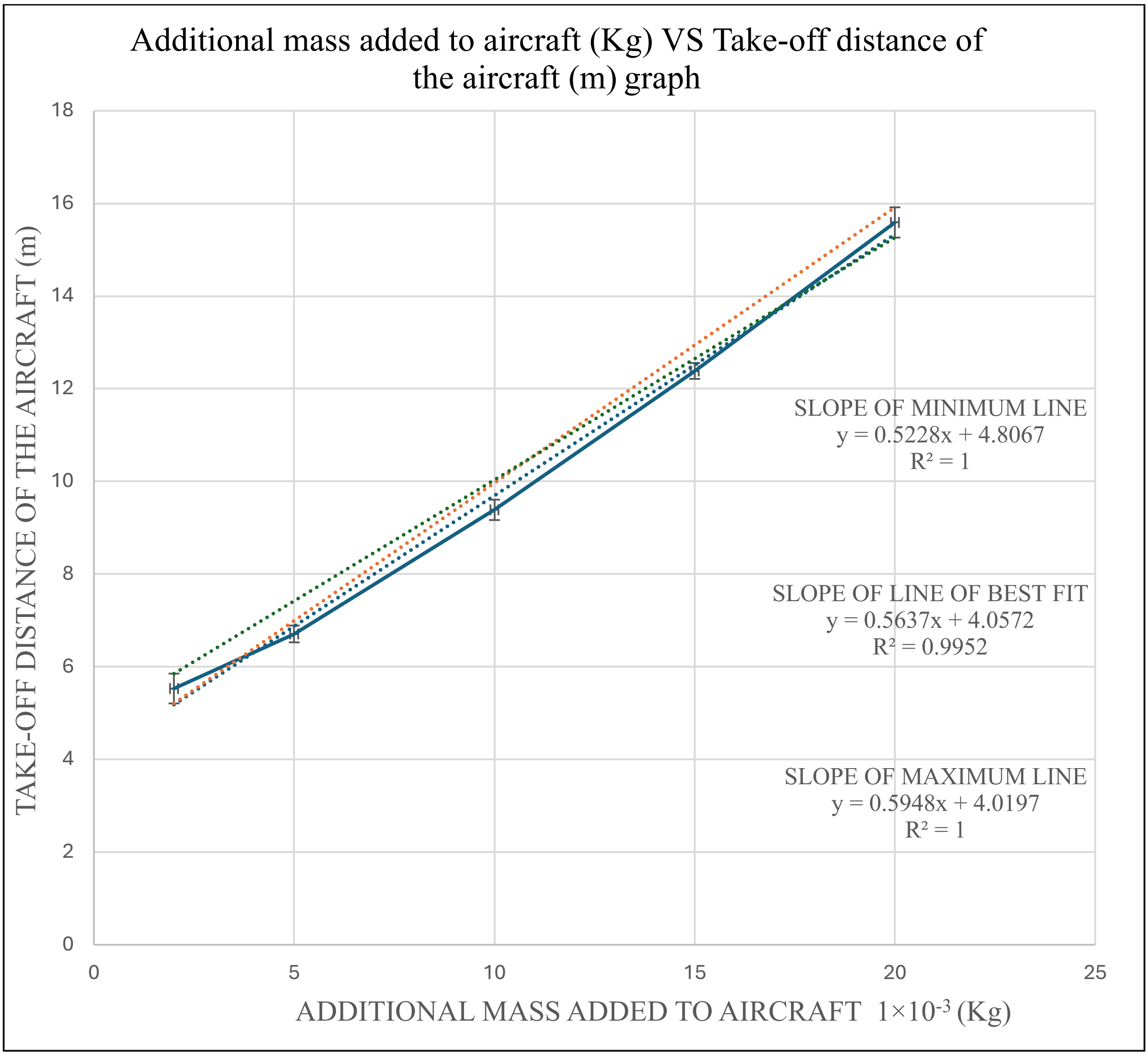
$$= 0.1815 \text{ meters}$$

-Quantitative Processed Data in SI units

Table 3- Processed data of average take-off distance for each additional mass attached to aircraft in SI units.

Additional mass attached to aircraft (Kg) ($\pm1\times10^{-5}$ Kg)	Average take-off distance (m) ($\pm1\times10^{-5}$m)	Error in take-off distance (m)
0	4.2190	± 0.1950
2×10^{-3}	5.5308	± 0.3215
5×10^{-3}	6.7086	± 0.1815
10×10^{-3}	9.3866	± 0.2200
15×10^{-3}	12.385	± 0.1710
20×10^{-3}	15.5894	± 0.3265

GRAPHICAL ANALYSIS-



Graph 1: Additional mass added to aircraft (Kg) VS Take-off distance of the aircraft (m)

Slope of Line of Best Fit (Blue)- $y = 0.5637x + 4.0572$ Coefficient of Determination (R^2) = 0.9952
Slope of Minimum Line (Orange)- $y = 0.5228x + 4.8067$ Coefficient of Determination (R^2) = 1
Slope of Maximum Line (Green)- $y = 0.5948x + 4.0197$ Coefficient of Determination (R^2) = 1

The y-intercepts of the equations above represent the distance required to take-off without any additional mass attached to the aircraft. As per the equation of the line of best fit the aircraft requires 4.0572 meters to take-off without any additional mass attached to the aircraft. This value aligns with the recorded data of 4.2190 meters with an error margin of 5.74% which supports the hypothesis.

As per the equation of the line of best fit, the slope of the line of best fit is 0.5637. This represents the change in take-off distance for each unit mass increase in the additional mass attached to the aircraft. For every increase in 1 gram of mass of the aircraft, the take-off distance increases by approximately 0.5637 meters.

The equations of the minimum and maximum lines provide us with a value of error range for the predicted take-off distance. The slope of the minimum line, 0.5228, and the slope of the maximum line, 0.5948, represent the lower and upper bounds of the possible change in take-off distance for each increase in 1 gram of additional mass added to the aircraft.

EVALUATION-

The conducted experiment was designed with the intention to investigate how the take-off distance required by a toy aircraft is affected by additional mass added to it. The take-off distance was measured using the Tracker software. As supported by the Pearsons constant (0.9952) the data collected shows a strong positive correlation between the distance required to take-off and the additional mass added to the aircraft. For example, when the mass of 2×10^{-3} kg was added to the aircraft, the average distance required to take-off increased to 5.5308 ± 0.3215 m. Similarly, for the additional mass of 20×10^{-3} kg, the average take-off distance increased to 15.5894 ± 0.3265 m. This trend in increase of the take-off distance aligns with the hypothesis which was that by increasing the mass of the plane, the distance required to take off will also increase. Since the mass of the aircraft is more, the lift force required to overcome the weight will also increase. To increase the lift force required for take-off the engines will have to provide thrust for a longer period. This longer period will result in an increased distance required for the aircraft to take-off.

Despite the clear trend, this experiment was subjected to several sources of error and uncertainty. Random errors were evident from the standard deviations of the data. For instance, the first trial had a standard deviation of 0.2495, while the second trial's deviation decreased to 0.1314, indicating greater variability in the former. These deviations suggest that while the measurements were precise, some variability occurred across trials.

The uncertainty values for each measurement indicate variability in reliability. The largest uncertainty was recorded for the 2×10^{-3} Kg mass (± 0.3215 m), while the uncertainty for the 15×10^{-3} kg mass was smaller (± 0.1710 m). These differences could reflect improvements in measurement consistency for higher masses, possibly due to the reduced influence of small external factors such as air resistance or friction. However, this variability highlights the need for further refinements in the methodology.

Table 4- Random Errors		
Source of error	**Impact on results**	**Improvement**
Drag Coefficient	During experimentation it was assumed that the drag coefficient was constant for all trials. A constant drag coefficient is not possible due to slight orientation changes while placing aircraft at initial point. This leads to a change in the drag coefficient as the aircraft accelerates which may lead to a variation in the data collected for take-off distance.	Maintain a consistent orientation relative to the direction of motion (e.g., no pitching, yawing, or rolling during take-off).
Uncertainty of Equipment used	The Tracker software, while effective for measuring take-off distances, relied on manual marking of reference points, which introduces human error and subjectivity. Additionally, the resolution of the video recording equipment may have limited the software's ability to precisely detect small variations in distance. The mass values, measured with an uncertainty of $\pm 1\times10^{-5}$ kg, were sufficiently precise, but slight deviations in placement or alignment of the additional mass on the aircraft could have affected its centre of gravity, indirectly influencing the results.	Utilising a higher resolution and frame rate camera will enhance the precision of the video taken. This would allow more accurate calculations and detections done by the Tracker Software.
Environmental Factors	Environmental variables, such as friction on the runway surface or minor air resistance, may not have been completely controlled, potentially affecting the results.	Conduct the experiment indoors or in an environment with minimal air turbulence to avoid variations in airflow utilising a runway with constant friction force which does not vary across the runway.
Human Involvement	While Tracker software was used for distance measurement, human involvement in marking specific points during the analysis introduces an element of subjectivity and potential error.	The number of trials conducted could be increased to reduce the influence of random errors and improve the reliability of the averages.

Potential systemic errors also may have affected the results of the experiment. The following could be some of the systemic errors that could be accounted for.

Table 5- Systemic Errors		
Source of error	**Impact on results**	**Improvement**
Tracker Software	Tracker software requires calibration and a reference measurement to provide data for all further calculations. If these have slight errors in them all the experiments data collection gets affected.	Calibrating and referencing the measurements with accuracy.
Sample Size taken for experimentation	Only five trials of five different mass were conducted which decreases the generalisability of the claim. Small sample size is subject to consideration of more errors.	Conducting more trials using more masses.

Regardless of the limitations, the investigation had strengths. With the use of the Tracker Software, human interaction with measurement was minimised, minimizing human reaction time error with regards to manual methods. As observed, the data trend strongly supports the hypothesis, which shows that the methodology was conducted correctly in recording the relationship between the additional mass added to the aircraft and take-off distance.

Theoretical predictions based on the Newton's second law of motion and the equations of motion can be compared to the data trend recorded. The greater the mass, a greater force is required to overcome the inertia and to reach sufficient take-off velocity. This results in longer take-off distances. These experiments findings align with Newton's theoretical explanation even though small margins of error can arise due to various random and systemic errors such as environmental factors.

The error analysis calculations further bring forward the reliability of data. The error percentage were extremely low for a smaller data sample. For example, the percentage uncertainty for the first trial data point 5.5308± 0.3215 m was 5.81%. Likewise, error analysis calculations for other data trials reveal that uncertainty changes with the change in additional mass added too and displays the reliability of data.

The experiment successfully demonstrated the effect of additional mass on the take-off distance of an aircraft, showing a clear positive correlation consistent with theoretical expectations. While random and systematic errors influenced the precision and accuracy of the measurements, the strengths of the methodology such as the use of Tracker software and consistent trends increase credibility of the findings.

CONCLUSION-

To conclude, the result from the investigation portrays a clear relationship between the take-off distance and the additional mass attached to the aircraft. As the additional mass attached to the aircraft increases the distance required to take-off increased. The data supports the trend where the take-off distance for a 2-gram additional mass was significantly shorter than a 20-gram additional mass attached.

The increase in take-off distance with additional mass can be attributed to the increased inertia of the aircraft. As the mass increases, the aircraft's resistance to changes in its motion also increases. This increased inertia requires a greater force to accelerate the aircraft to take-off speed, resulting in a longer take-off distance.

The graph shows a linear relationship between the additional mass added to the aircraft and the take-off distance. The equations of the lines of best fit, minimum line, and maximum line confirm this linear trend. The R^2 values for all three lines are remarkably close to 1, indicating a strong correlation between the two variables.

Overall, the findings of this investigation support the hypothesis that an increase in mass leads to an increase in the take-off distance for a toy aircraft.

EXTENSION-

For further investigation, the experiment could be extended to explore additional factors affecting the take-off distance of the aircraft. For instance, the relationship between take-off distance and wing shape (aerodynamic profile) could be analysed by testing different wing designs while keeping the mass constant. Similarly, investigate the effect of thrust variations, such as using different propulsion mechanisms or power levels, on take-off distance.

Another investigation would be to study the impact of surface texture or runway material on the take-off distance by testing on various surfaces, such as smooth, rough, or inclined planes, to simulate real-world conditions. Investigating the role of environmental factors, such as air density (by altering temperature or altitude), could provide insights into how external conditions influence the aircraft's performance.

Additionally, testing the same setup with a scaled-down model in a wind tunnel would allow for a more controlled environment to study drag, lift, and other aerodynamic forces in detail. Finally, comparing experimental results to computational simulations using fluid dynamics software could validate the findings and identify discrepancies, providing a deeper understanding of the physical principles involved.

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Tracker Software- Used to measure the take-off distance.