OrbitalPredict – Analyzing and Forecasting SpaceX Landing Success

Bindu Priya Gundu

Contents

Executive Summary

- This project followed a structured methodology starting with **data collection via APIs and web scraping**, followed by **data wrangling** to clean and prepare the data. **Exploratory Data Analysis** was conducted using both **SQL** and **visualization techniques**, enhanced by **interactive mapping with Folium**. An **interactive dashboard** was built using **Plotly Dash**, and the workflow concluded with **machine learning predictions** to derive actionable insights.
- The analysis revealed several key insights: **success rates improved over time**, indicating advancements in technology and operations. Among launch sites, **KSC LC-39A had the highest success rate**, while orbits such as **ES-L1, SSO, HEO, and GEO** showed consistently high success. **Heavier payloads initially experienced higher failure rates**, but performance improved significantly in later missions. Finally, **predictive analysis using the DecisionTreeClassifier demonstrated high accuracy** in forecasting landing outcomes, validating its effectiveness for future predictions.

Introduction

- This project aims to predict the successful landing of SpaceX's Falcon 9 first stage, a key factor in launch cost-efficiency. SpaceX offers launches at $62 million due to its reusable first stage, compared to $165 million charged by competitors. By accurately forecasting landings, IBM Developer Skills Network can make competitive bids. The project follows a structured pipeline—starting with data collection through APIs and web scraping, followed by wrangling, exploratory analysis using SQL and visualizations, and interactive mapping with Folium. A dashboard was developed using Plotly Dash, and machine learning models, particularly DecisionTreeClassifier, were used for prediction. Insights show improved success rates over time, with KSC LC-39A and orbits like ES-L1 and GEO achieving high success. Heavier payloads initially had higher failure rates but improved over time. Solving this problem allows companies to estimate launch costs more accurately and compete effectively. Key questions explored include success rate trends, influential factors, and model accuracy.

Methodology

Executive Summary

Data collection methodology

- Retrieval and consolidation from multiple SpaceX API endpoints
- Web scaping tabular data from Wikipedia

Perform data wrangling

- Extracted relevant records
- Flattened fields and resolved missing values

Perform exploratory data analysis (EDA) using visualization and SQL

- Visualize variable relationships
- Look at the data in aggregate

Perform interactive visual analytics using Folium and Plotly Dash

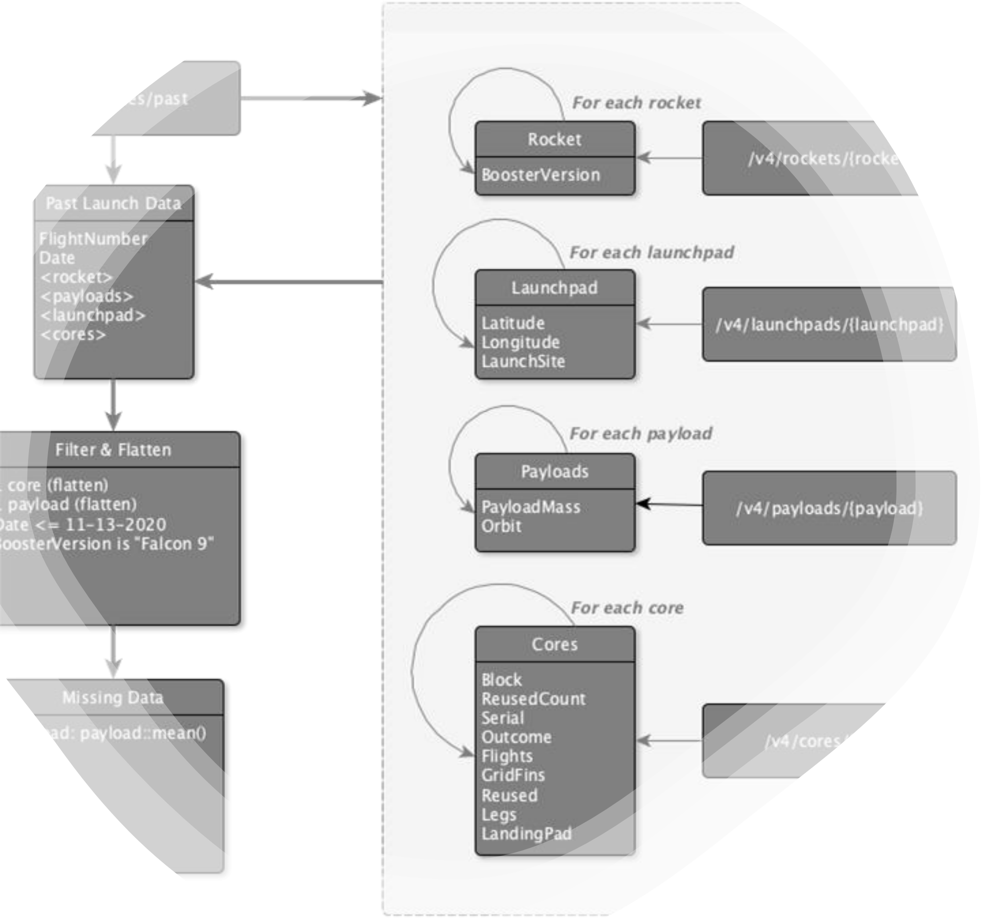
- Mark all launch sites on a map
- Mark successful and failed launches
- Calculate distances to proximate locations
- Provide for interactive exploration of the data

Perform predictive analysis using classification models

- Build, evaluate, and compare several predictive classification models

Data Collection

- Data was collected using a combination of retrieval techniques:
  - HTTP requests against various SpaceX API endpoints:
    - Initial launch data was obtained from: **/v4/launches/past**
    - Additional data was backfilled from:
      - **/v4/rockets**
      - **/v4/launchpads**
      - **/v4/payloads**
      - **/v4/cores**
  - Tabular data from the List of Falcon 9 and Falcon Heavy launches Wikipedia page.

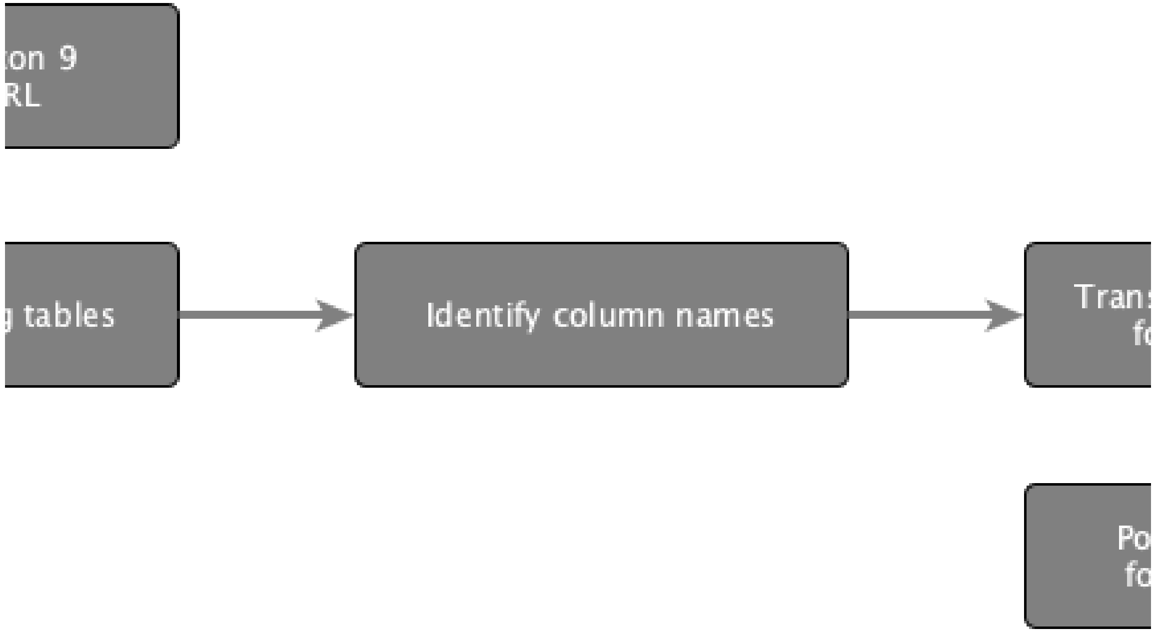


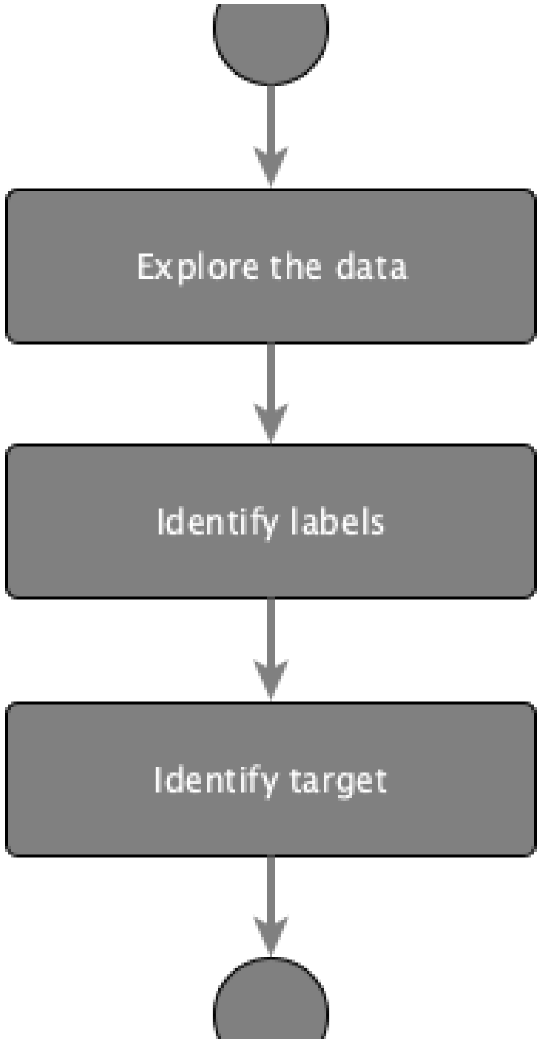
Data Collection – SpaceX API

- The initial data was obtained from the \`/v4/launches/past\` API endpoint.
- Additional data was backfilled from the \`rocket\`, \`launchpad\`, \`payloads\`, and \`cores\` API endpoints, for records with extant corresponding IDs.

Data Collection - Scraping

- Web scraping workflow:
  - Send HTTP Get to Falcon 9 Launch page at Wikipedia, to retrieve the HTML source
  - Create a BeautifulSoup object to extract the tables containing launch data
  - Populate a Pandas DataFrame using the extracted columns





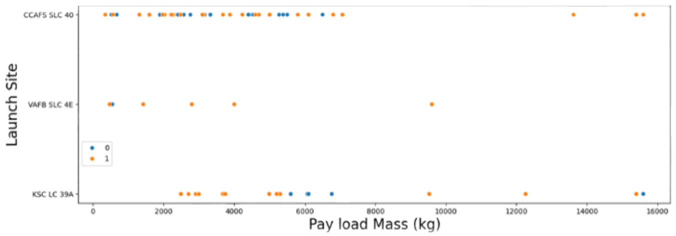
Data Wrangling

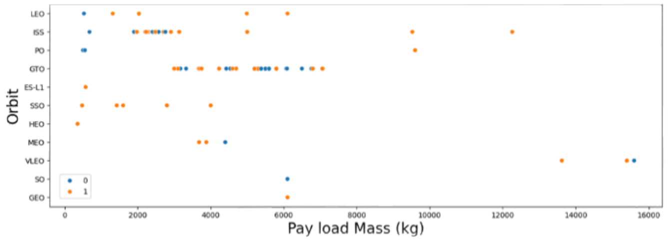
- Goals:
  - Use Exploratory Data Analysis (EDA) to find patterns in the data.
  - Determine the labels for training supervised models.
- Steps:
  - Find missing values as a percentage of each attribute
  - Identify column types, numerical or categorical
  - Show launches per Launch Site
  - Show distribution of Orbit type in the data set
  - Explore outcomes, and group them by binary outcome (success or failure)
  - Store outcome as "Class" label, to be used as target value in training

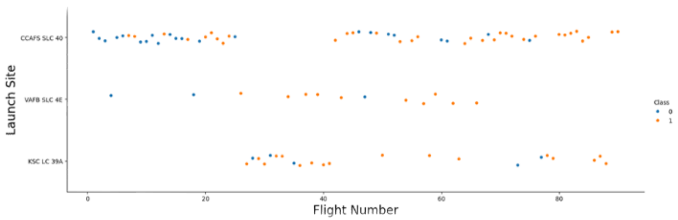
EDA with Data Visualization

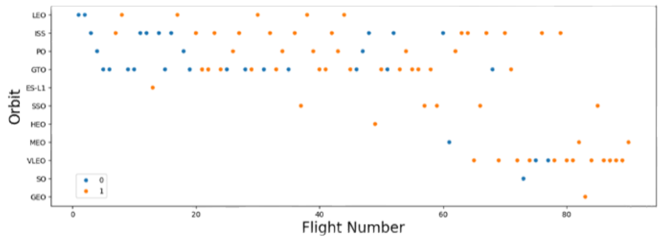
- Visualize relationships to gain insight into the importance of each variable:
  - Flight Number and Outcome
  - Flight Number and Launch Site
  - Payload and Launch Site
  - Orbit and Outcome
  - Flight Number and Orbit
  - Payload and Orbit
  - Yearly success rate
- Expand categorical variables into "dummy" columns
- Convert numerical columns into float64

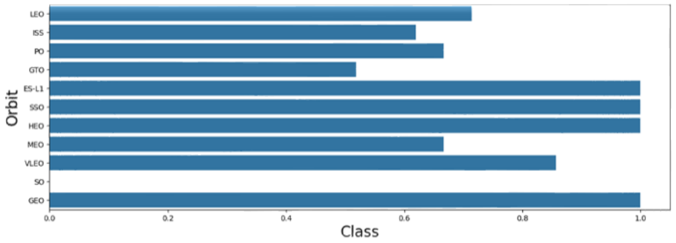
- Notebook (GitHub URL)

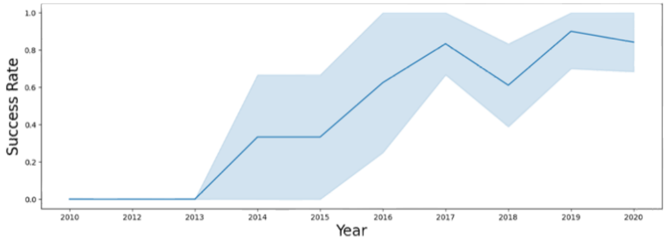








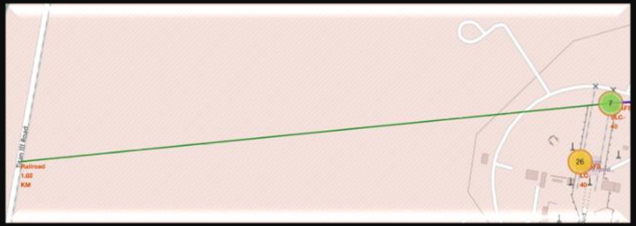




EDA with SQL

- SQL Queries Performed:
  - Show each unique launch site
  - Show 5 records where launch site names begin with 'CCA'
  - Display the total payload mass carried by boosters launched by 'NASA (CRS)'
  - Display the average payload mass carried by the v1.1 Falcon 9 booster
  - List the date of the first successful ground landing outcome
  - List the booster versions with successful outcomes landing on the drone ship with payloads between 4000kg and 6000kg.
  - List the number of successful and failed mission outcomes
  - List all of the booster versions that carried the max payload mass
  - List the month name, outcome, booster version, and launch site for missions with failure outcomes landing on a drone ship in 2015.
  - Show the distribution of outcomes between June 4th, 2010 and March 20th, 2017
- Notebook (GitHub URL)

Build an Interactive Map with Folium

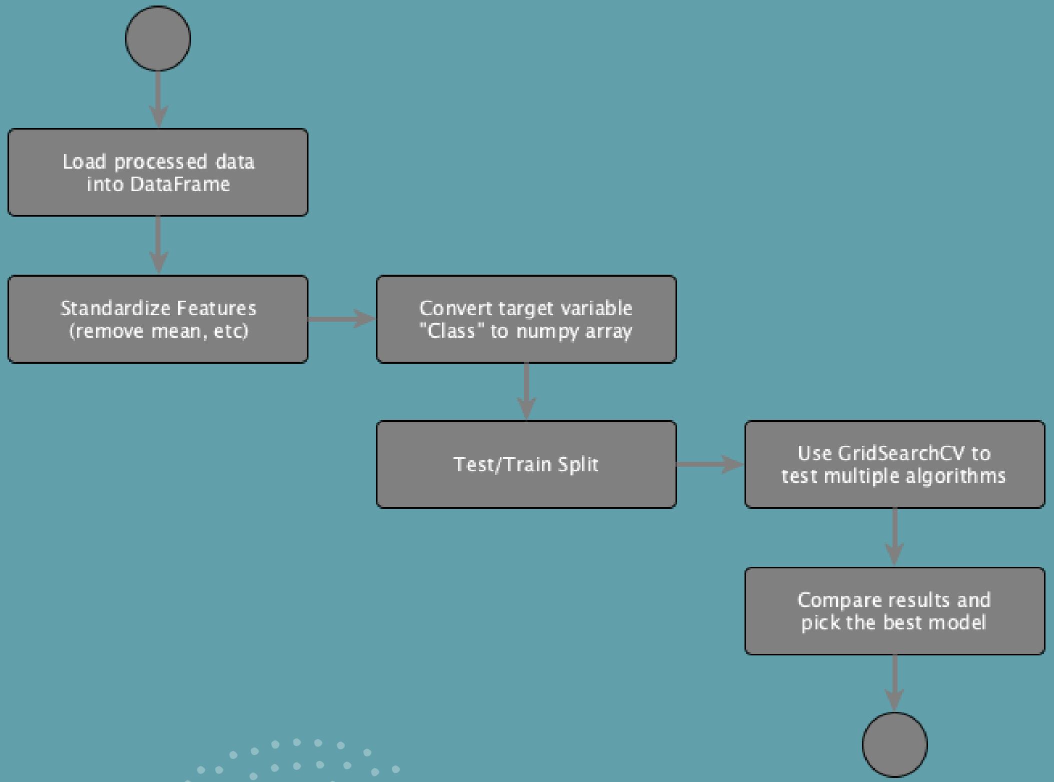


- To find geographical patterns in the data the following items were marked on a map of launch sites:
  - All Launch Sites
  - Successful and Failed Launches
  - Distances between a launch site and proximate landmarks

Build a Dashboard with Plotly Dash

- To enable interactive exploration of the data, a Plotly Dash dashboard was developed to include:
  - A dropdown selector to choose a Launch Site, affecting:
    - A pie chart
      - All sites selected: shows the breakdown of successful outcomes across all sites
      - A launch site selected: shows the breakdown of successful vs failed launches for the given site
    - A scatter plot
      - All sites selected: shows outcome by payload mass and booster version for all sites
      - A launch site selected: shows outcome by payload mass and booster version for the given site
  - A Payload Mass range selector that filters data points on the scatter plot
- Plotly Dash App (GitHub URL)

Predictive Analysis (Classification)



- Load data
- Apply StandardizedScaler on X
- Convert Y to numpy array
- Split training and testing data
- Use GridSearchCV to test hyperparameters for multiple algorithms:
  - Logistic Regression
  - SVC
  - Decision Tree Classifier
  - K Neighbors Classifier
- Notebook (GitHub URL)

Results

1

Exploratory data analysis results

2

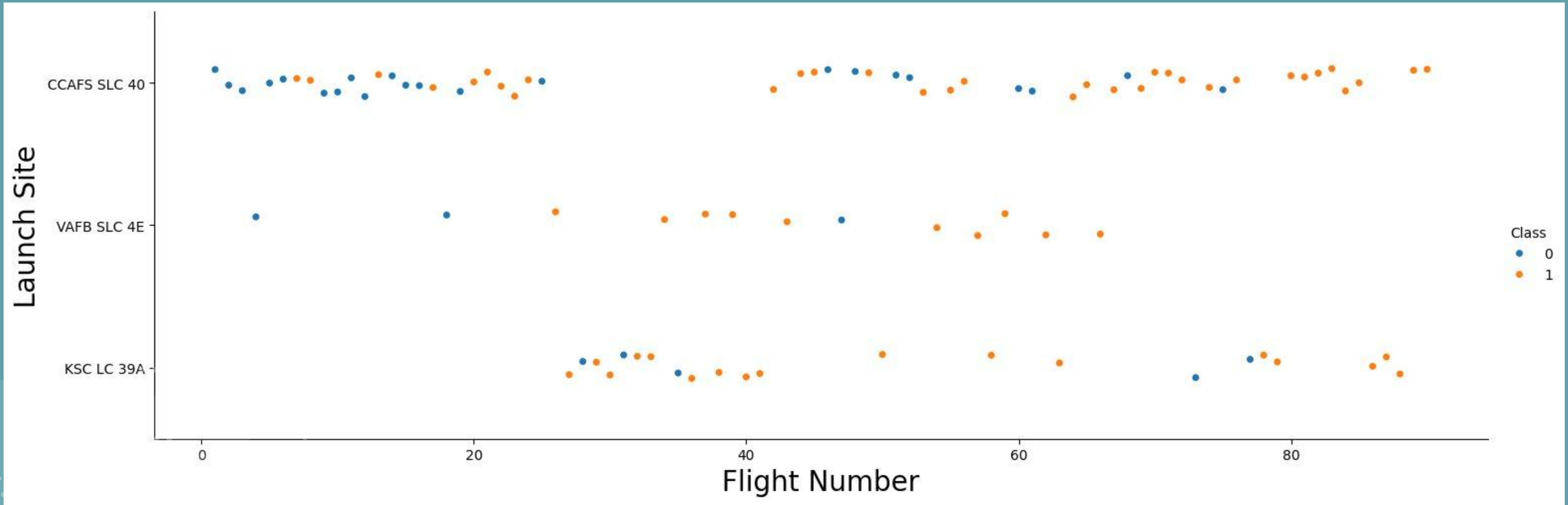
Interactive analytics demo in screenshots

3

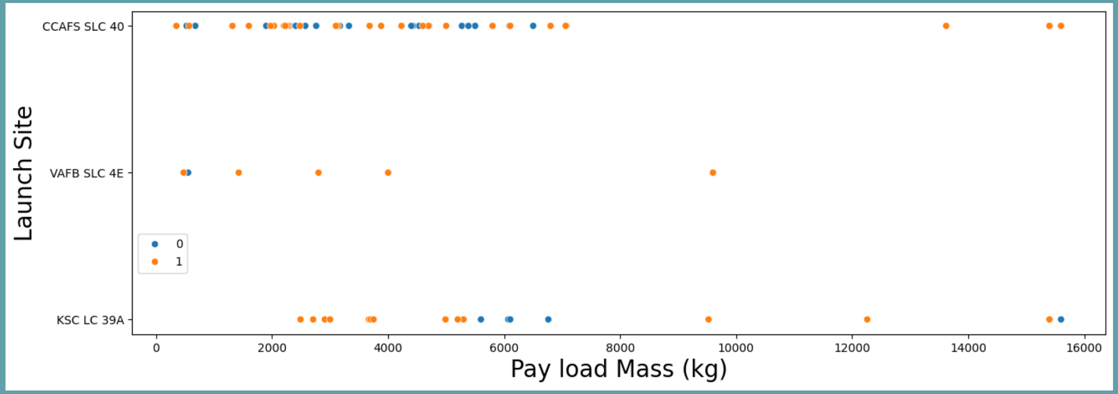
Predictive analysis results

Flight Number vs. Launch Site

- All sites show a mix of first stage landing successes and failures, with successes increasing over time.
- Early flights predominantly resulted in failures, indicating improvements to technology or process.
- While CCAFS SLC 40 has the most total flights, VAFB SLC 4E appears to have a relatively higher proportion of successful landing outcomes.

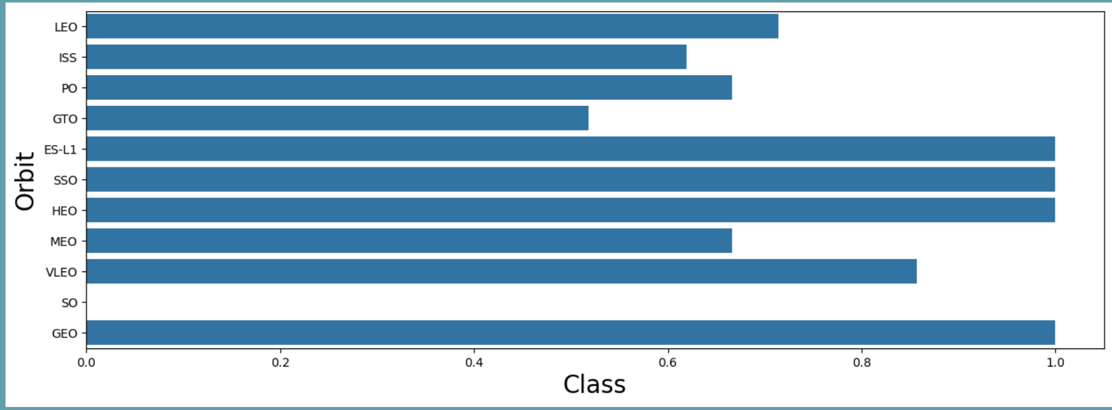


Payload vs. Launch Site



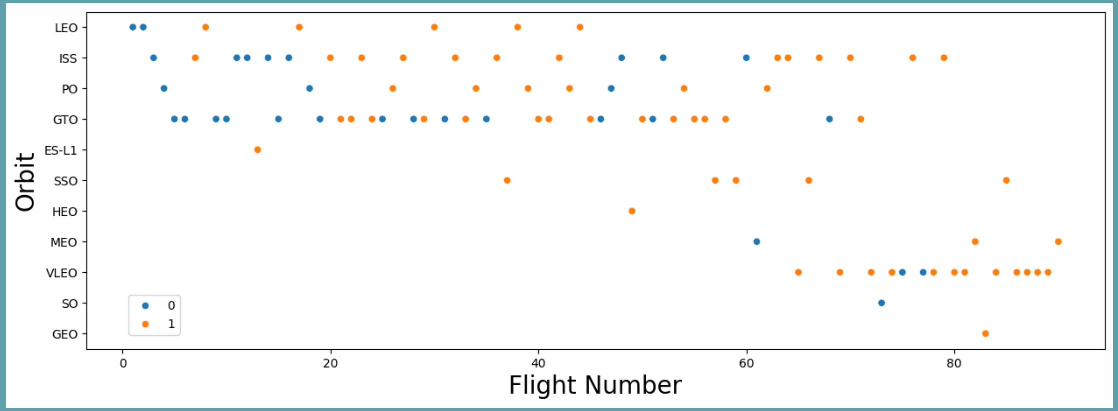
- All sites show a wide range of payload weights, from light to heavy payloads.
- Early flights trend toward lighter payloads, representing the bulk of the landing failures.
- This suggests technological or operational improvements lead to a greater rate of success with heavier payloads.

Success Rate vs. Orbit Type



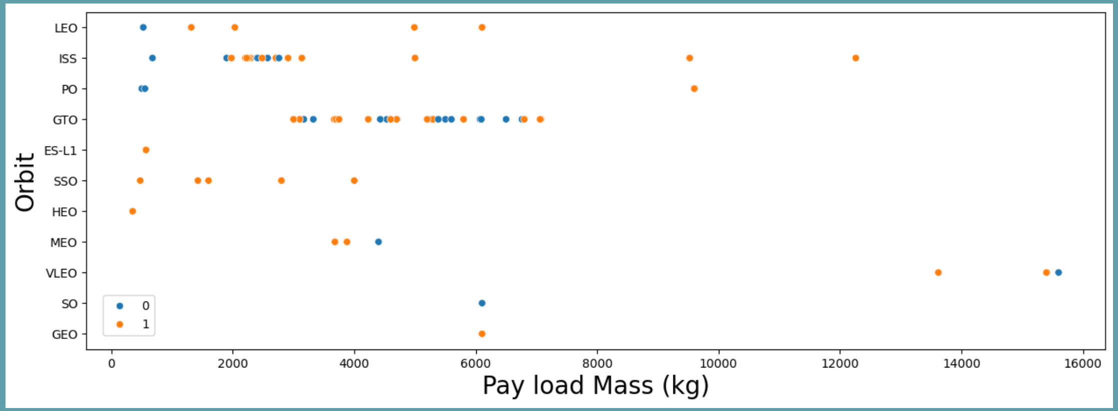
- Some orbits, such as ES-L1, SSO, HEO, and GEO consistently show high success rates.
- Others such as GTO show more mixed outcomes, suggesting some orbit types may introduce operational or technological challenges.
- With only one launch, there is not enough data for the SO orbit type to provide an accurate analysis.

Flight Number vs. Orbit Type



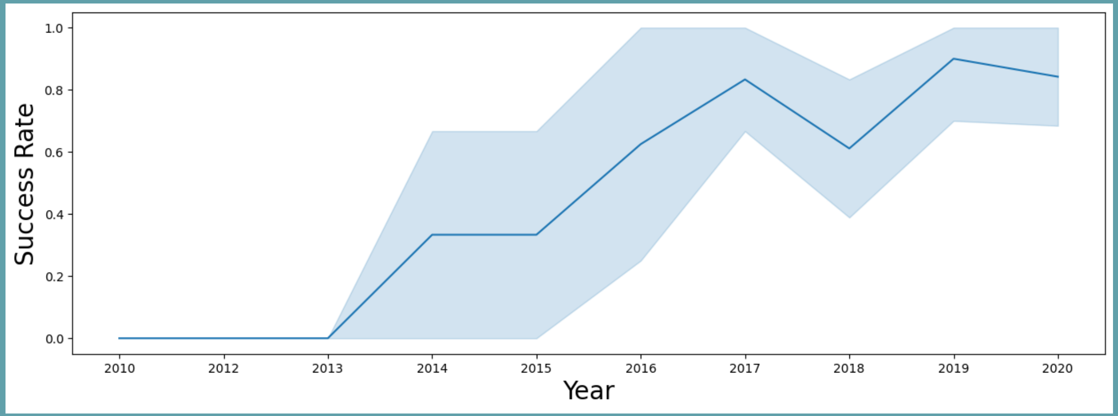
- Many orbits are represented throughout the flight number range, some orbits are not attempted until later flights.
- There is a noticeable improvement in landing success as flight numbers increase, indicating an accumulation of experience and ongoing improvements.

Payload vs. Orbit Type



- Many orbits are represented across a wide range of payload masses, but others like SSO, MEO, HEO and GEO show a generally lower range.
- Orbits with a constrained payload range, tend to show a higher rate of landing success.
- While payload mass does not appear to directly determine mission success, its interplay with orbit suggests a significant correlation.

Launch Success Yearly Trend



- Yearly trend shows a consistent progression from early challenges to high reliability in first stage landings over time.
- From 2016 onward, SpaceX experienced year over year improvement in success rate with a minor setback in 2018.

All Launch Site Names

- There are four unique Launch Sites
  - CCAFS LC-40
  - VAFB SLC-4E
  - KSC LC-39A
  - CCAFS SLC-40

- SELECT DISTINCT Launch_Site from SPACEXTABLE;

Launch Site Names Begin with 'CCA'

Date	Time (UTC)	Booster_Version	Launch_Site	Payload	PAYLOAD_MASS__KG_	Orbit	Customer	Mission_Outcome	Landing_Outcome
2010-06-04	18:45:00	F9 v1.0 B0003	CCAFS LC-40	Dragon Spacecraft Qualification Unit	0	LEO	SpaceX	Success	Failure (parachute)
2010-12-08	15:43:00	F9 v1.0 B0004	CCAFS LC-40	Dragon demo flight C1, two CubeSats, barrel of Brouere cheese	0	LEO (ISS)	NASA (COTS) NRO	Success	Failure (parachute)
2012-05-22	7:44:00	F9 v1.0 B0005	CCAFS LC-40	Dragon demo flight C2	525	LEO (ISS)	NASA (COTS)	Success	No attempt
2012-10-08	0:35:00	F9 v1.0 B0006	CCAFS LC-40	SpaceX CRS-1	500	LEO (ISS)	NASA (CRS)	Success	No attempt
2013-03-01	15:10:00	F9 v1.0 B0007	CCAFS LC-40	SpaceX CRS-2	677	LEO (ISS)	NASA (CRS)	Success	No attempt

- First five records where launch sites begin with `CCA`

- SELECT * FROM SPACEXTABLE WHERE Launch_Site LIKE 'CCA%' LIMIT 5;

Total Payload Mass

- The total payload carried by boosters from NASA (CRS) is **45,596kg**.

- SELECT SUM(PAYLOAD_MASS__KG_) AS TOTAL_PAYLOAD
- FROM SPACEXTABLE WHERE Customer = 'NASA (CRS)';

Average Payload Mass

- The average payload mass carried by booster version F9 v1.1 is **2,534.67kg**.

- SELECT AVG(PAYLOAD_MASS__KG_) AS AVG_PAYLOAD_MASS
- FROM SPACEXTABLE WHERE Booster_Version LIKE 'F9 v1.1%';

First Successful Ground Landing Date

- The first successful landing outcome on ground pad occurred on **December 22nd, 2015**.

- SELECT MIN(Date) as LaunchDate
- FROM SPACEXTABLE
- WHERE Landing_Outcome = 'Success (ground pad)';

Successful Drone Ship Landing with Payload between 4000 and 6000

- The boosters which have successfully landed on drone ship and had payload mass greater than 4000 but less than 6000 are:
- SELECT Booster_Version, PAYLOAD_MASS__KG_
- FROM SPACEXTABLE
- WHERE Landing_Outcome = 'Success (drone ship)'
- AND PAYLOAD_MASS__KG_ BETWEEN 4000 AND 6000;

Booster	Payload Mass
F9 FT B1022	4,696kg
F9 FT B1026	4,600kg
F9 FT B1021.2	5,300kg
F9 FT B1031.2	5,200kg

Total Number of Successful and Failure Mission Outcomes

- Total number of successful and failure mission outcomes

- SELECT CASE
-     WHEN Mission_Outcome LIKE 'Success%' THEN 'Success'
-     WHEN Mission_Outcome LIKE 'Failure%' THEN 'Failure'
- END as Mission_Status, COUNT(*)
- FROM SPACEXTABLE
- GROUP BY Mission_Status;

Mission Status	Count
Failure	1
Success	100

Boosters Carried Maximum Payload

- The maximum payload sent was **15,600kg**.
- The boosters that carried the maximum payload are:

- SELECT
- DISTINCT Booster_Version,
- PAYLOAD_MASS__KG_
- FROM SPACEXTABLE
- WHERE PAYLOAD_MASS__KG_ = (
-   SELECT MAX(PAYLOAD_MASS__KG_) FROM SPACEXTABLE
-)
- ORDER BY Booster_Version;

Booster Version
F9 B5 B1048.4
F9 B5 B1048.5
F9 B5 B1049.4
F9 B5 B1049.5
F9 B5 B1049.7
F9 B5 B1051.3
F9 B5 B1051.4
F9 B5 B1051.6
F9 B5 B1056.4
F9 B5 B1058.3
F9 B5 B1060.2
F9 B5 B1060.3

2015 Launch Records

- List of failed landing outcomes in drone ship, their booster versions, and launch site names for in year 2015:

- SELECT
- CASE strftime('%m', Date)
- WHEN '01' THEN 'January'
- WHEN '02' THEN 'February'
- WHEN '03' THEN 'March'
- WHEN '04' THEN 'April'
- WHEN '05' THEN 'May'
- WHEN '06' THEN 'June'
- WHEN '07' THEN 'July'
- WHEN '08' THEN 'August'
- WHEN '09' THEN 'September'
- WHEN '10' THEN 'October'
- WHEN '11' THEN 'November'
- WHEN '12' THEN 'December'
- END as Month,
- Landing_Outcome, Booster_Version, Launch_Site, Date
- FROM SPACEXTABLE
- WHERE strftime('%Y', Date) = '2015' AND Landing_Outcome = 'Failure (drone ship)';

Month	Outcome	Booster	Launch Site
January	Failure (drone ship)	F9 v1.1 B1012	CCAFS LC-40
April	Failure (drone ship)	F9 v1.1 B1015	CCAFS LC-40

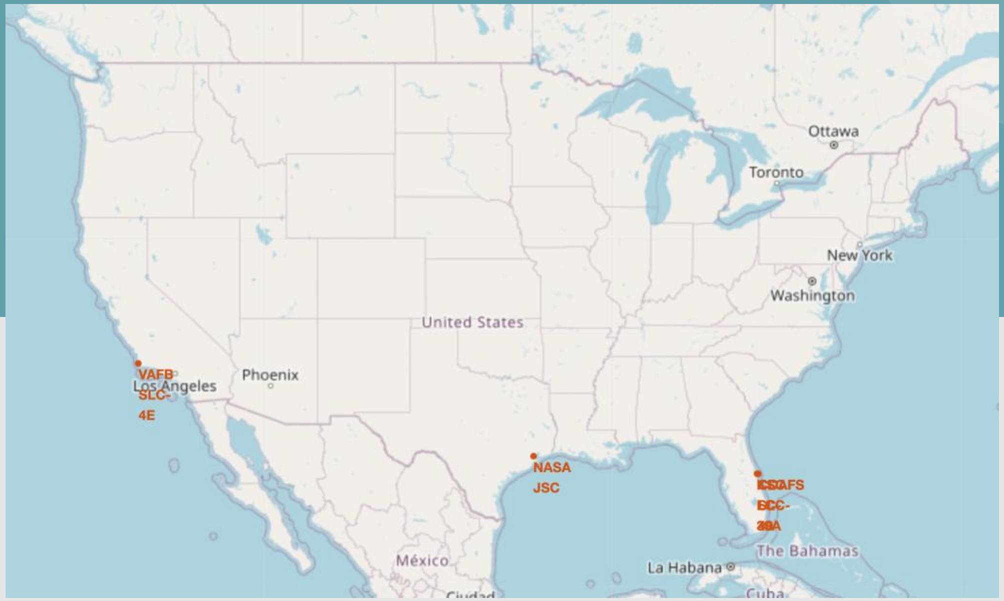
Rank Landing Outcomes Between 2010-06-04 and 2017-03-20

- Rank the count of landing outcomes between the date 2010-06-04 and 2017-03-20, in descending order:

```
SELECT
  Landing_Outcome,
  COUNT(*) as Count
FROM SPACEXTABLE
WHERE
  Date BETWEEN
    '2010-06-04' AND '2017-03-20'
GROUP BY Landing_Outcome
ORDER BY Count DESC;
```

Landing Outcome	Count
No attempt	10
Success (drone ship)	5
Failure (drone ship)	5
Success (ground pad)	3
Controlled (ocean)	3
Uncontrolled (ocean)	2
Failure (parachute)	2
Precluded (drone ship)	1

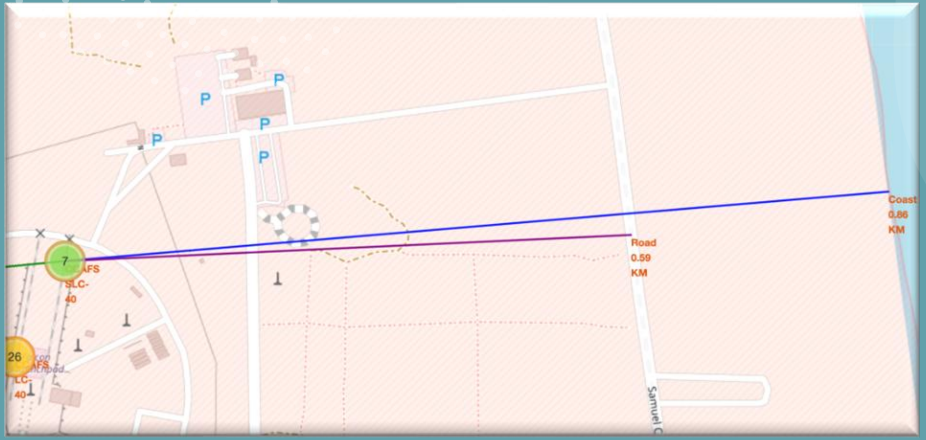
Launch Site Locations

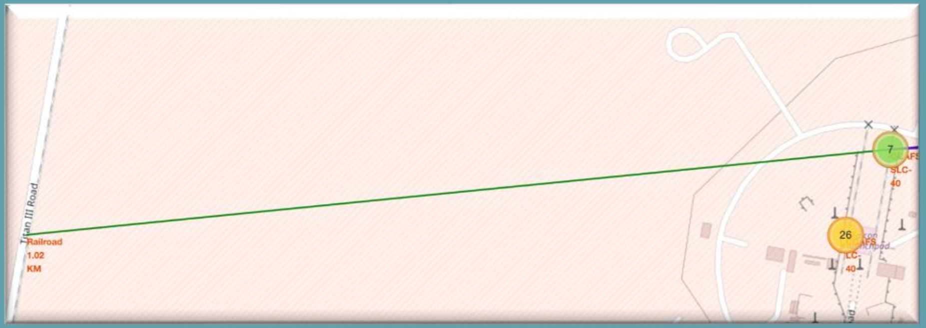


- Launch sites are located near coastal regions in Florida and California to reduce risk of catastrophic failures affecting human activities.

Notable Proximate Locations

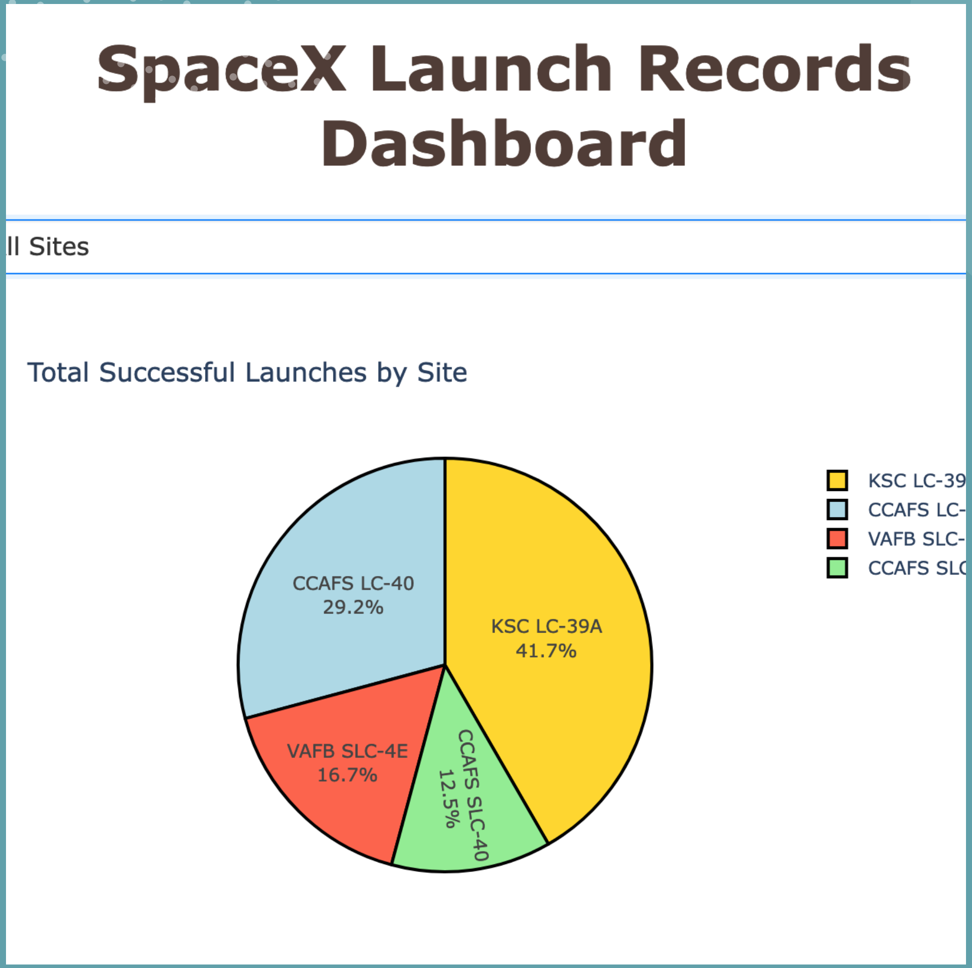
- Notable locations shown
  - Railway (1.02KM)
  - Roadway (0.59KM)
  - Coast (0.86KM)





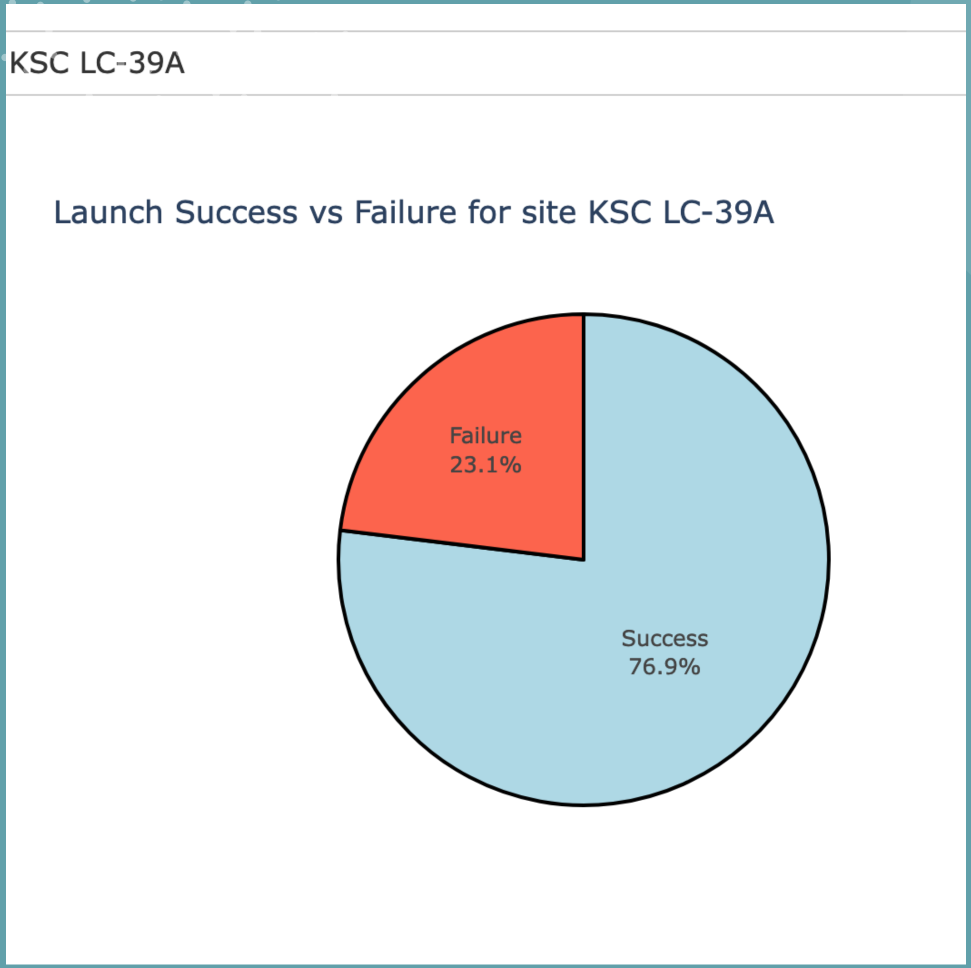
All Launch Sites: Successful Landings

- KSC LC-39A experienced the highest proportion of successful landings, followed by CCAFS LC-40.
- VAFB SLC-4E and CCAFS SLC-40 the lowest.



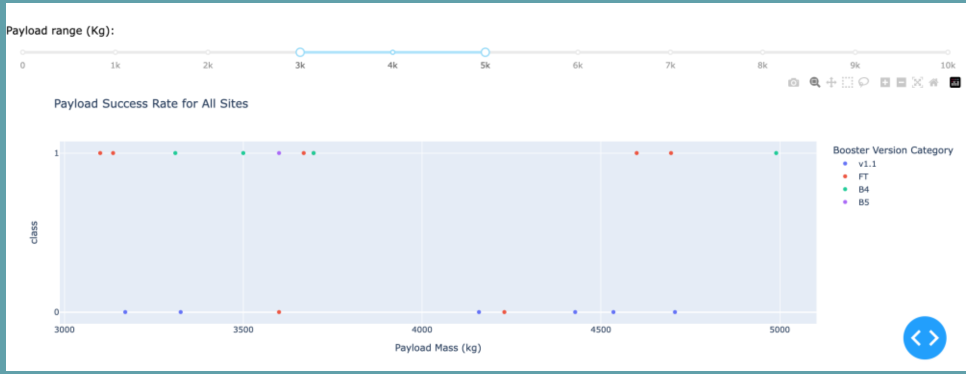
Per-site Launch Success Ratio: High

- KSC LC-39A had the highest ratio of successful landings



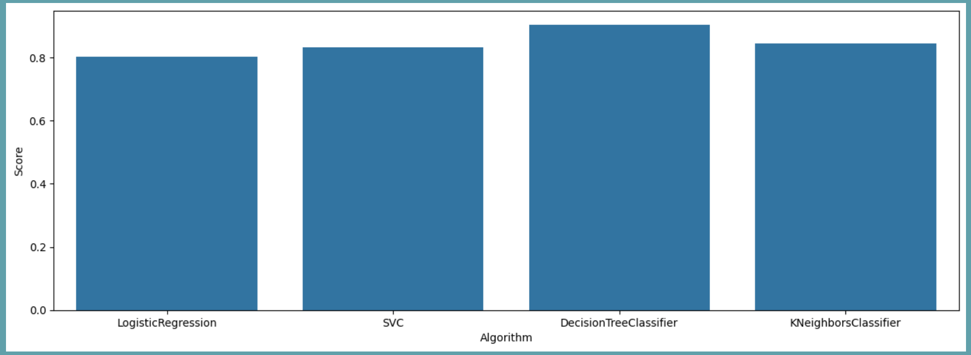
Payload Range

- With a payload mass between 3,000kg and 5,000kg, v1.1 boosters performed the worst.
- In the same payload range, B4 and B5 boosters had the best success rate, followed by FT.



Classification Accuracy

Of the algorithms tested, the DecisionTreeClassifier was the most accurate.



Confusion Matrix

14 observations were correctly predicted as successful landings (true positive)

3 observations were correctly predicted as failed landings (true negative)

1 observation was incorrectly predicted as a successful landing (false positive)

No observations were incorrectly predicted as a failed landing (false negative)

Conclusions

- The analysis revealed that **success rates have steadily increased over time**, reflecting ongoing operational improvements and technological advancements. **Orbital destination** played a significant role, with **ES-L1, SSO, HEO, and GEO** demonstrating the most consistent success in landings. **Launch site** also emerged as a strong predictor, with **KSC LC-39A** achieving the highest success rate, followed closely by **CCAFS LC-40**. Various **machine learning models** were tested to predict landing outcomes, and many showed acceptable performance. Among them, the **DecisionTreeClassifier** stood out, delivering the best results with high **accuracy, precision, and recall**, making it a reliable model for forecasting the success of Falcon 9 first stage landings.

- Thank you