

# **Bias in Adult Income Dataset**

Submitted by: Group 2

Course: DATA-6550

## 1. Introduction

Artificial intelligence and machine learning systems are rapidly deployed in the high-stakes decision-making contexts that directly impacts people's lives, from the automated resume screening and credit card scoring to the health risk assessment and mostly criminal justice predictions. However, combining these evidences show that these frameworks are mostly perpetuate and extend existing societal biases. In 2018, Amazon stopped using an AI recruiting tool which was systematically downgrading women's resumes. In 2019, Apple Card came across a regulatory check when its algorithm was caught offering women lower credit limits as compared to men who had similar financial portfolios. These drawbacks share a similar root cause: automated machine learning systems only learn patterns from the historical data, and when that particular data reflects historical differences through bias, inequalities, the resulting models result and automate that discrimination in the decision process.

At the main point of algorithmic bias is the training data. In this project we investigate most of these challenges using a detailed analysis of the Adult Income dataset taken from the UCI Machine Learning Repository which is one of the most widely used datasets in the machine learning community for research and education.

Using a comparative analysis of four classification models which were considered for this dataset (logistic regression, decision tree, random forest, and SVM), we demonstrate bias across multiple fairness metrics, also evaluate trade-offs between accuracy and fairness, and moreover, we proposed concrete mitigation strategies at the different levels. Our major findings show that the dataset shows severe gender imbalance (67.5% male), racial imbalance (86% White), and also income disparities (males 2.7x more likely to earn >\$50K), which we tested using all models learn. Demographic parity violations were ranging from 2.4% on SVM to 19.2% with Decision Tree. The main objectives of our analysis are are briefly presented below:

1. Identify and then quantify biases in the dataset, specifically gender and racial bias in income distribution
2. Evaluate demographic distributions to reveal sampling and representation biases
3. Analyze how biases affect automated machine learning model performance across multiple algorithms
4. Compare fairness metrics across different classification models and propose mitigation strategies

## 2. Dataset

The Adult Income dataset which is extracted from the 1994 U.S. Census Bureau by researchers named Ronny Kohavi and Barry Becker. This UCI dataset holds 48,842

records with 14 demographic and employment features (age, education, occupation, race, gender, hours worked) are used to estimate if the annual income exceeds \$50,000. We further choose this dataset because it has commonly been used in many academic papers and multiple educational courses, which makes it prominent of how bias goes through the ML models. More importantly, it holds explicit protected attributes which are race and gender from a historical period of 1994. This allows us to measure how historical differences reflect in data and goes through modern algorithms. Also, the evaluation of the demographic composition of dataset reveals significant imbalances in terms of gender and racial distribution:

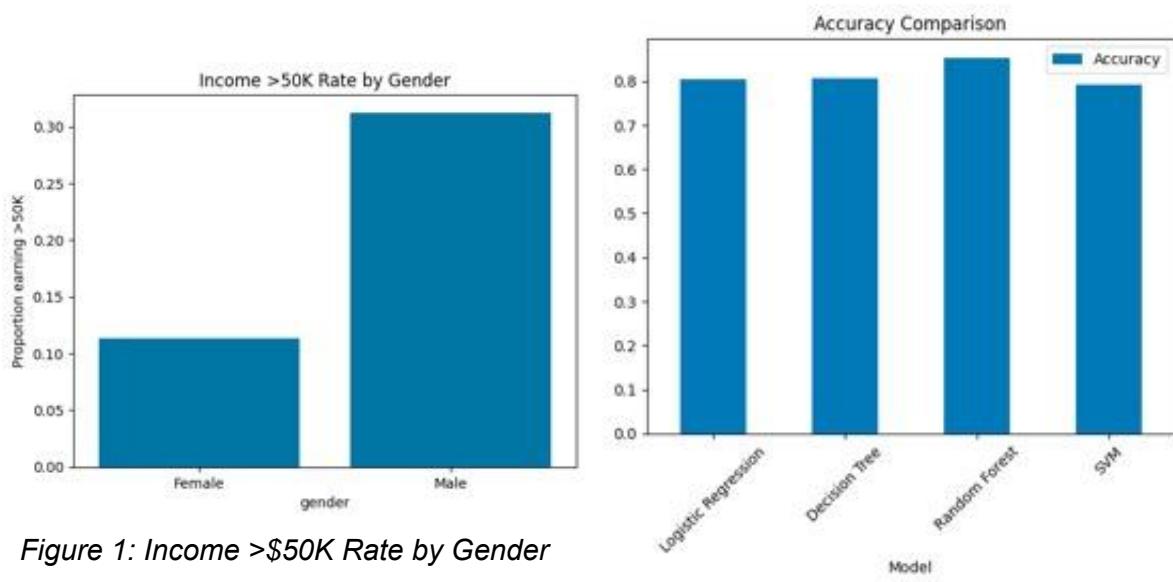
**Gender Distribution:** Males make 67.5% of the dataset with 32,975 records, while female representation is only 32.5% which makes 15,867 records. This 2:1 ratio shows substantial sampling bias that can affect model generalization.

**Racial Composition:** The dataset is mostly White individuals who are 86.0% of the dataset, with Black individuals representing only 9.3%, Asian-Pacific Islanders 2.9%, American-Indian-Eskimos 1.0%, and Other 0.8%. This great imbalance limits the model's ability to learn patterns for minority groups, which leads to disparate performance.

Furthermore, the income distribution across the demographic groups shows stark disparities based on gender and race, which are further discussed below:

**By Gender:** Male individuals have a 31.2% rate of earnings above a threshold of \$50K, compared to 11.4% for females. This huge gap reflects the historical wage inequality and the occupational segregation patterns from the year 1994 market.

**By Race:** Asian-Pacific Islander individuals reflect the highest high-income rate (28.3%), which is followed by White (26.2%), Other (12.7%), Black (12.6%), and American-Indian-Eskimo (12.2%). These differences show complex historical factors, which not just include immigration patterns, educational access, but also systemic discrimination.



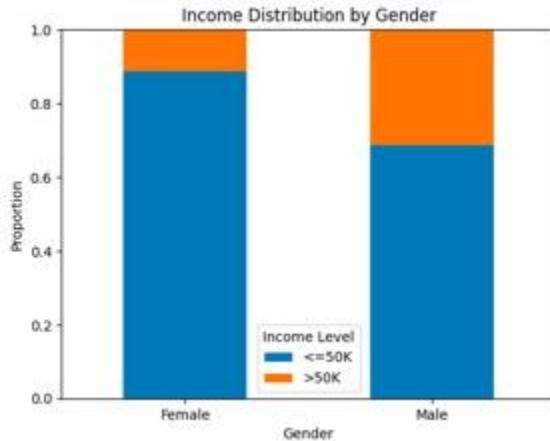
*Figure 1: Income >\$50K Rate by Gender*

*Figure 2: Income >\$50K Rate by Race*

### 3. Methodology

The evaluation began with the data preprocessing steps. Mainly, missing values, shown by '?' in the original dataset, were taken care of analyzing their distribution across features. Categorical variables were also encoded using label encoding to be used by machine learning algorithms to process the data. Attention was further paid to the binary encoding for sex in which 0 is for female and 1 is for male and the income target variable is 0 for  $\leq \$50K$  and 1 for  $> \$50K$ . The dataset was well-structured, with minimal missing data; however, approximately 7% of records lacked occupation and work class information.

We conducted detailed exploratory data analysis to grasp the distribution of features and identify potential biases. This involves analyzing income distributions among gender, race, occupation, and education levels using visualization techniques and some statistical methods. Cross-tabulations between the attributes of race and gender and income outcomes showed substantial disparities that showed deeper investigation. The stacked bar chart analysis demonstrated some of the disproportionate majority of females in the low-income category.



*Figure 3: Income Distribution by Gender*

We employed and compared four classification algorithms to analyze both predictive performance and the fairness characteristics:

**Logistic Regression:** A linear model is providing interpretable coefficients, which are trained with the LBFGS solver for a maximum of 1000 iterations.

**Decision Tree:** A non-linear model which uses recursive partitioning, and offers high interpretability through some rule-based decisions.

**Random Forest:** An ensemble method which combines multiple decision trees to improve the generalization and also reduce overfitting.

**Support Vector Machine (SVM):** A maximum-margin classifier which finds the optimal decision boundary in the feature space.

The dataset was split into 80% training and 20% testing sets using the stratified sampling to maintain class proportions in our dataset. All models were employed using scikit-learn library with the default hyperparameters to establish baseline performance.

To evaluate bias, we computed two main fairness metrics:

**Demographic Parity Difference:** Measures the positive prediction values between males and females. A value of 0 shows perfect demographic parity, whereas larger absolute values show greater disparate impact. This metric evaluates whether the model's predictions are fairly distributed across the protected groups.

**True Positive Rate (TPR) Difference:** Also called the equal opportunity difference, this evaluates the difference in true positive rates among males and females. It analyzes whether people who truly earn >\$50K are equally likely to be identified regardless of sex. Smaller values give fairer treatment of qualified candidates among groups.

## 4. Analysis and Results

Underconsidered four classification models achieved good accuracy scores, with Random Forest also known as RF gave best overall. However, only the metric of accuracy hides the significant fairness concerns:

Model	Accuracy	Demographic Parity Diff	TPR Diff
Logistic Regression	80.4%	0.119	0.181
Decision Tree	80.6%	0.192	0.060
<b>Random Forest</b>	<b>85.3%</b>	0.178	0.049
SVM	79.3%	<b>0.024</b>	<b>0.047</b>

Table 1: Classification models Performance Metrics

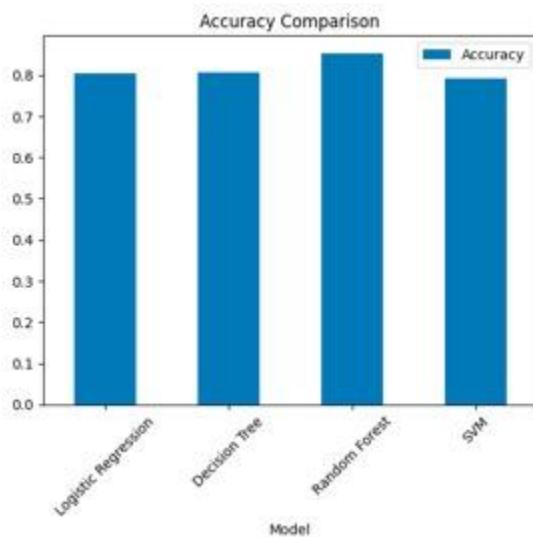
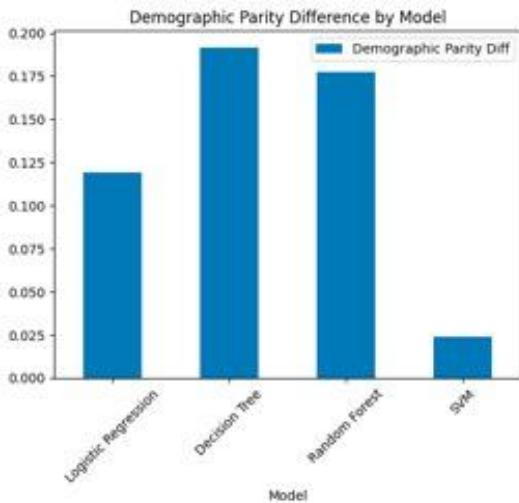
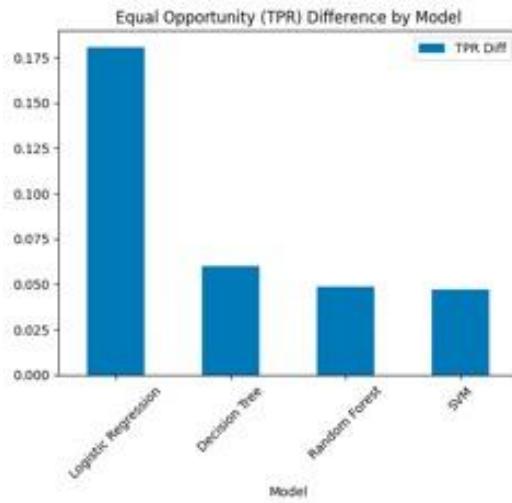


Figure 4: Model Accuracy Comparison

The metric of fairness analysis shows a critical trade-off among accuracy and fairness. Random Forest goes to the highest accuracy of 85.3% but it shows prominent demographic parity violation which is 0.178, which means that males are 17.8% more likely to be predicted as the high earners than females candidates. On the other hand, SVM achieves the overall best fairness value, with only a 2.4% change in demographic parity, but accuracy of SVM is greatly low which is only 79.3%.



*Figure 5: Demographic Parity Difference by Model*



*Figure 6: Equal Opportunity (TPR) Difference by Model*

The decision tree reflects the most bad demographic parity (0.192), it learns and extends gender bias strongly. However, its performance is good on Equal Opportunity (TPR difference of 0.060), which shows that, among high earners or people earning more than 50K, it treats both genders similarly. This shows that different fairness metrics can demonstrate different stories about the model behavior.

The dataset's gender bias analysis solidifies the concept that all models somehow favor males in the income predictions. Even SVM which is the fairest model also exhibits measurable bias. This rose from the data distribution, in which the males are overrepresented in high-income individuals and higher educational levels. The models learn these patterns while training, mainly passing historical discrimination into decisions through automated systems.

The TPR difference evaluation shows that logistic regression gives the largest equal opportunity violation (0.181), which means that among individuals who really earn more than \$50K, males are 18.1% highly likely to be accurately predicted than females. This type of bias is specially concerning in fields like hiring or promotion decisions. In these jobs it means that qualified female candidates in the pool are more likely to be overlooked.

The dataset shows patterns of occupational segregation by sex. Males are overrepresented in higher-paying roles like technical and managerial, on the other hand females are considered in lower-paying services and administrative roles. This occupational distribution mainly serves as income disparity and reflects a structural bias hidden in the labor market data. When automated models like machine learning train on this data, they encode these historical patterns of discrimination, potentially reflecting them into the future estimations.

The deep racial imbalance in the dataset in which 86% are White creates many problems. Number one, the models have inadequate data to learn and train on true patterns for minority groups, resulting in higher error rates for these groups. Second, the similarities of race and gender gives compound drawbacks; minority women experience the most underrepresentation and experience the big prediction errors. Third, the high-income values of Asian-Pacific Islander individuals at 28.3% and White at 26.2%, show higher than Black (12.6%) and American-Indian-Eskimo (12.2%), showing historical economic inequalities that these models will learn and then use in future predictions.

## 5. Discussion

Our detailed analysis shows fundamental challenges in creating fair automated machine learning systems. We noticed a prominent accuracy-fairness trade-off: Random Forest had the highest accuracy of 85.3% but with a bias of 17.8% demographic parity difference. On the other hand, SVM demonstrated better fairness of 2.4% demographic parity difference at the cost of lower accuracy which is 79.3%. This requires some context-dependent decisions which are: high-stakes fields like hiring may prove accepting lower accuracy for the fairer outcomes. Although, fairness itself cannot be considered singular: The decision tree in our study showed poor demographic parity of 19.2% yet gave a nice equal opportunity showing in 6.0% TPR difference, reflecting that different fairness metrics can conflict with each other. Data scientists must choose criteria closely aligned with their task which can ensure equal opportunity for employment, and also achieve demographic parity in the resource allocation.

Deployment of classification models which are trained on this kind of data holds serious risks. Even if gender is eliminated as a main feature, education, field of work and hours in the field work as proxies, which enables systematic discrimination. The unalignment in the data collected in 1994 and the current model execution is equally problematic. Female laborers participate and their occupational distribution has changed greatly over past decades, which means that models trained on historical data risk on random patterns show outdated discrimination and violate the equal opportunity laws. The data scientists must evaluate if certain estimation tasks should be carried out through automated systems, if the data in hand is valid for the intended use, and what actual safeguards must be put in place to prevent any harm. The use of the dataset, which is Adult Income dataset, in ML research has proved as the deployment of biased models in real systems.

## 6. Bias Mitigation Strategies

Addressing the bias needs observations at multiple levels. Let's talk about the data level first, we can balance the dataset using resampling and reweighting minority groups like females and racial minorities, supplement 1994 census data. Then at the

model level, we can use fairness constraints during training to use prominent libraries like Fairlearn or AIF360 to make sure demographic parity. Results presented in this report suggest that fairness achieved using SVM could also be achieved by random forest if we maintain appropriate constraints. Some adversarial debiasing trains models with important components that penalize estimation, which forces the primary model to give predictions that don't reveal gender or race. Optimization applies different automated decision thresholds for different groups, while maintaining the overall accuracy to improve fairness without any retraining.

Then at the **process level**, we establish bias audits to measure the model performance among demographic subgroups using multiple fairness metrics. Involve the representatives from the communities using focus groups to make sure that the fairness definitions go along with experiences and identify any harm that other metrics may miss out.

We also recommend a **hybrid approach** which can initiate data augmentation while using recent and balanced datasets to lower the historical and sampling bias. Also, we can apply fairness constraints during the training to target demographic parity less than 5% and TPR difference less than 5%. Moreover, we can use threshold optimization to fine-tune the fairness criteria without sacrificing excessive accuracy; and implement the fairness auditing system if metrics go bad. This multi-layered approach takes care of bias at not just the data level but also at model and process levels to maximise the chances of achieving both accurate and fair estimations while maintaining accountability.

## 7. Conclusion

This overall analysis of the dataset using different machine learning algorithms showed a great gender and racial bias among all different models. Males are estimated to make above \$50,000 which is 2.7 times higher than females which shows pure dataset imbalances. Our overall analysis also showed a fundamental trade-off among accuracy and fairness. Random Forest although gave the highest accuracy of 85.3% with significant bias of 17.8% demographic parity gap, while SVM came up with the best fairness of 2.4% but at the lower accuracy of 79.3%.

We presented some actionable mitigation strategies which are data augmentation, fairness-constrained learning and the threshold optimization along with ongoing auditing. Moreover, just presenting some technical solutions is not sufficient. Meaningful progress needs commitment to fairness, transparency on the trade-offs, and willingness to redo the deployment phase when the fairness metric cannot be assured. As today, AI systems greatly influence employment decisions so it is important to identify and mitigate bias as an ethical obligation. The data considered for this project carries the biasness from history. We must make sure that our algorithms are built on a more equal opportunity future rather than enforcing the unjust patterns from past datasets.