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PREDICTIVE MODELING FOR PUBLIC POLICY DESIGN: THE IMPACT OF ARTIFICIAL LIGHTS AT NIGHT (ALAN) ON BIRD STRIKES

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ABSTRACT

Bird strikes present a growing concern to wildlife preservation efforts and pose safety and economic challenges in aviation and urban design that amalgamates a sociotechnical system. Our review of recent evidence suggests that artificial light at night (ALAN) is a contributing factor to bird strikes, especially during migration seasons, when birds are more likely to be disoriented by bright urban lighting.

In this paper, we explore the relationship between light pollution and bird strikes in aviation, with a focus on the application of predictive modeling to inform public policy. Central to our exploration lies is the foundational paradigm of Cyber-Physical-Social Systems (CPSS) that underscores the interaction between the cyber, physical, and social spaces, ensuring effective model-based system design. Multiple criteria are used to perform exploratory data analysis and train a predictive model, including the FAA wildlife strike database, a light pollution GIS map, and BirdCast migration forecasts.

Through exploratory data analysis and predictive modeling techniques, we identify critical correlations between light pollution levels and bird strike incidents. These findings are used to reveal significant trends and offer a model capable of predicting bird strike occurrences with implications for urban planning, lighting design, and aviation safety. We emphasize the potential of these predictive models in informing public policy decisions, aiming to mitigate bird strikes while considering ecological and industrial factors through model-based systems design. Moreover, we acknowledge our method's limitations and provide recommendations for future research to refine the model's accuracy and applicability in a policy-making context.

Keywords: Artificial Light at Night (ALAN), Bird Strikes, Cyber-Physical-Social System (CPSS), Predictive Modeling, Public Policy Decision-Making, Model-Based System Design, Sociotechnical System

1. FRAME OF REFERENCE

Social problems are characterized by the presence of a plethora of interconnected factors that collectively contribute to their complexity. To address these problems necessitates an effective public policy design that anchors in informed approaches. In the intersection of ecological conservation, aviation safety, and urban design, the increasing threat of bird strikes and the adverse effects of Artificial Lights at Night (ALAN) necessitates a transdisciplinary approach guided by 'systems engineering' and 'design' to design public policies through better-informed decisions. Through model-based systems design we demonstrate the interaction between the social and technical variables of the sociotechnical system, highlighting the utility of Cyber-Physical-Social System (CPSS) in addressing the complexities inherent in such interconnected issues.

Bird strikes are influenced by many anthropogenic and ecological variables and present a growing challenge in aviation safety and urban design. When examining the factors influencing bird strikes, a crucial aspect involves comprehending the interaction among ecological factors (driven by bird migration patterns and wildlife preservation), urban design, and aviation safety. Bird migration patterns and behavioral changes due to impact of ALAN majorly account for the social space whereas wildlife preservation, urban design, and aviation safety incorporates social and physical spaces for model-based system design. This requires a comprehension of intricate systems interactions to facilitate well-informed decisions, aiming not only to decrease bird strikes but also to enhance human safety.

Through this paper, we aim to contribute to the progression of machine learning based predictive modeling approach in 'systems engineering' and 'design' by addressing a challenge rooted in a complex system that involves 'birds as objects' to design public policies. It endeavors to explore various domains of interaction with the overarching goal of designing enhanced policies. Before delving into the main approach, it is critical to comprehend some fundamental background to understand the significance of bird strikes. In this section, we review the literature on bird strikes and identify research gaps, introducing the promising potential of predictive modeling in designing mitigation efforts.

1.1 Overview of Bird Strikes and Their Significance

Bird strikes, incidents where birds collide with a moving vehicle (usually an aircraft), have emerged as a significant concern for both wildlife conservation and aviation safety. Historically, these events were considered rare occurrences, but with the expansion of global air traffic and changes in natural habitats, they have become increasingly common, posing a threat to both avian populations and human safety.

Severe strikes are capable of causing critical flight issues, posing safety risks to passengers and crew. In 2009, US Airlines Flight 1549 took off from New York and was shortly after struck by a flock of birds, resulting in the loss of all engine power. The pilot landed the flight successfully in the Hudson River with no injuries to passengers or crew, in an incident that quickly became known as "the Miracle on the Hudson" [1].

Furthermore, the significance of bird strikes extends beyond the immediate risk to flight safety. From an ecological perspective, these incidents highlight the broader issue of how human activities, such as aviation and urban development, intersect with and impact wildlife. Birds, especially migratory species, face numerous threats from habitat loss, climate change, and urbanization. The specific challenge of *Artificial Light at Night* (ALAN) contributes to this by disorienting birds during their flight, making them more prone to collisions with aircraft [2].

The implications of bird strikes are multifaceted. Economically, they cause substantial damage to aircraft, leading to high repair costs and operational delays. For wildlife, the loss of birds, particularly those from already declining species, exacerbates the challenges of conservation efforts [3].

The interplay of factors underscores the need for a multifaceted approach to addressing bird strikes. Understanding the role of ALAN in this context provides a tangible point of intervention. By examining the impact of artificial lighting on bird behavior and the resulting increase in strike incidents, we can begin to design public policies and interventions that mitigate these risks. The objective of designing such policies is twofold: enhance aviation safety by reducing the frequency and severity of bird strikes, and contribute to wildlife conservation efforts by minimizing one of the anthropogenic risks to bird populations.

Our focus in this paper is on predictive modeling, aiming to bridge the gap between empirical evidence and actionable policy. By leveraging data on bird migration, light pollution, and bird strike records, we develop a model that can predict the likelihood of strikes at any given time and location. This predictive capacity is crucial for designing interventions that are both effective and efficient, targeting resources to times and places where the risk of bird strikes is highest. Through this work, we contribute to the ongoing dialogue between conservationists, aviation professionals, and policymakers, seeking solutions that balance human needs with the imperative of wildlife preservation.

1.2 Discussion of Artificial Light at Night (ALAN) as a Contributing Factor

Artificial Light at Night (ALAN) represents a pervasive environmental change affecting ecosystems worldwide. ALAN is defined as the introduction of artificial light into previously dark nighttime environments; this disrupts the natural light cycles, profoundly influencing the behavior, physiology, and distribution of wildlife, including birds. The impact of ALAN on avian species is multifaceted, affecting their migration patterns, foraging behaviors, predator-prey interactions, and even reproductive cycles [4].

The theoretical underpinnings linking ALAN to changes in bird behavior derive from the intrinsic connection between light and the biological rhythms of many species. Birds, like many other organisms, rely on natural light cues for navigation, timing their migrations, and other critical behaviors. The disorientation caused by bright, artificial lighting, especially in urban areas, can lead to increased incidences of bird strikes [4]. These strikes not only pose a significant threat to avian populations but also present safety and economic challenges in aviation and urban environments [3].

Research in this area has begun to shed light on the extent of ALAN's impact. Studies have shown that nocturnally migrating birds, attracted or disoriented by intense light sources, are particularly at risk. This phenomenon is exacerbated during migration seasons when large numbers of birds are on the move, making them more vulnerable to collisions with illuminated structures [5].

1.3 Research Gap Identification

The intersection of Artificial Light at Night (ALAN) and its impact on bird strikes, particularly within the realm of aviation and urban planning, represents an evolving field of study. While the body of research acknowledging ALAN's ecological ramifications is growing, significant gaps persist, particularly in the context of predictive modeling and its application to public policy decision-making.

Existing Research Overview

The focus of existing research has largely been on documenting incidents of bird strikes and examining the direct effects of ALAN on wildlife behavior. Many studies have confirmed that ALAN can disorient migratory birds, leading to increased mortality rates due to collisions with illuminated structures [5]. However, these studies often concentrate on isolated aspects of the issue, such as the immediate behavioral responses of birds to ALAN or the characteristics of light pollution in specific geographical areas.

Highlighting the Need for Data Analysis and Predictive Modeling

Despite these valuable insights, a comprehensive analysis that integrates diverse data sources to predict bird strike occurrences remain scarce. Based on the discussion of existing research, we suggest that the gaps that need to be bridged to design bird strike mitigation efforts are as follows:

- **Comprehensive Models:** There is a dearth of predictive models that incorporate various factors influencing bird strikes, such as migration patterns, light pollution levels, and urban development.
- **Policy-Oriented Research:** Few studies explicitly bridge the gap between ecological research and policy implementation, leaving a void in resources that policy-makers can directly apply to mitigate the impact of ALAN on bird strikes.

A Call for Integrative Approaches

This gap in the literature underscores the need for an integrative approach that leverages exploratory data analysis (EDA) and predictive modeling. Such an approach can offer new insights into the complex dynamics at play, facilitating the development of more effective strategies to mitigate bird strikes. By synthesizing data from the FAA Wildlife Strike Database, a light pollution GIS map, and BirdCast migration forecasts, we aim to construct a predictive model that can serve as a valuable tool for informing public policy and urban planning decisions.

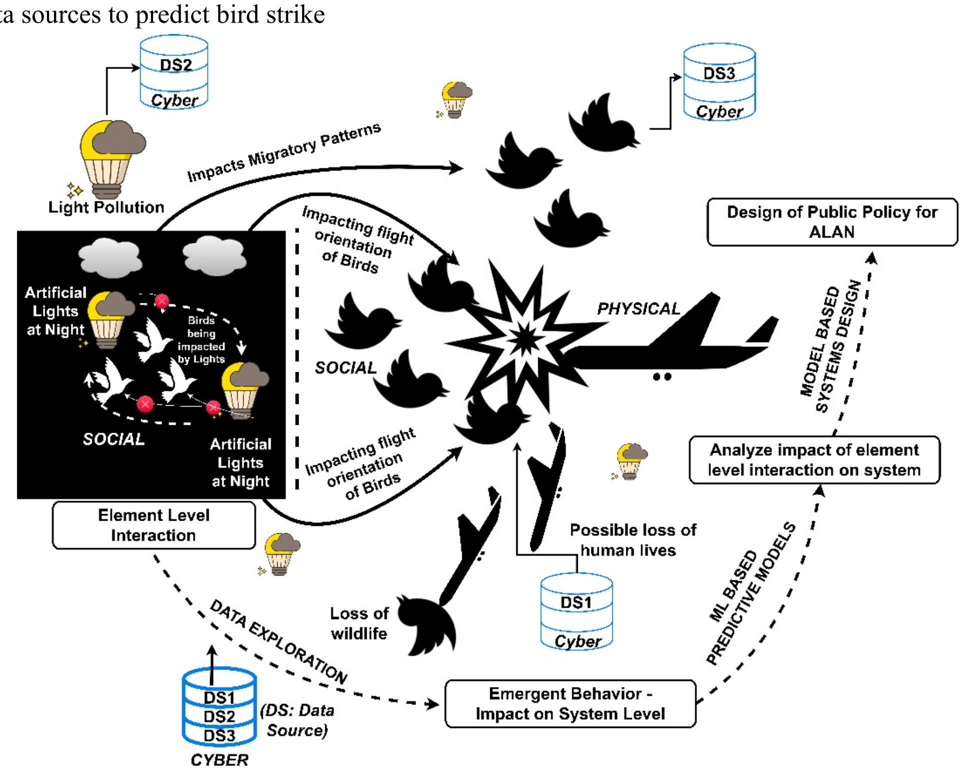

FIGURE 1: CONCEPTUAL MAP: POLICY DESIGN FOR IMPACT OF ALAN ON BIRDS AS CPSS

Organization of the Paper

- In **Section 2**, we detail the methods employed in integrating multiple data sources and outline our approach to predictive modeling.
- In **Section 3**, we present the results of our exploratory data analysis and the outcomes of our predictive modeling efforts, highlighting key findings and their implications.
- In **Section 4**, we discuss the interpretation of our results, explore the limitations of our method, and suggest directions for future research.
- In **Section 5**, we offer closing remarks by summarizing the significance of our findings and their potential impact on public policy and conservation efforts.

In the following sections, we aim to address the identified research gaps, contributing to a deeper understanding of ALAN's impact on bird strikes and offering actionable insights for mitigation strategies.

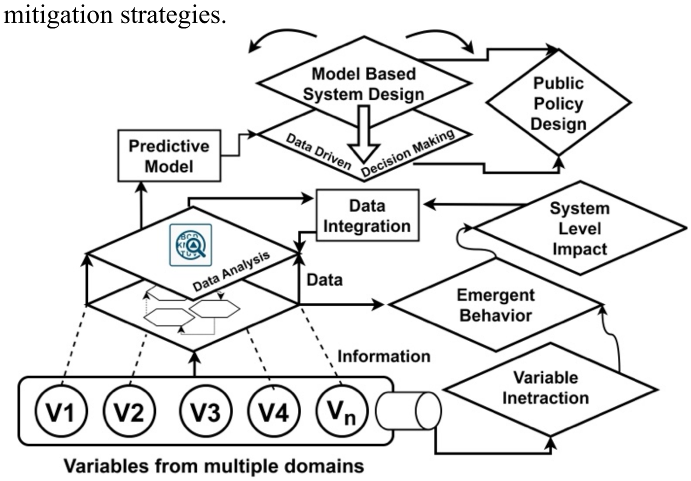

FIGURE 2: ADDRESSING ALAN AS MODEL BASED DATA DRIVEN SYSTEM DESIGN

2. METHOD

In this section we detail on our method for model-based system design to design policies aimed at mitigate the impact of ALAN on bird strikes, thus, achieving a parallel objective to safeguard human lives due to aircraft accidents. We describe our conceptual map through which we illustrate the interconnectedness of the challenge within the paradigm of CPSS.

Impact of ALAN on Bird Strikes as a Complex System

Through Figure 1, we illustrate our conceptual map for model-based, data-driven system design approach to design public policy, aimed at mitigating the impact of Artificial Lights at Night (ALAN) on bird strikes to reduce potential aviation incidents. The influence of nighttime artificial lighting disrupts bird flights by disturbing melatonin production, leading to disorientation [4]. This light pollution not only affects flight orientation but also induces variations in flight timing. Consequently, birds undergo behavioral changes, altering their migratory patterns, resulting in detours, delayed departures, or stopovers in suitable habitats.

We approach this as a system with interacting component-level variables causing system-level impact due to emergent behavior. Analyzing the interaction effects between light pollution and behavioral shifts in birds, while considering the system holistically, is imperative. The focus extends beyond the critical analysis of ALAN's direct impact on bird strikes; it encompasses an understanding of emergent effects resulting from the interaction between various variables. Further elucidation of this approach is provided in the subsequent sections, delving into the intricacies of systems engineering principles and policy design considerations. Through the proposed approach we aim the following:

1. Analyze the interaction between component-level variables and assess its impact on the emergent behavior of the system.
2. Analyze interactions between transdisciplinary variables comprising diverse social and technical domains.
3. Utilize model-based system design for better-informed decision-making.
4. Investigate and discern the primary variables with the most significant impact on bird strikes.

In this paper, we integrate multiple data sources to investigate the impact of Artificial Light at Night (ALAN) on bird strikes and train a model to predict strikes, leveraging the FAA Wildlife Strike Database (DS1 in Figure 1), a light pollution GIS map (DS2 in Figure 1), and BirdCast migration forecasts (DS3 in Figure 1).

Addressing ALAN as model-based system design

Introducing our model-based system design approach in Figure 2, where a spectrum of variables provides invaluable insights for system design. In this intricate system, the exchange of information is not immediately apparent, given the diverse social and technical domains encompassing aviation, wildlife, and light emission. However, our method accounts for the nuanced interactions between these variables through robust data exploration methods. The primary aim is to empower decision-makers by furnishing them with comprehensive data-driven insights, derived from our model-based system design. These insights, extracted from the intricate web of interconnected variables, serve as a cornerstone for designing well-informed policies that harmonize the complexities of aviation, wildlife preservation, and urban lighting dynamics.

This model-based system design as shown in Figure 2, is supported by the conceptual map that is presented in Figure 1. This is embodied in the CPSS paradigm. The aircrafts, represented in Figure 1, form the major elements of physical space, whereas the light pollution in environment, birds, and the change in their behavior are primary entities of social space. The geographical and urban planning factors contribute to both social and physical spaces. The data sources that are presented as DS1, DS2, and DS3, in Figure 1, and explained in detail in Section 2.1, forms the cyber space that enables data driven design for this model-based system design.

In Figure 3, we outline our approach to predictive modeling through a sequence of steps including problem identification, data source selection, exploratory data analysis (EDA), and predictive model construction. This is further expanded in the following sections.

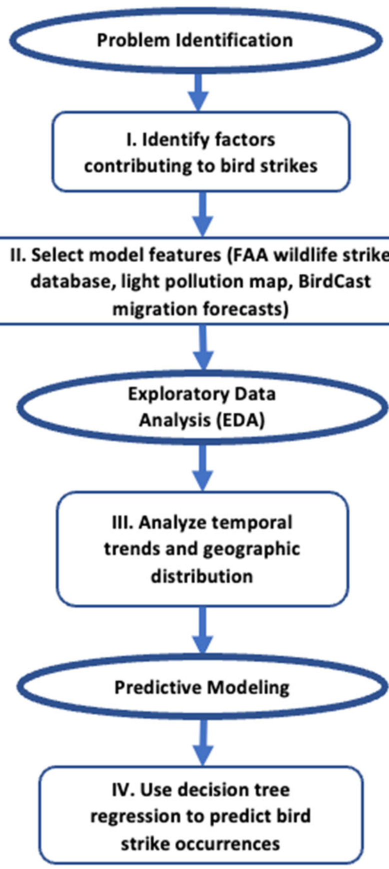

FIGURE 3: DIAGRAM OF PREDICTIVE MODELING APPROACH

2.1 Description of Data Sources

We use the FAA Wildlife Strike Database to provide initial exploratory data analysis (EDA) findings on the distribution of bird strikes, including trend analysis, species-specific analysis, and temporal patterns (Section 3.1). In Sections 3.2 and 3.3, we incorporate the light pollution GIS map and BirdCast migration forecasts to perform statistical tests and build a model capable of predicting bird strike occurrences. By examining the confluence of these data sources, we seek to contribute to the broader understanding of ALAN's ecological impacts, with a specific focus on the role of spatiotemporal predictive modeling to inform public policy design.

FAA Wildlife Strike Database

This database [6] provides a comprehensive record of bird strike incidents reported to the Federal Aviation Administration, with over 286,000 reported strikes from 1990 through 2023. Approximately 97% of all recorded strikes with aircraft in the United States involve birds, though strikes with other animals such as deer and coyotes have also been reported [7]. Bird strikes are voluntarily reported, primarily by pilots and airport personnel. Records generally include details on the date, time, location, species involved, and the extent of damage to the aircraft. This dataset serves as the foundation of our analysis, offering insight into the frequency and distribution of bird strikes in the United States.

GIS Light Pollution Map

Light pollution data is represented through a Geographic Information System (GIS) raster that maps the intensity and distribution of light pollution across North America, sourced from satellite data in 2020 [8][9]. This map includes 15 color bands, with each band corresponding to a discrete light pollution category. Color bands are ordered by increasing ratios of artificial sky brightness to natural sky brightness, measured in magnitudes per square arcsecond. We use this data to quantify the light pollution level at each bird strike location, allowing us to perform correlation analysis and train a predictive model.

BirdCast Migration Forecasts

The BirdCast project offers forecasts of bird migration in North America, providing valuable data on the movement of birds, especially during peak migration periods [10]. Data were graciously provided to us for this project by Alexander Tedeschi, Andrew Farnsworth, Adriaan Dokter, and Julia Wang at Cornell. We use 2023 forecast data, captured each day at 0600Z, to train our predictive model. These data are divided into GeoTIFF files for each month, with each layer containing a time dimension. For any single day, there are 4 raster bands:

- *U* (ground speed component west to east in m/s)
- *V* (ground speed component south to north in m/s)
- *MTR* (migration traffic rate in birds/km)
- *VID* (vertically integrated density in birds/km^3)

Moreover, there are 4 extra bands corresponding to the *Kriging* variance of each variable. Kriging variance, in the context of BirdCast, reflects the uncertainty associated with predictions of bird migration intensity across different geographic locations. BirdCast utilizes Kriging, a geostatistical interpolation technique, to estimate bird migration patterns based on sparse observational data. The Kriging variance provides a measure of the expected error or uncertainty of these estimates, indicating how much confidence we can have in the predicted migration intensities at locations where direct observations are not available [11]. This helps researchers to better understand and predict bird movements, aiding in conservation efforts and minimizing human-wildlife conflicts.

2.2 Methods for Preparing and Integrating Data

The foundational step of our Exploratory Data Analysis (EDA) and modeling results involves the preparation and integration of three data sources: the FAA Wildlife Strike Database, a light pollution GIS map, and BirdCast migration forecasts. This process requires a systematic approach to ensure the integrity and usability of the combined dataset for analysis and predictive modeling.

FAA Wildlife Strike Database Preparation

The initial task involved converting the FAA Wildlife Strike Database from its native Microsoft Access Database format into a CSV file format. This conversion facilitated the importation of data into Python for further analysis and manipulation. The preparation phase, executed in a pandas data frame, emphasized verifying data integrity through checks for missing values, duplicates, or inconsistencies, ensuring a robust dataset for subsequent analysis.

Geo-referencing Light Pollution GIS Raster

To integrate the light pollution data with the bird strike database effectively, the light pollution GIS raster was georeferenced [12] using QGIS software. Georeferencing involved assigning real-world coordinates to each pixel of the raster image, aligning with the WGS 84 - EPSG:4326 coordinate reference system. This step enables the spatial joining of light pollution data with bird strike incidents by matching latitude and longitude values, providing a geospatial context to the analysis.

BirdCast Migration Forecast Integration

The BirdCast migration forecasts, offering insights into bird migration patterns, were integrated by leveraging Python's GIS libraries (rasterio and pyproj) to process GeoTIFF files. This integration allowed us to join datasets by latitude, longitude, and day of the year, enriching the analysis with temporal and spatial dimensions of bird migration in relation to light pollution.

2.3 Exploratory Data Analysis (EDA) Techniques

Our EDA begins with a deep dive into the FAA wildlife strike dataset, aiming to unveil patterns and anomalies that could inform our subsequent predictive modeling efforts. By employing Python libraries including pandas and matplotlib, we conduct a series of analyses focusing on temporal trends, geographical distributions, and species-specific strike rates.

- **Temporal Trends**: We analyze bird strike occurrences over time, identifying peak periods that correspond with migratory seasons [13]. Through this analysis, we observe a noteworthy uptick in strikes during spring and fall migrations.
- **Geographic Distribution**: Utilizing GIS tools, we map bird strikes against light pollution levels, uncovering hotspots where high ALAN levels coincide with increased strike incidences. This spatial analysis highlighted urban areas as zones of elevated risk.
- **Species-Specific Analysis**: By examining the species involved in reported strikes, we discern patterns indicating that certain migratory birds are more susceptible to ALAN-related incidents. This insight points to the need for species-specific mitigation strategies.

Visualizations, including maps, bar plots, and line plots are provided in Sections 3.1 and 3.2 to illustrate spatial and temporal relationships between bird strikes and light pollution. These visual tools enhance our understanding of the data and guide our model design choices, detailed in Section 2.4.

2.4 Statistical and Machine Learning Techniques for Predictive Modeling

Building upon the foundational data joins and EDA detailed in the preceding sections, we employ a combination of statistical tests and machine learning techniques to understand the impact of ALAN and develop a predictive model of bird strike incidents. This approach aims to harness the predictive power of our integrated datasets to forecast bird strike risks with greater precision and to identify effective mitigation strategies.

Correlation Analysis

Kendall's τ and Spearman's ρ rank correlation coefficients are calculated to explore the strength and direction of the relationship between bird strikes and light pollution levels [14]. This allows us to quantify the impact of ALAN on bird strikes and determine its predictive strength in model construction.

Predictive Modeling with Decision Tree Regression

Focusing on a decision tree regression model, implemented using Python's scikit-learn library [15], allowed us to model the continuous outcome variable representing the frequency of bird strikes under varying conditions. This model was chosen for its interpretability and ability to handle non-linear relationships between predictors and the target variable [16].

- **Model Development**: The decision tree was trained using features identified as significant through our statistical tests, including time of day and light pollution level.
- **Feature Importance**: Through our model, we provide insight into feature importance, highlighting which variables most significantly affect bird strike rates and aiding in the prioritization of mitigation efforts.

TABLE 1: TRAINING DATASET FOR PREDICTIVE MODEL

Number of Strikes (y)	Month of the Year (X)	Day of the Month (X)	Latitude (X)
Longitude (X)	Light Pollution Level (X)	(MTR) Migration Traffic Rate (X)	(VID) Bird Density (X)

Data are grouped by latitude, longitude, and day of the year. The training dataset, outlined in Table 1, contains one dependent variable (y) and seven predictors (X).

Evaluation and Validation

To ensure the reliability and applicability of our model, we implement the following evaluation and validation strategies:

- **Performance Metrics:** Mean Squared Error(MSE), Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), and R-squared (R^2) were used to quantify the model's accuracy in predicting bird strike rates, offering clear measures of predictive performance.
- **Cross-Validation**: We implemented k-fold cross-validation with k=5 to assess the model's generalizability across different subsets of the data, ensuring robustness against overfitting.
- **Hyperparameter Tuning**: To avoid overfitting and enhance predictive accuracy, we tuned the tree's depth to 20, the minimum samples for splitting to 2, and the minimum samples per leaf to 10. The model was developed using an 80-20 train-test split.

Application to Public Policy Design and Mitigation Strategies

The approach suggested through model-based system design we envision to assist decision-makers in making better-informed decisions by designing effective policies. This is carried through careful consideration of multiple domains including ecological conservation, aviation safety, and urban development. Our findings, as revealed through directed data exploratory methods that guide decision tree regression modeling, have potential applications in formulating bird strike mitigation strategies. By identifying key predictors of bird strikes, aviation authorities, and wildlife conservationists can implement targeted measures, such as altered flight paths and lighting adjustments during high-risk periods identified by the model.

The utility of this model in public policy design carries profound implications for the formulation of bird strike mitigation strategies. By pinpointing key predictors of bird strikes through our model and predicting the bird strikes as the geographical location changes, aviation authorities and wildlife conservationists can deploy targeted engineering measures. For instance, the model's insights can inform the scheduling of flight paths and facilitate adjustments in lighting systems during high-risk periods, thus embodying a tangible application of engineering solutions in mitigating the impact of bird strikes on aviation safety and ecological preservation.

Moreover, the suggested model-based design offers designers an approach to grasp the interconnections among diverse variables within complex systems, facilitating a comprehensive understanding of interactions at the element level and their subsequent impact on the entire system. Additionally, it aids designers in comprehending the emergent effects stemming from the intricate interplay of multiple interactions. This proposed method, model-based system design, and its application offer additional potential for computational automation, empowering designers to create adaptive policy frameworks. These policies would dynamically evolve in response to fluctuations in variable parameters, guided by shifts in the environment.

This real-time adaptive approach offers decision support to aviation industries, urban planning departments, and wildlife conservationists. It enables them to make more informed decisions at the nexus of wildlife conservation and the prevention of inadvertent hazards for flights. The result is a suite of intelligent solutions for mitigating the impacts of Artificial Lights at Night (ALAN) by designing effective public policies.

3. RESULTS

Our exploratory data analysis (EDA) focuses on temporal trends and the geographic distribution of bird strike occurrences, while our predictive modeling efforts provide a starting point for policymakers to make informed predictions of bird strikes given relevant environmental, temporal, and geographic predictors.

3.1 Exploratory Data Analysis (EDA) Findings

Our EDA focused on extracting patterns and trends from the FAA wildlife strike dataset. Below, we discuss the findings, as revealed through the figures below.

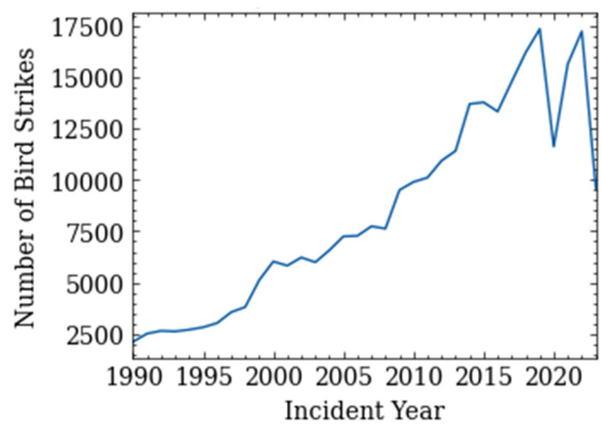

FIGURE 4: YEARLY BIRD STRIKES TREND (1990-2023)

In Figure 4, we observe an overall upward trend in bird strikes over the period from 1990 to 2023, revealing a notable increase in incidents except for 2020, a year with significantly reduced airport traffic due to the effects of COVID-19 on public transportation protocols. The overall upward trend underscores growing challenges in aviation safety and wildlife management, warranting further investigation into contributing factors such as environmental changes or aviation industry growth.

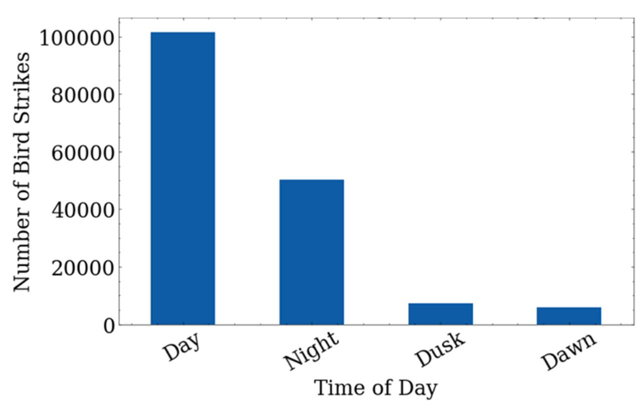

FIGURE 5: RECORDED BIRD STRIKES BY TIME OF DAY (1990-2023)

In Figure 5, we observe differences in voluntarily reported time-of-day data for bird strikes in the FAA database, with four discrete categories including “Day”, “Night”, “Dusk”, and “Dawn”. We observe that 61.5% of bird strikes occurred during the daytime, 30.4% occurred at night, and the remaining 8.1% occurred at dawn or dusk.

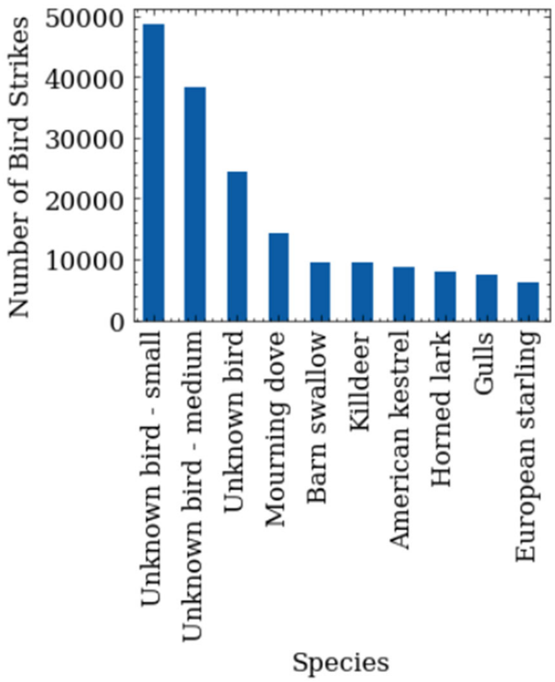

FIGURE 6: SPECIES-SPECIFIC ANALYSIS (TOP 10 SPECIES INVOLVED IN BIRD STRIKES

Through our species-specific analysis in Figure 6, we observe that certain bird species are more frequently involved in strikes. Three generic categories make up the top-represented values in the bar plot, namely “Unknown bird – small”, “Unknown bird – medium”, and “Unknown bird”. Following these are specific species including mourning dove, barn swallow, kildeer, and American kestrel. We observe that smaller bird species are most represented in this bar plot and are more commonly affected by aviation-related bird strikes.

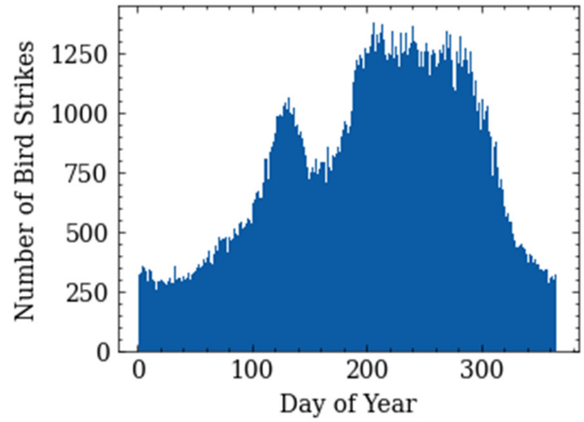

FIGURE 7: DISTRIBUTION OF BIRD STRIKE OCCURENCES BY DAY OF YEAR (1990-2023)

In Figure 7, time series analysis across the day of the year from 1990 to 2023 illustrates seasonal trends in bird strikes, with peaks observed during migration periods in spring and fall. This pattern reflects the natural behaviors of bird populations and their movement across regions, emphasizing the need for seasonal considerations in airport flight operations and wildlife management to mitigate the risk of bird strikes.

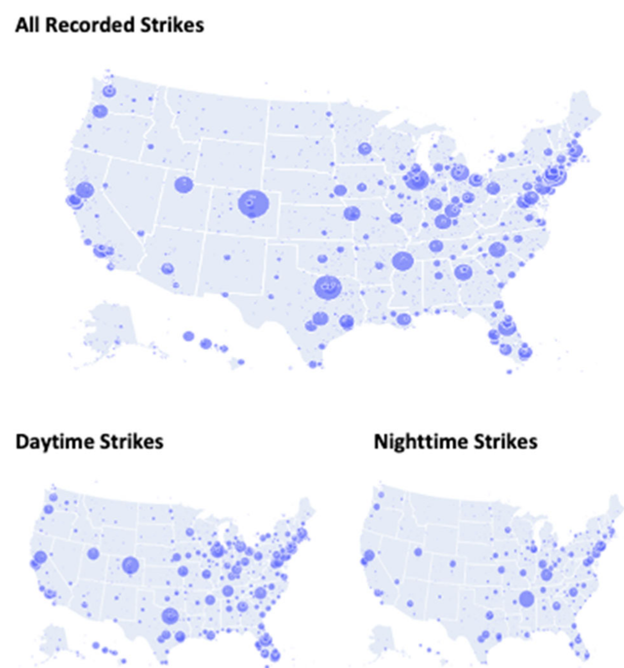

FIGURE 8: RECORDED BIRD STRIKE LOCATIONS IN THE UNITED STATES (1990-2023)

In Figure 8, we provide a geographic analysis of bird strikes, where we observe bird strike hotspots across the United States. Larger circles indicate a higher number of bird strikes at a given location. Airports situated near migration routes and urban centers are identified as particularly vulnerable. Moreover, we observe noteworthy differences between daytime and nighttime strike occurrences. This spatial analysis is critical for prioritizing areas for intervention and guiding the deployment of resources for bird strike prevention.

3.2 Correlation Analysis of Bird Strikes and Light Pollution

In this section, we present the findings from our correlation analysis, focusing on Kendall's τ and Spearman's ρ rank correlation coefficients to investigate the relationship between light pollution and bird strike incidents.

- Kendall's τ coefficient is calculated to be 0.33, with a p-value less than 0.01, indicating a statistically significant correlation that is not due to random chance.
- Spearman's ρ correlation coefficient is calculated to be 0.42, with a p-value less than 0.001, indicating a statistically significant correlation. This outcome corroborates the findings from Kendall's τ, highlighting a robust association between variables.

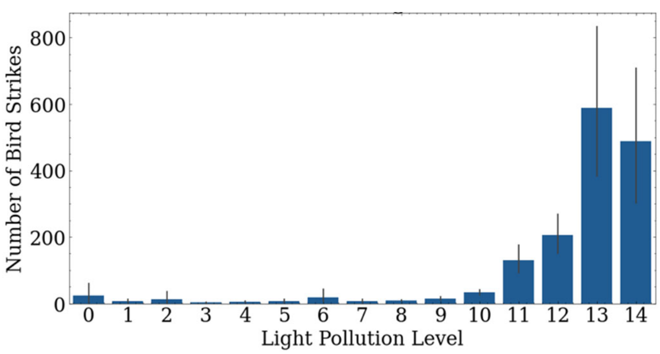

FIGURE 9: BAR PLOT OF LIGHT POLLUTION LEVELS AGAINST BIRD STRIKE COUNT

In Figure 9, we plot discrete light pollution level categories, ranging from 0 to 14, against strike records in the FAA wildlife strike database, observing overall higher strike counts as light pollution levels increase. These findings corroborate our correlation tests and suggest that light pollution is a significant factor influencing bird strike occurrences, with higher levels of light pollution associated with increased rates of these incidents.

3.3 Predictive Modeling Outcomes

In the predictive modeling segment of our paper, we discuss the outcomes of the decision tree regression model and its potential applicability in a public policy design context.

Model Performance Metrics

- **Mean Squared Error** (MSE): 4.64
- **Root Mean Squared Error** (RMSE): 2.15
- **Mean Absolute Error** (MAE): 1.20
- **R-squared** (R^2): 0.78

These metrics indicate the model's average predictive error and fit quality, with an R-squared value of 0.78 suggesting that the model explains approximately 78% of the variance in bird strikes.

K-folds Cross-validation

Using K-folds cross-validation, we evaluate the model across different subsets of the dataset to minimize the potential bias of a single train-test split. The average MSE and MAE across the folds were 4.58 and 1.21, respectively. These results closely align with the initial evaluation, suggesting consistent model performance across various data segments.

Monthly Performance Metrics

In Table 2, the average absolute error and squared error vary from month to month, showing differences in prediction accuracy over time. For example, January has an average absolute error of 0.67 and a squared error of 1.42, while May has slightly higher errors, with an average absolute error of 1.09 and a squared error of 3.99.

TABLE 2: MONTHLY AVERAGES OF PERFORMANCE METRICS IN TRAINING DATASET

Month	Average Absolute Error	Average Squared Error
January	0.67	1.42
February	0.65	1.25
March	0.77	1.64
April	0.98	2.92
May	1.09	3.99
June	0.98	3.12
July	1.15	4.11
August	1.16	3.87
September	1.17	4.26
October	1.13	4.20
November	0.97	3.04
December	0.73	1.65

Overall, across the entire dataset:

- The **average absolute error** is approximately 0.95, suggesting that, on average, model predictions deviate from the actual number of strikes by about 0.95 strikes.
- The **average squared error** is approximately 2.96, reflecting the average squared deviation of the predictions from the actual values, adjusted for the scale of the dataset.

Relevance to Public Policy Design

The decision tree regression model's predictions provide actionable insights for policymakers and conservation efforts. For instance, the model may help identify specific time frames and geographical areas with increased bird strike risks, allowing for pre-emptive action to mitigate these risks. These insights can guide the development of comprehensive public policies that balance the needs of urban development, aviation safety, and wildlife conservation.

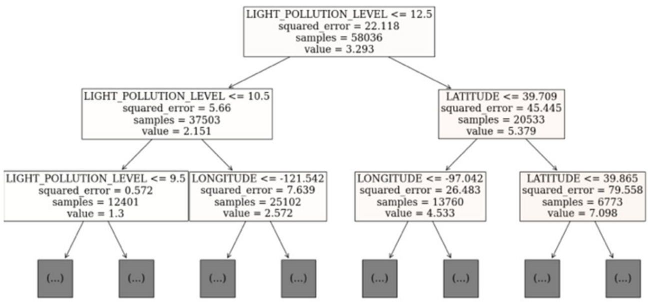

FIGURE 10: VISUAL OF DECISION TREE REGRESSION MODEL (FIRST THREE LEVELS)

In Figure 10, we observe that light pollution has the strongest predictive value in the model we use to predict bird strikes. The *value* component inside each leaf node (i.e., in the top node, value=3.293) represents the average (mean) of the target variable (number of bird strikes) for all the samples in the node. For visibility, the first three levels of the tree are presented in this figure.

We suggest that the predictive value of light pollution in this model further emphasizes the need for policies that address ALAN. Recommendations might include the adoption of bird-friendly lighting technologies, enforcement of lighting regulations during migration seasons, and the incorporation of predictive modeling into urban planning processes. Such policies could significantly contribute to reducing bird strike incidents, ultimately fostering safer aviation practices and promoting conservation efforts.

4. DISCUSSION

In this section, we interpret the results of our data analysis and predictive modeling efforts, discussing its applicability in public policy design, the potential limitations of our method, and directions for future work.

4.1 Results Interpretation

The findings from our investigation into the impact of Artificial Light at Night (ALAN) on bird strikes, underscored by predictive modeling, provide insights into the complexities of wildlife preservation within human-modified landscapes. By elucidating the relationship between ALAN and bird strikes, we aim to shed light on broader ecological and safety implications, offering a foundation for informed public policy and urban planning decisions.

Contextualizing within Aviation Safety and Urban Planning

Our analysis reveals a correlation between increased levels of light pollution and the incidence of bird strikes, which not only highlights the risks posed to avian populations but also underscores the safety and economic challenges facing the aviation industry. By mapping bird strike occurrences against light pollution levels, we have identified high-risk zones, which often correlate with urban areas and major flight paths. This suggests that mitigating the effects of ALAN could significantly enhance aviation safety by reducing the frequency of bird strikes.

Moreover, based on the temporal and geographic patterns discerned through our EDA, we emphasize the necessity of considering bird migration dynamics in urban planning and aviation safety strategies. The peaks in bird strikes during migration seasons underscore the importance of temporal adjustments in lighting policies, potentially dimming or redirecting lights during these critical periods to minimize disorientation among migratory birds.

Practical Applications for Public Policy Design

The model-based system design that leverages the capabilities of predictive modeling is a potential tool for policymakers and urban planners, offering the capability to forecast bird strike occurrences at a given time and location with a considerable degree of accuracy. This approach enables designers to advance principles of systems engineering and design through model-based system design to design effective public policies. By integrating various data sources, including the FAA Wildlife Strike Database, a light pollution GIS map, and BirdCast migration forecasts, we provide a starting point for selecting relevant predictors contributing to bird strikes. This anchors in the idea of information model for social problems that focus on effective utilization of multiple information sources and integrating them that enables designers to understand the cause of emergent behavior of the system resulting in fundamental developments in designing systems for social problems. This integrated approach facilitates the design of targeted mitigation strategies, such as:

- Incorporating predictive modeling into urban planning processes to implement mitigation efforts at high-risk locations and timeframes.
- Adjusting urban lighting schemes during migration periods to reduce attraction or disorientation of migratory birds.
- Planning new developments or modifying existing structures to mitigate the impact of light pollution on surrounding ecosystems.

These practical applications highlight the relevance of our findings to the development of public policies that balance human needs with wildlife conservation. By informing such policies with predictive modeling, we can proactively address the challenges posed by ALAN, enhancing both aviation safety and biodiversity conservation.

Summary

The implications of our research extend beyond the specific issue of bird strikes, touching on broader concerns related to urban development, ecological preservation, and public safety. Our findings serve as a call to action for integrating ecological considerations into the design and implementation of lighting technologies, urban planning practices, and aviation safety protocols.

4.2 Paper Limitations

In this paper, we contribute new insights into the relationship between Artificial Light at Night (ALAN) and bird strikes, utilizing predictive modeling to inform public policy and conservation strategies. However, it is crucial to acknowledge the limitations that accompany our findings to pave the way for future research and application enhancements.

Analysis of General Light Pollution Rather Than Specific Light Sources

One primary limitation lies in our analysis of general light pollution levels, which does not discriminate between different types of lighting sources. Specifically, our GIS light pollution map captures light pollution observed from satellite data, which includes artificial lighting sources as well as industrial sources like flaring from oil and gas sites [17]. This means that our correlation analysis and predictive model do not incorporate ALAN as a variable directly, but instead use general satellite-observed light pollution to approximate its impact. Future research could improve upon our model by controlling for other light pollution sources to isolate the impact of ALAN more directly.

Limited Feature Selection in Predictive Model

Our predictive model, while robust, is constrained by the variables included. Factors such as altitude and airport traffic volume could also significantly influence bird strike occurrences. The inclusion of these additional predictors might enhance the model's accuracy and applicability. Future research should consider integrating these and other relevant variables to construct a more comprehensive model that captures the complexity of factors influencing bird strikes.

Other Limitations and Areas for Improvement

- Spatial and Temporal Resolution: The granularity of data used in our analysis might not capture variations in light pollution (2020 data) or bird migration patterns (1/day forecast data) over the time period of bird strikes we studied (1990-2023). Higher-resolution data could offer more precise insights into the spatial and temporal dynamics of bird strikes.
- Voluntary Reporting Bias: Reliance on the FAA Wildlife Strike Database, which is based on voluntary reporting, may introduce bias. Not all bird strikes are reported, especially those that do not result in significant damage. Efforts to incorporate more systematic data collection methods could reduce this bias.
- Generalizability Across Regions: Our study focuses on the United States, and while the model shows promise, its applicability to other geographical regions remains to be tested. Different migratory patterns, species diversity, and urban lighting standards could affect the model's relevance in other contexts.

Summary

Acknowledging these limitations highlights areas for further exploration and improvement. Each limitation presents an opportunity for advancing our understanding of ALAN's impact on bird strikes and refining our approach to mitigating this issue. Future research that addresses these limitations can build on the foundation laid by this study, enhancing the effectiveness of public policy and conservation efforts aimed at reducing the negative consequences of artificial lighting on wildlife.

4.3 Policy and Future Research Recommendations

Our findings offer insights with implications for public policy, urban planning, and conservation strategies. To maximize the utility and applicability of this research, we aim to extend these insights into actionable recommendations for policymakers and researchers. In this section, we outline key recommendations for both policy development and future research directions.

Policy Recommendations

1. **Lighting regulation and standards:** Through our correlation analysis and predictive modeling in Section 3, we identify a significant relationship between light pollution levels and bird strike occurrences; therefore, we recommend the development and enforcement of lighting standards that specifically aim to minimize ALAN's impact on wildlife. Adopting bird-friendly lighting technologies could be a critical step in mitigating bird strikes in identified high-risk areas (as mapped in Figure 5).
2. **Urban planning and design:** In our analysis, we identify urban areas as zones of elevated bird strike risk due to light pollution (Section 3.1 and Figure 5). In response, urban planners and developers can integrate considerations of ALAN and its effects on wildlife into the planning and development process. This could include designing buildings and lighting systems that reduce light spill and glare and turning off or dimming lights during peak migration periods. Our findings, particularly the spatial analysis highlighting bird strike hotspots, may be helpful in guiding these efforts. Moreover, leveraging predictive modeling can inform targeted mitigation efforts at high-risk locations and timeframes.
3. **Public awareness and engagement:** The significant impact of ALAN on increasing the incidence of bird strikes, as evidenced in our findings, underscores the need for public awareness campaigns. These campaigns can educate citizens and stakeholders about the consequences of ALAN on biodiversity and bird migration, fostering community involvement in conservation efforts.

Future Research Recommendations

1. **Detailed analysis of ALAN as a light source:** In our correlation analysis and predictive model (Sections 3.2 and 3.3), we use satellite-observed light pollution levels to approximate the impact of ALAN on bird strikes. Future research could improve upon our model by controlling for other sources of light pollution in satellite data, such as industrial sources, to isolate the impact of ALAN more directly.

2. **Expansion of predictive modeling variables:** Incorporating additional variables into predictive models, such as altitude and air traffic data, could enhance the model's accuracy and applicability. Exploring machine learning techniques may uncover complex interactions between the variables that are not readily apparent.
3. **Cross-regional and longitudinal studies:** Given the geographic and temporal patterns of bird strikes identified in our EDA (Section 3.1), expanding the research to include different geographic regions and conducting longitudinal studies over extended periods can help validate the model's generalizability and adaptability to changing environmental and anthropogenic conditions.
4. **Impact assessment and policy evaluation:** Reflecting on our policy recommendations, there is a need for empirical studies assessing the effectiveness of implemented policies and mitigation strategies. This might involve monitoring bird strike incidents over time to evaluate the impact of changes in lighting practices and urban development on bird populations.

5. CLOSING REMARKS

In this paper, we aim to uncover relationships between Artificial Light at Night (ALAN), bird strikes, and the implications for public policy and urban planning. Through exploratory data analysis, correlation analysis, and the development of a predictive model, we have illuminated the significant impact of ALAN on increasing the incidence of bird strikes, particularly in areas with high levels of light pollution and during critical migration periods. Moreover, we have taken strides toward addressing the previously identified gaps in research.

Summary of Significant Results

Our findings confirm that ALAN is a contributing factor to bird strikes, with clear correlations between increased light pollution levels and the frequency of these incidents. The predictive model developed as part of this research offers a valuable tool for forecasting bird strike occurrences at any given time and location in the United States, enabling policymakers and conservationists to implement targeted mitigation strategies. By integrating data from the FAA Wildlife Strike Database, a light pollution GIS map, and BirdCast migration forecasts, we have demonstrated the potential of predictive modeling in informing more effective and proactive approaches to wildlife conservation and aviation safety.

Implications for Urban Planning and Lighting Design

The insights gained from our research have implications for urban planning and lighting design. By adopting bird-friendly lighting technologies and incorporating considerations of ALAN into the planning process, urban developers can play a critical role in reducing the negative impacts of artificial lighting on avian populations. Furthermore, the development and enforcement of lighting standards that minimize unnecessary exposure to ALAN can significantly contribute to the preservation of biodiversity in urban environments. Thus, in summary, we propose an approach for system designers to design public policies through model-based system design by allowing them to:

1. Analyze the interaction between component-level variables and assess its impact on the emergent behavior of the system.
2. Analyze interactions between transdisciplinary variables comprising diverse social and technical domains.
3. Utilize model-based system design for better-informed decision-making.
4. Investigate and discern the primary variables with the most significant impact on bird strikes.

Looking Ahead

We seek to mitigate the impact of artificial lighting on wildlife through informed urban design and decision-making. By adopting an informed and proactive approach to public policy design, we can mitigate the adverse effects of ALAN, fostering a safer and more sustainable coexistence between human and avian populations. Further, we envision designing adaptive systems that support self-adaptive public policies enabling decision makers to make better informed decisions pivoted at the integration of preserving wildlife, preventing flight accidents and informed urban planning for a sustainable tomorrow.

We are happy to share our data with those who may wish to use it; to obtain the data, please contact the first author.

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