Customized Implementation of Advanced Safety Sensors for Small Motor Carriers through Vehicle Inspection and Crash Data Analytics

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ABSTRACT

Effective deployment of vehicle safety technologies (e.g., brake, tire, and light sensors) is essential for reducing fatal crashes and economic losses in fleet operations. In 2021, small motor carriers (<= 30 vehicles), which own only 8% of vehicles involved in crashes, were responsible for 76% of crashes resulting in fatalities. However, effective deployment of safety sensors for small carriers is challenging due to the lack of knowledge about how to plan the use of safety sensors subject to the budget limits of each carrier while fully considering their operational contexts. Navigating policy-level decision-making with scant vehicular and contextual data poses a critical challenge to conducting thorough analyses for providing tailored sensor adoption strategies for small fleets. This research delves into analyzing vehicle component issues within various small motor carriers, drawing insights from a national motor carrier performance dataset and a local vehicle inspection dataset to highlight the importance of customization of safety sensors and region-level regulation for sensor deployment. Considering age and region diversity, the results show that brake and lighting sensors are critical for vehicles aged 24 to 29 in Regions 1 and 2, with violation probabilities of 0.38 and 0.21, respectively. Also, vehicles aged 6 to 23 in Region 6 could benefit from all three sensor types. Such findings could help optimize budget allocation without requiring comprehensive technology acquisition across all fleet vehicles. In addition, similar outcomes inform policymakers and manufacturers about technology management and regulation to ensure the effectiveness of safety sensors in the automotive industry.

INTRODUCTION

Deploying vehicle safety technologies in fleet operations, specifically in the context of small motor carriers, is critical in the demand to reduce fatal crashes and economic losses. In 2021, small motor carriers, owning a mere 8% of all vehicles involved in crashes, were disproportionately responsible for 76% of crashes resulting in fatalities and 50% of all crashes in the United States. These staggering statistics, derived from the carrier-level crash analysis, underline a systemic issue within the small motor carrier industry, where motor carrier size significantly influences safety outcomes.

A significant development in the regulatory landscape was the mandate implemented by the U.S. Department of Transportation on December 18, 2017, requiring the use of Electronic Logging Devices (ELDs) (Federal Register 2015). These devices, aimed at reducing driver fatigue by enforcing work-hour restrictions, were expected to decrease accident rates. However, research indicates that while compliance with hours-of-service regulations increased, especially among small carriers, accidents did not decrease correspondingly. For small carriers, accident counts remained steady or even increased, possibly due to increased unsafe driving behaviors, such as speeding, potentially a response to the productivity losses induced by the ELD mandate. (Scott et al. 2019). The analysis regarding the impact of ELDs on accident rates raises a critical question: *Why is the small motor carrier segment disproportionately affected by safety challenges, and what can be done to address these issues*?

According to (FMCSA 2006), defective brakes contribute to 29% of fatal and injury crashes involving large trucks and tire problems account for 6% of these crashes. Moreover, in the case of light vehicles, tire-related and brake-related crashes contribute to 43.3% and 25%, respectively (NHTSA 2008). Furthermore, based on the national data analyses, the most frequent inspection violations in crashes were related to lighting at 15.7%, brake at 15.6%, and tire at 7.3%. In light of these statistics, this study aims to identify crash patterns and safety violations, particularly related to brake, tire, or lighting systems, by analyzing vehicle age and region types data. The goal is to pinpoint which vehicle age groups and regions, in combination, exhibit higher incidences of safety violations and crashes. This analysis is crucial, as defective brakes, improper tire maintenance, and lighting issues are predominant vehicle-related factors in commercial vehicle crashes.

Emerging brake, tire pressure, and lighting performance sensors hold promise in addressing these issues. However, challenges such as sensor durability, accurate data transmission, and maintenance personnel training are notable obstacles. These challenges clarify the need for systems that are not only technologically advanced but also user-friendly and adaptable to the specific operational frameworks of small carriers.

In summary, this research identifies a critical gap in the motor carrier industry's safety management, particularly for small fleets. By analyzing crash and inspection violation data in conjunction with the effectiveness of existing brake, tire, and lighting monitoring sensors, this research reveals the relationships between 1) *region and vehicle age and crash probabilities*, 2) *region and vehicle age and the probability of lighting, brake, and tire inspection violation that involved in crashes; 3) special risks faced by motor carriers in different regions for different vehicles*. Exploring these relationships provides actionable insights into enhancing safety sensors' adoption and policy decisions tailored to small motor carriers' needs. The subsequent sections of this study will present the literature review, methodology, results, discussion, and conclusion, respectively, with the ultimate goal of enhancing the safety performance of small motor carriers.

LITERATURE REVIEW

The motor carrier industry, a critical component of the global supply chain, has seen significant advancements in safety technologies. However, small motor carriers (defined as those with $\leqslant 30$ vehicles) face unique challenges in adopting these technologies, impacting their safety performance and overall compliance with regulations. Some reviewed literature highlights the challenges faced by small motor carriers in adopting safety technologies and the need for tailored strategies. This study analyzes the vehicle critical component issues to bridge the knowledge gap on safety sensor adoption strategies for small motor carriers based on their vehicles' age and the region they operate in.

Larger carriers are able to invest substantially in safety technologies and personnel (Miller 2020). In contrast, small carriers often struggle with limited budgets and safety cultures, hindering their ability to adopt advanced safety technologies (Goettee et al. 2010). This gap in technology adoption is not merely a matter of financial constraints but also reflects a lack of tailored safety management strategies suitable for small-scale operations (Bergoffen et al. 2012). In addition, smaller firms often lag to adopt new technologies, primarily due to cost considerations (Cantor et al. 2006). Furthermore, smaller carriers often have higher crash rates (Cantor et al. 2014), which can be attributed to less strict safety practices and lower technology adoption rates, constraints in human and physical capital resources, lack of investment in scientific knowledge, and fewer vehicle maintenance schedules (Cantor et al. 2016).

The necessity for customized safety technology use strategies for small motor carriers is an emerging theme in the literature. Small carriers operate under significantly different conditions compared to their larger counterparts, necessitating tailored approaches to safety sensor adoption. Previous research collectively suggests that one-size-fits-all solutions often fall short of addressing the unique challenges faced by small fleets. These small carriers require strategies that are not only cost-effective but also align with their operational realities. This study aims to identify effective sensor adoption to enhance the safety performance of small motor carriers.

METHODOLOGY

This study collected and analyzed vehicle inspection and crash datasets to capture how the inspection outcomes can serve as indicators of safety-critical sensors for vehicles widely used by small motor carriers, and what regions and environments of vehicle operations need customized safety sensor use. The authors collected a national motor carrier performance dataset with crash and vehicle information, and a local vehicle inspection dataset with vehicle mileage and detailed inspection results compared with the national dataset. A summary of the data content used in this research is provided in

Table *1*.

Table 1. Data source summary

Source	Local Vehicle Inspection Dataset	National Crash and Inspection Violation Datasets
Description	Annual vehicle inspection records from Pennsylvania	Annual crash report and roadside inspection violation records of the United States
Coverage Period	2005-2021	2017-2021
Types of Data Collected	VIN, make, model, model year, carrier location and ZIP code, component inspection outcomes, odometer readings	VIN, make, model, model year, inspection violation category, DOT of the motor carriers, carrier location

The authors then employed an analytical approach, focusing on the relationship between vehicle age, regional factors, and crash incidences in Pennsylvania. The methodology encompassed data preprocessing, probabilistic analysis, and data visualization, using a combination of automated decoding, data grouping, and statistical calculations.

Figure 1 illustrates the overall research process.

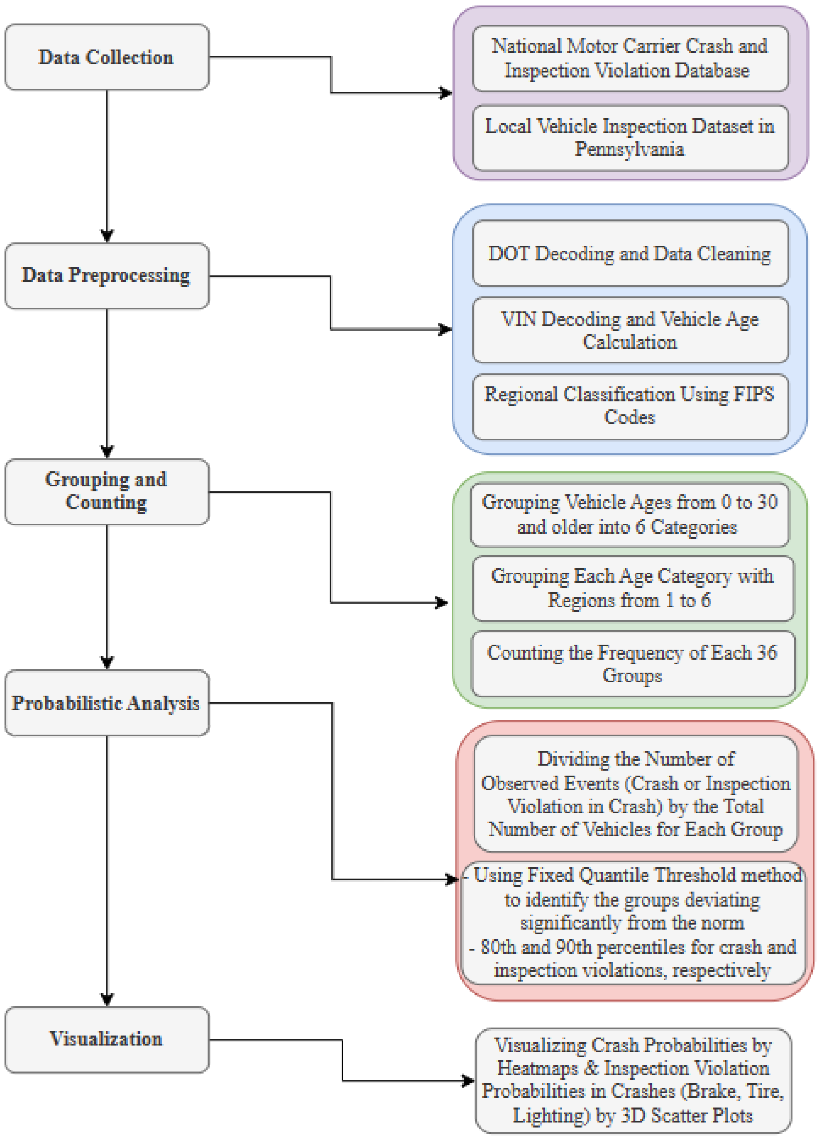

Figure 1. Research process designation

Decoding the Department of Transportation (DOT) numbers was the initial step to ascertain the power units of each motor carrier. This step was crucial to support the claims regarding the safety issues made by small fleets. **Error! Reference source not found.** shows the process of comparing the safety performance of small carriers with large and mid-size carriers.

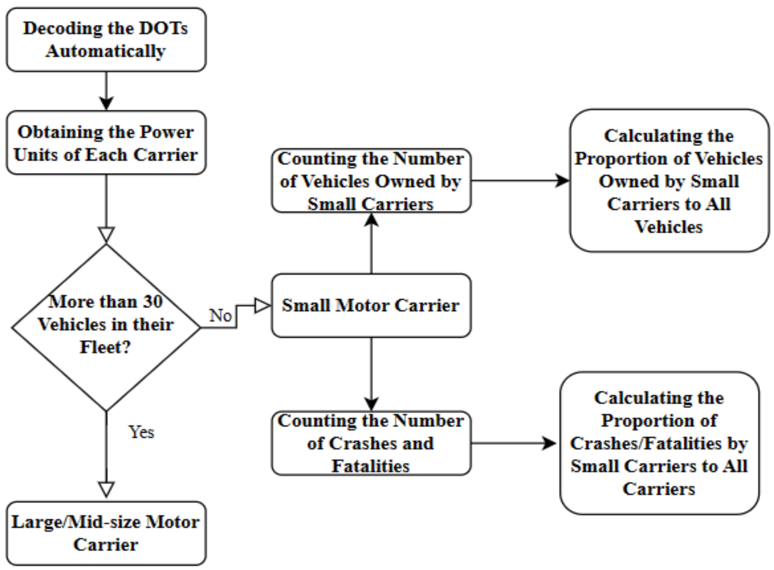

Figure 2. Separating motor carriers based on their fleet size and comparing their safety performance

The authors used a region classification scheme provided by the Center for Disease Control's National Center for Health Statistics ((NCHS 2017) to classify the carrier regions based on population density, ranging from large central metros (coded as 1) to non-core areas (coded as 6). This classification was derived from state and county codes in the datasets.

Figure *3* shows the distribution of different region types in Pennsylvania.

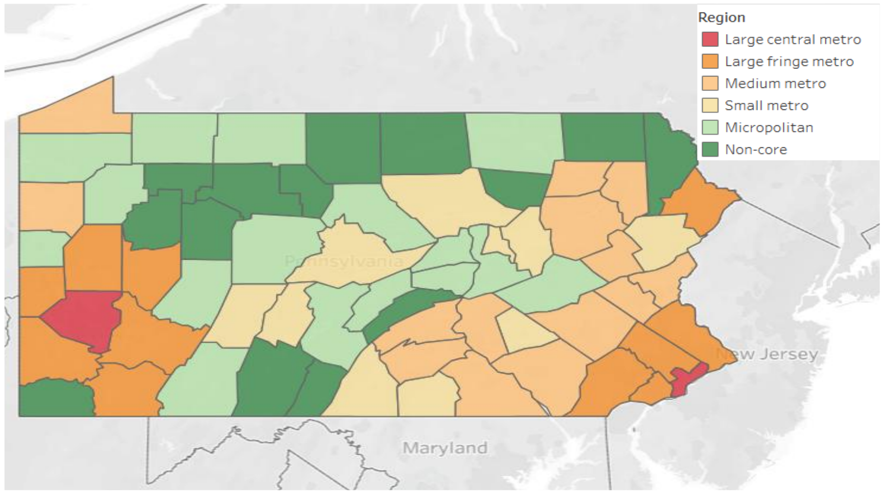

Figure 3. Region classification of Pennsylvania based on the population density

Then, the authors calculated the crash and inspection violations (for brake, tire, and lighting) probabilities using the equation below. The local vehicle inspection source for Pennsylvania is considered as the total population, and only Pennsylvania-specific records are used from the national datasets, representing the observed events.

$$\mathrm{P}(E) = \frac{Number\ of\ observed\ events\ (crashes\ or\ violations\ within\ each\ group)}{Total\ number\ of\ opportunities\ \ (total\ vehicles\ in\ each\ group)}$$

In this analysis, the authors applied the Fixed Quantile Threshold method to define high-risk groups based on crash probabilities and inspection violation probabilities, identifying significant deviations from the norm and typical patterns. Thresholds set at the 80th and 90th percentiles distinguished groups with high probabilities—exceeding 5% for crashes, 37% for brakes, 23% for tires, and 19% for lighting violations—highlighting areas in need of urgent intervention.

RESULTS

Over the five years from 2017 to 2021, the heatmaps in Figure 4 illustrate a varying landscape of crash probabilities across different age groups and regions in Pennsylvania, shedding light on critical trends that inform safety sensor deployment strategies.

The heatmaps depicting crash probabilities from 2017 to 2021 in Figure 4 suggest that Region 6 has consistently been a focal point for crashes across multiple age groups, particularly for those aged 18 to 29. However, in 2020 and 2021, this trend does not hold as strongly, indicating a potential shift in crash probabilities towards younger vehicles. The data supports the need for region-specific and age-targeted safety sensor deployments.

In addition, based on motor-carrier level analysis for crashes in 2021, the authors found that the rate of crashes per power unit for small motor carriers in Region 6 is 11%, while for larger carriers this rate is 1%. The result suggests that although small carriers own much fewer vehicles in comparison to larger carriers, they contribute to more crashes in non-core areas of Pennsylvania.

The analysis of brake violation probabilities in crashes across various regions and age groups from 2017 to 2021, as demonstrated in Figure 5, shows that vehicles in Region 6, aged 6 to 23 exhibit higher probabilities of brake violations. This outcome is closely followed by vehicles within the 24 to 29 age range in Region 1 and the 18 to 23 age group in Region 3, with brake violation probabilities of 0.38 and 0.37, respectively. Similarly, Figure 6, which indicates the probabilities of tire violations in crashes during the same period, illustrates that vehicles aged 12 to 17 in Region 6 have the highest risk with a probability of 0.36, followed by the oldest vehicles, those above 30 years old, in Region 1 with a probability of 0.3. Additionally, vehicles aged 6 to 11 and 18 to 23 in Region 6 are other critical groups in terms of tire sensor adoption. Moreover, lighting violation probabilities in crashes, as outlined in Figure 7, suggest that vehicles aged 6 to 23 in Region 6 with average lighting violation probabilities of 0.24, 0.23, and 0.20, and vehicles aged 24 to 29 in Region 2 with violation probability of 0.21, should be prioritized for lighting sensor implementation.

Overall, the patterns reveal that Region 6, particularly for vehicles aged 6 to 23, stands out as a critical risk area for all three types of inspection violations. This consistent finding emphasizes the need for targeted adoption of brake, tire, and lighting sensors for these specific age groups in non-core areas to enhance vehicular safety and compliance.

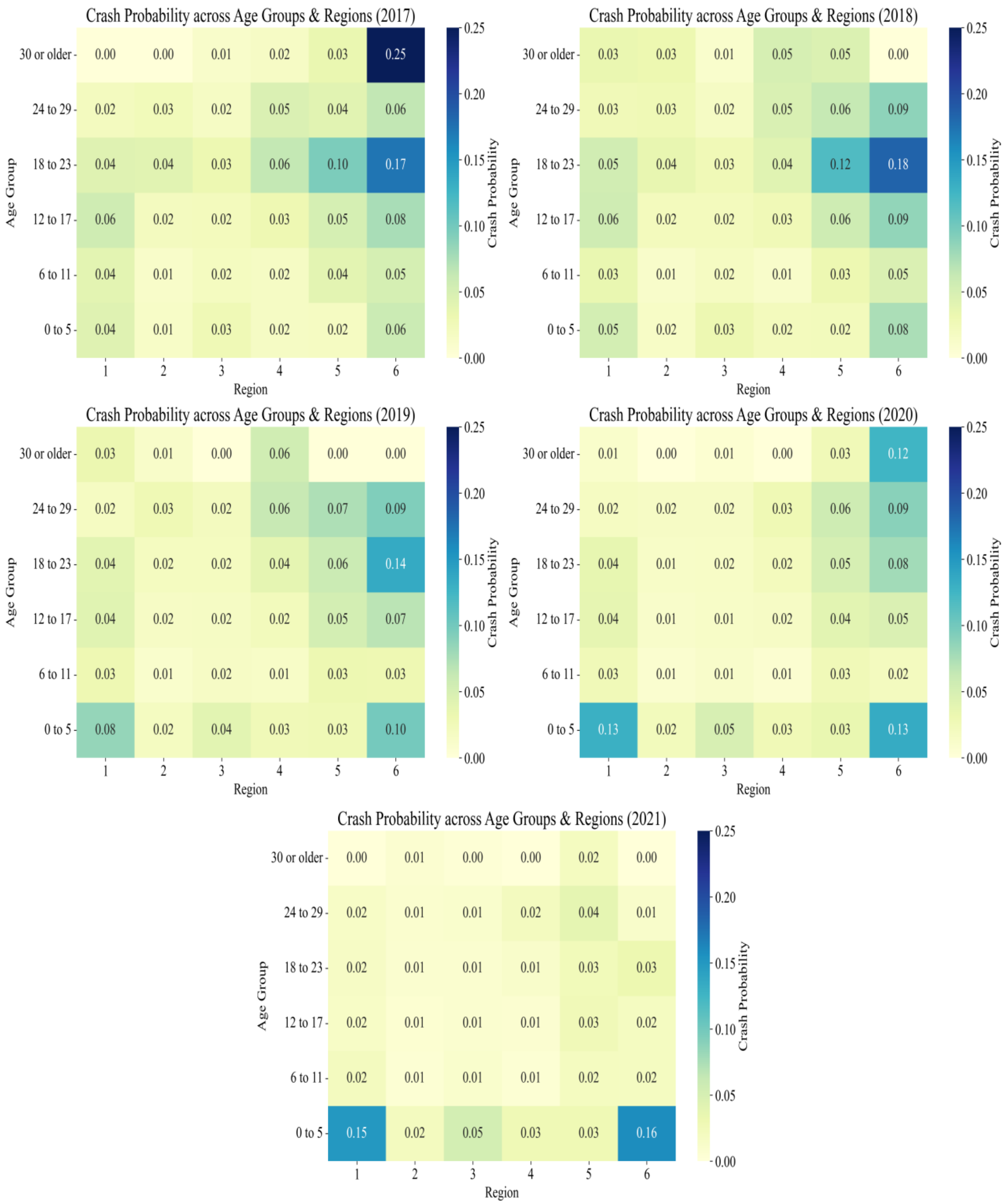

Figure 4. Crash probabilities in different age groups and regions from 2017 to 2021

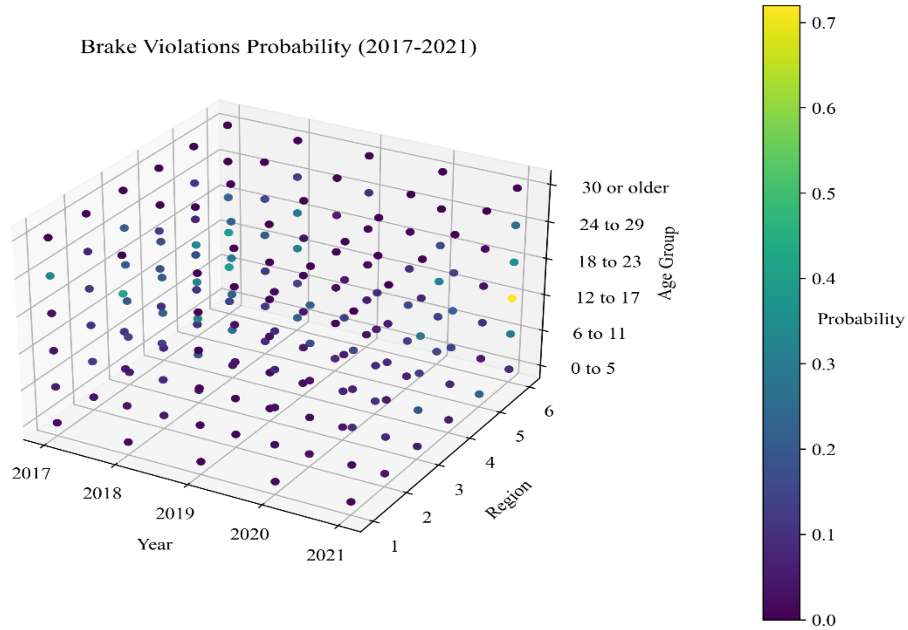

Figure 5. Probabilities of brake violations in different age groups and regions in crashes from 2017 to 2021

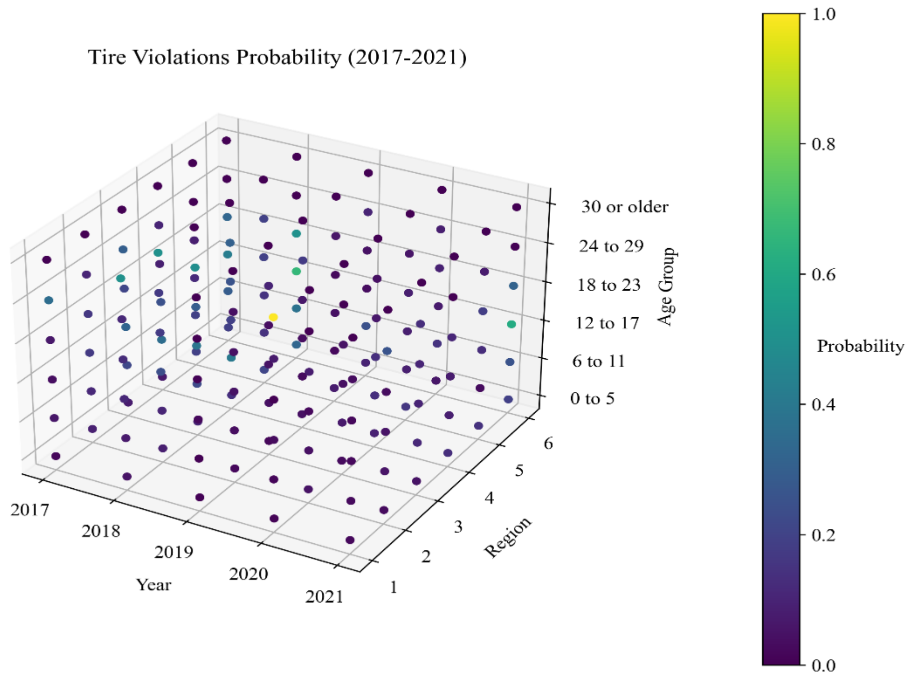

Figure 6. Probabilities of tire violations in different age groups and regions in crashes from 2017 to 2021

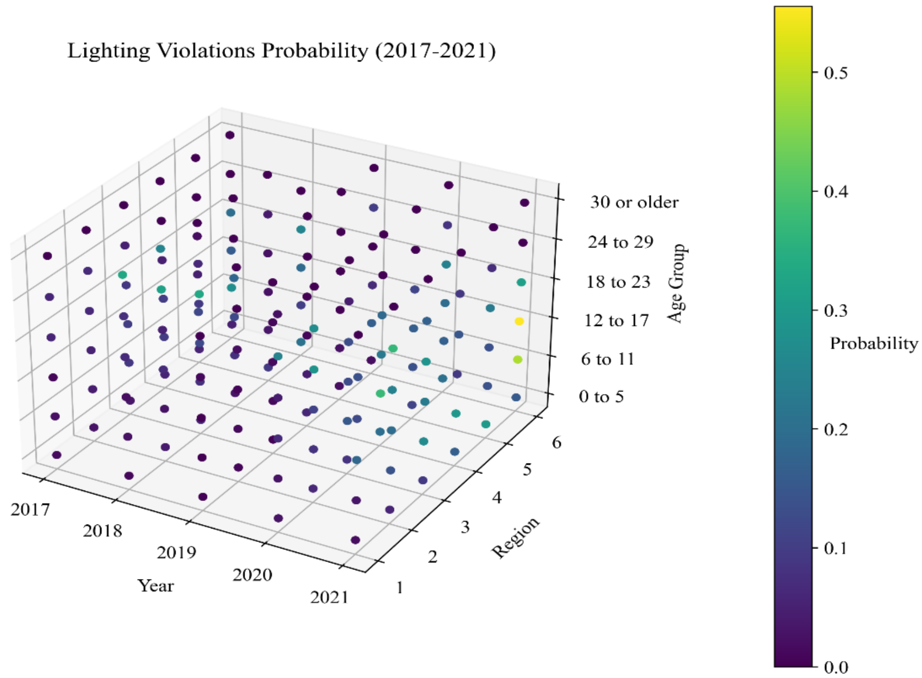

Figure 7. Probabilities of lighting violations in different age groups and regions in crashes from 2017 to 2021

DISCUSSION

Future studies will analyze patterns in inspection violations alongside crash data over multiple years to determine if there is a consistent correlation over time. The research will primarily focus on whether the frequency of past violations can predict future crash rates, and how these patterns vary with vehicle age and across different regions. Time-series analysis will be the main tool used to identify trends and similarities in the data year after year. The goal is to construct a process model that captures and explains the relationship between inspection violations and crashes, which could be tested in various regional contexts. Successful replication of the model in different settings would reinforce its value in "Explainable AI," enhancing our understanding of the factors contributing to road safety outcomes.

CONCLUSION

This research embarked on an analytical exploration to understand the probabilities of brake, tire, and lighting inspection violations in crashes, focusing on vehicle age and region type. The goal was to help small motor carriers allocate their resources efficiently based on their fleets' needs.

From 2017 to 2021, this study observed a fluctuating landscape of crash probabilities, with specific age groups and regions exhibiting higher risks. Region 6, where small motor carriers predominate, accounting for 83% of operations, consistently emerged as a high-risk area, particularly for vehicles aged 18 to 29 years. Surprisingly, younger vehicles (0 to 5 years) showed higher probabilities of crashes in recent years, a finding that challenges conventional expectations. This study highlights that those vehicles aged 6 to 23 in Region 6 would benefit from the adoption of all three brake, tire, and lighting sensors. The results suggest a need for brake and lighting sensors in vehicles aged 24 to 29 years in Regions 1 and 2, respectively, and tire sensors in vehicles aged

30 and above in Region 1. These targeted interventions could provide small motor carriers with a strategic approach to invest in safety sensors that align with the needs of their vehicle fleets. Future research will investigate the correlation between inspection violations and crash trends through time-series analysis, further refining the strategies to improve the safety performance of small carriers.

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