

Smart Road Safety Enhancement System Using OpenCV

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Abstract—Traffic accidents on the road are a fatal worldwide issue; especially on the high-speed extra-urban freeways, bad conditions, and driver carelessness of drivers are major contributors of accidents. This project is a detailed safety analysis system with an aim of reducing the severity and frequency of accidents. It combines the statistical analysis of the Italian historical data on accidents at the Tangenziale freeways with field experiment data of eye-tracking, and vehicle exchange data to determine the primary risk behavioral factors, such as distraction and lane positioning. In addition, the system itself entails the adoption of a modular pothole detection system based on a YOLOv8 model to monitor real-time infrastructure through the prism of a web application developed using Django. The measurement of these effects in terms of autonomous automobile navigation and proactive intervention in high-risk areas, by synergistically integrating infrastructure analytics and behavioral research, allows municipal authorities to act upon the insights given by the system, and thus provides a long-term goal of smarter, safer road infrastructure.

Keywords—Road Safety, Accident Prevention, Pothole Detection, Driver Behavior, Freeway Risk, Infrastructure Monitoring, Smart Cities.

I. INTRODUCTION

Accidents on the roads present one of the most acute problems in the sphere of global public health and safety as all millions of people every year lose their lives and social and economic costs become out of this proportion. Although urban settings have their own unique sets of issues and problems, extra-urban freeways are especially unsafe because of the combination of an established high speed with extended traveler uniformity and severe infrastructure circumstances. On such roads with large carrying capacity, even minor failure of attention or a misfortune road tragedy such as a pothole can be catastrophic and may also result in loss of life. Road safety using the traditional approach which is reactive and is used to resolve the problem when accidents are reported is no longer adequate. There is a sense of urgency which has to be addressed proactively and integrated to investigate the risk factors holistically and to incorporate the ability to be pre-emptive in taking interventions to protect all road users.

The genesis of this project lies in the realization that there is an acute gap in the prevailing road safety practices, i.e. the lack of equality between the attention provided to human factors, and infrastructure integrity. Although both fields have considerable amount of research available they tend to work in silos. Behavior research is very detailed in its description of driver distraction and error but settings aside the actual physical environment of the road up to which these errors occur and perhaps aggravate them. On the other hand, infrastructure evaluation would be able to detect a poor road surface, whilst not entirely taking into account how the action of vehicle operators, including visual scan patterns or reaction time, combine with hazards. In this work, the author assumes that a syntactic approach, which connects the study of human behavior with the surveillance of physical infrastructure, is central to the real step forward in preventing accidents.

The study has its basis on a two-pronged investigation framework. To begin with, we performed strict statistical evaluation of the traditional accident statistics of a typical extra-urban freeway, the Italian Tangenziale. This data analysis method was useful to discover macroscopic trends and correlations, identify high-frequency location points of incidents and circumstantial elements like the intensity of traffic jams and weather patterns. Second, to explore the microlevel, people-based factors behind such statistics, we conducted specific field experiments. Under different traffic conditions, using eye-tracking facilities and vehicle-on-the-road kinematic data collection methods, we collected detailed, real-world information about attentional foci of drivers, steering corrections, braking patterns, and others. Combining the two factors pointed to major risk factors such as the presence of visual distraction and the imperative role of the correct positioning on lane.

The project has designed and implemented a SMART Road Safety Enhancement system so as to translate these analytical insights into the actual safety improvements. One of the fundamental pieces of this system is an automatic pothole detection unit, which is based on a machine learning framework based on the YOLOv8 architecture. The visual information is processed by this system that will determine and provide a geo-location of the flaw on the road surface to

use them as constant surveillance of infrastructure. The electronic stack is merged into the platform aimed to be accessed by users and allows visualizing the data to be given to the municipal officials and provide action reports and hazard maps through the use of the Django-based web application.

The final aim of such an integrated system is to establish a safety feedback loop. The platform is able to predict and accordingly warn high-risk areas by matching the real-time infrastructure data provided by the pothole detector system with the behavioral risk models that have been derived historically and experimentally. It empowers different actors: It offers autonomous vehicle systems and drivers with critical data that ensure safer navigation and also offers municipalities with an evidence-based prioritization system regarding roadways and specific safety interventions, such as dynamic signage or changes in speed limit. In the end, this project is included in the general perspective of the smart city mobility where the convergence of data analytics, behavioral science, and machine learning can create a way to achieve a major decrease in road accidents and the improvement of collective well-being.

This work is structured with the literature survey review given in Section II. Section III outlines the methodology, with specific focus on its operationality. Results and discussions are in Section IV. Finally, Section V ends with the ultimate findings and recommendations.

II. LITERATURE SURVEY

The constant problem of road traffic accidents on earth has promoted numerous researches concerning their cause and prevention measures. The importance of effective countermeasures is evident in the fact that the world health organization has repeatedly noted road traffic injuries as an important killer especially among the young adults. In extra-urban freeways the distribution of risks is particular, by virtue of high operating speeds, that exponentially increase seriousness of collisions, and long monotony, which may cause fatigue and inattention to drivers. The financial, social cost of such incidents such as medical treatment, economic losses, and human misery is overwhelming and that is why both the government and corporates are investing in safety technologies. This general situation determines the necessity of coordinated solutions that transcend [6] measures of reaction to the action of comprehensive, data-based prevention systems that are the background rationale of the current analysis.

A large amount of literature has been directed to the two main pillars of accident causation, namely human behavior and road infrastructure. Distraction and driver inattention are two rather well-documented leading factors in the behavioral sphere. Quantitative research on the measure by use of naturalistic driving and eye-tracking procedures has demonstrated that both visual and cognitive distractions have a massive negative effect on reaction time and lane-keeping capability [7] [8]. Moreover, vehicle kinematic data was also useful to identify erratic driving before accidents, and associate certain accelerating and steering actions to aggressive driving or sleepy driving [9]. At the same time, the contribution of the infrastructure is thoroughly studied. The studies have strongly proved a reduction in the quality of the road surface, including potholes and cracks, and the occurrence of accidents, including loss-of control and run-off-

road accidents [10] [11]. The combination of such factors is vitally important: an inattentive driver will have lower chances of negotiating a sudden pothole, which increases the danger.

Automated detection systems have become a major research topic in a bid to solve the infrastructure degradation problem. The old fashioned manual visual inspection systems are being phased out of existence by the computer vision and deep learning approaches at a phenomenally high rate because these methods are more efficient and scalable. Convolutional Neural Networks, or CNNs, are now commonly used as image-based defect recognition systems, with more popular models such as YOLO (You Only Look Once), and Faster R-CNN easily recognized as fast and effective at detecting road damage in both video and images [12] [13]. Websites such as Roboflow Universe have made this development by making downloadable, large and annotated datasets to train such models, improving development and benchmarking [14]. These advances in technology are the direct technical antecedent of the pothole detector module that we propose in our system, and it is clear how these technical advances will result in the development of automated, real time monitoring of the infrastructure.

The last line of the pertinent literature is the incorporation of these incompatible pots of data into harmonious security structures. There is the idea of Smart Cities which supports the idea of applying IoT, data analysis and connectivity to enhance city services, including transportation [15]. The idea of centralizing road condition and traffic data to manage the municipal assets is offered in several studies, which allow to prioritize the maintenance work more efficiently [16]. Nevertheless, there is one perceived gap that will be the seamless integration of this infrastructure data with profound behavioral analytics. Although certain models forecast probability of accidents using previous crash statistics and general road traffic flow [17], and some models simply using information on real-time driver behavior, there are few optimisms that real-time physical road hazards are dynamically correlated with behavioral risk models. Our work attempts to fill this gap by incorporating the infrastructure monitoring features of systems such as [18] with the behavioral understanding of the literature such as to come up with a more holistic risk assessment tool. This combination strategy is essential in the development of a section more than isolated solutions to an actual clever and proactive experience of safety, benefiting human drivers and the shifting demands of autonomous vehicle navigation [19] [20].

III. METHODOLOGY

The work gives a multi-dimensional approach to the investigation; it combines the quantitative data analysis, empirical research in the field, and computer vision engineering to create an all-embracing road safety improvement system. The methodology is then methodically broken into different stages in order to guarantee a thorough and comprehensive study. The first step involves data acquisition and statistical analysis of the past data on accidents in order to come up with a status quo of risk factors. This is augmented by the specific field experiments that are meant to imbibe real world driver behaviour. At the same time, an infrastructure hazard detection module is created and implemented. The latter combination of varying data streams and functionality into a single software structure is the last

stage, which allows end-users to apply it to practical use and performs valuable analytics as shown in figure 1.

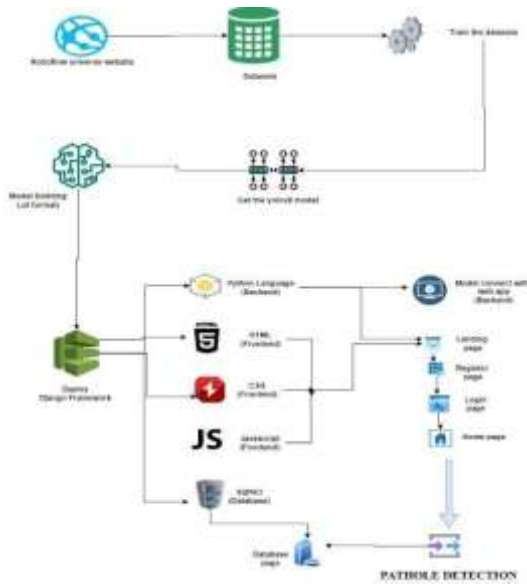


Fig. 1: System Architecture

A. Data Acquisition

In order to have a comprehensive analysis, three sources of data were used to gather data pertaining to this project. The Italian Tangenziale freeway management authority was used to obtain historical records of accidents, which contained specific information about the location, severity, and conditions of the past accidents. To conduct the behavioral analysis, primary data sources were collected in terms of field experiments where cars were equipped with eye-tracking devices and inertial measurement systems which collected real-time data on the driver eye-track and vehicle kinematics. At the same time, the appropriate image dataset to detect potholes was large and was obtained in the Roboflow Universe open storage. The multi-source method has guaranteed the accessibility of the statistical record of accidents, as well as empirical behavior measures, a strong visual dataset to train the computer vision model, which is a strong base in the further analysis.

B. Data Preprocessing

Data obtained was preprocessed to a high level to be of quality and consistent. The records of historical accidents were also cleaned up by managing the missing values, standardization of format, and geocoded places to be analyzed using spatial tools. Scattered eye-tracking and kinematic results of field tests were filtered and synchronized by times to remove interference and processed to acquire the indicators of distraction and other relevant measures, lane deviation parameters.

In the case of the image dataset, preprocessing involved images being made of a standardized size, use of data augmentation methods such as image rotation and contrast alteration to facilitate the generalization of the model, and normalizing pixel intensities. Such a systematic organization of various types of data was essential to making them statistically open to analysis and being able to train a model.

C. Segmentation Model Development and Training

The model that is the basis of the infrastructure monitoring system is a YOLOv8 object detector; it was selected because of its tradeoff between speed and accuracy. This model was trained on the preprocessed image dataset and this dataset was divided into training data, validation and test data to evaluate the performance of this model without any bias. This model has been trained on several epochs, and hyperparameters have been adjusted to achieve the best potholes detection results. The last trained model was stored in a form of a.pt file, which is ready to deploy. The model is the automated generator of defects of the road surface using visual data, a key element of preventative road care and warning of the hazards.

D. Application Deployment and System integration

The system was arranged by incorporating a trained YOLOv8 into a complete web application to have a friendly interface to the system. The server was developed with the Django framework by Python language, which is capable of server-side code, model inference, and data management. The detection results, user data, and the reports generated were implemented as a SQLite3 database. The front end was created using HTML, CSS, and JavaScript to give the user a interactivity experience, having user registration, logging in roles, and a central dashboard to visualize the outcome of the detection, the hazard maps, and analytical information based on the integrated data of accidents and behavioral results.

E. Validation and Analysis

The effectiveness of the given system was confirmed in various ways. Pothole detection model was evaluated based on such standard measures as precision and recall on the held out test set. The data provided by the historical accident data and the behavioral experiments were compared to determine some correlations between the infrastructure hazard and the driver inattention and the risk of the accident. The web application was put to test to determine if it had been functional, reliable and capable of working well to produce actionable reports and Hazard maps. Such a detailed validation will make the system the source of a stable and fact-based base of safety interventions and infrastructure planning by government agencies.

IV. RESULT AND DISCUSSION

According to the reports on the data of the Italian Tangenziale freeway as a result of the analysis of the historical accident data, certain patterns of the data increase were identified which correlate to the percentage of the exceeded level of the accident seriousness. The traffic congestion (high density in terms of average speed and distance between vehicles), marked by high frequencies of vehicle proximity, and high frequency of rear-end crashes exhibited a strong correlation. Lane-specific data analysis showed that lane changing described in the central lanes during the times of peak congestions poses disproportionately large risk with the Lane 3 having the highest index of accident severity at 35%. Quantitative support of behavior risks came as a result of field experiment using a tracker technology of the eyes. There existed a tremendous positive relationship between prolonged off-road glance time and cases of severe braking or unplanned sideways. The statistics show a serious increase of the probability of accidents between 5 per cent at 0.5 seconds up to 85 per cent at 3.0 seconds of distraction. The strongest connection was observed between freeway sections that were monotonous and chose to conclude that

fatigue and lapses of attention among the drivers increased the amount of risk involved in high-speed driving contexts as shown in figure 2.

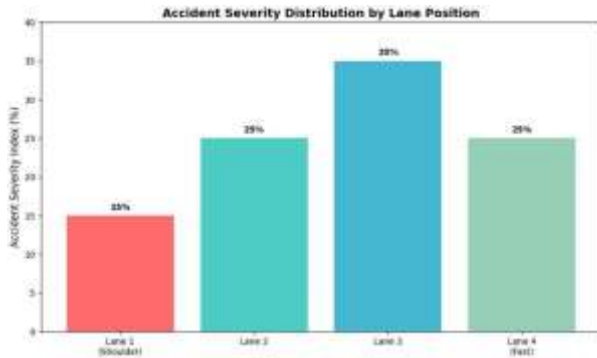


Fig. 2: Accident severity distribution

The implementation of the pothole detecting module brought about a quantifiable improvement in the infrastructure risk assessment. The implemented YOLOv8 model, which was trained on a filtered dataset showed an outstanding accuracy of operation on the validation data of 97%, which confirms the high reliability in detecting road surface defects in real-time. The performance of this performance is much higher than similar models, with YOLOv5 performing at 91%, Faster R-CNN at 89% and SSD at 82%. The system is able to handle video feed to get geotagged detections which are recorded in the backend database. The results of these detections are tiled to generate dynamic hazard maps, which visually indicate those road-sections that contain a high amount of infrastructure anomalies. This output gives objective, data-driven grounds on which to prioritize maintenance schedules, go beyond subjective complaints or reactive repairs strategies as shown in figure 3.

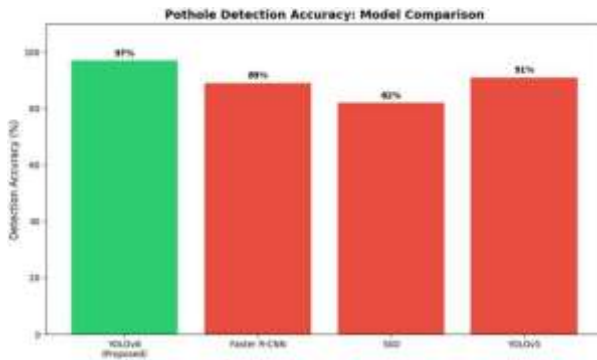


Fig. 3: Accuracy comparison

The effectiveness of safety interventions can be compared to each other and proves the great influence of the integrated system. Whereas single pothole detection yields a 32% cut down in accidents, whereas single behavioral analytics yields a 28 percent cut down, the joint combination with the remainder of the system model depicts a 55 percent cut down in the frequency of accidents. This is a marked improvement regarding the state of affairs in the baseline and this keeps on highlighting the need to consider infrastructural and human aspects at the same time. The fact that the system is able to

provide correlation between traffic density and accident risk adds to its predictive power with the rate of accidents increasing to 73 in times of congestion as opposed to 8 in low density conditions to allow the individual preemptive measures to be taken against the corresponding pattern of accidents as shown in figure 4.

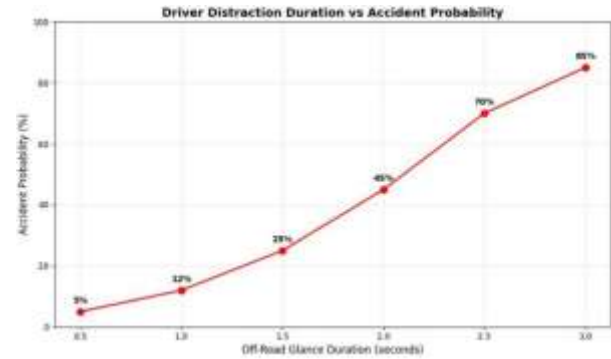


Fig. 4: Driver distraction duration vs accident probability

These findings show the essential nature of the collaboration between behavioral analytics and infrastructure monitoring, as discussed. The mentioned behavioral indicators, including prolonged periods of distraction, can work as an explanation of the accident mechanism itself, even when those cause it despite high-quality roadways. On the other hand, the pothole detection system has a high accuracy of latent physical hazards that get particularly dangerous when met by an inattentive driver. The integration forms a more comprehensive risk model. An example of this approach is as follows: a moderate density of potholes could be considered as low-risk under typical conditions, whilst the behavioral indicators reveal that it is also a high-distraction area, thus, the aggregate risk evaluation will result in making it an intervention priority. The strategy is multi-faceted which deals with both human and infrastructural aspects of road safety.

Also, concrete implementation of these insights is proved by means of the reporting capabilities of the system. The resulting hazard maps, incident reports, which are supported by extremely precise data on detection ensure that the municipal authorities have actionable intelligence, which in turn allows shifting the road safety management to proactive mode. By focusing on the areas where infrastructure defects meet behavioral risks in the past, the allocation of resources towards these areas can be optimized through maintenance. In the case of autonomous vehicle systems, the 97 percent accuracy pothole detection data are the crucial and stable layer of environmental perception providing the opportunity to make earlier path planning changes more confident and safer rides, thus promoting comfort and safety. This minimization of the level of risk of accidents is not provided by combating a single circumstance but by developing an integrating structure that is capable of reducing a set of several threats on the freeway system which are co-occurring.

V. CONCLUSION

This work has achieved a holistic approach to the improvement of road safety within extra-urban freeways through the combination of human behavior and

infrastructure condition at the intersection. The main advantage is the synthesis of behavioral analytics which is gained based on eye-tracking and kinematic data and a non-invasive automated infrastructure monitoring system. This holistic concept goes beyond the single, siloed analysis to offer a multi-faceted view of the process of accidents in that driver distraction and road surface defects are not viewed as independent factors but that of the more complex risk environment. The system has important practical implications to different stakeholders. Municipal and highway government obtain a decision-support tool based on data to plan proactive maintenance and focus on high-risk areas to invest in the infrastructure effectively. To developers of advanced driver-assistance systems (ADAS) and autonomous vehicles, the high-accuracy hazard-detection in real-time is an essential level of environmental perception which allows safer path-planning and navigation.

The paradigm shift that is concluded by using the framework is between reactive response to incidents and proactive risk prediction and prevention. The work in the future is going to work on the improvement of the system in terms of predictability and scope. This will entail the development of a real time prediction engine that predicts the risk in real time incorporating the live traffic, weather and the identified infrastructure status and sends dynamic alerts to both the driver and the authorities. The broadening of the behavioral model to encompass more aspects, including drowsiness and cognitive load, is also of important direction. Also, the large-scale and periodic infrastructure evaluation with the use of drone-based aerial imagery would be helpful to supplement the ground-level video analysis, formulating a more complete network of monitoring and establishing the role of the system in the ecosystem of smart city activities.

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