# A Digital Twin Based Approach to Control Overgrowth of Roadside Vegetation

**Varun Kumar Reja[1], Diana Davletshina[1], Mengtian Yin[1], Ran Wei[1], Quentin Felix Adam[1], Ioannis Brilakis[1] and Federico Perrotta[2]**

[1] Department of Engineering, University of Cambridge, UK
[2] AECOM, UK

varunreja7@gmail.com

**Abstract -**

**Roadside vegetation poses a significant risk to road safety, often contributing to traffic accidents by obstructing drivers' views and impeding visibility. This study investigates existing control methods, assesses their limitations, defines technology-agnostic information requirements for vegetation control, and proposes a Digital Twin-based solution. The methodology involves expert interviews, a literature review, and a real-world case study, demonstrating the solution's applicability. The study contributes to the field by offering insights into current practices, defining information needs, and presenting a novel approach for more effective roadside vegetation management. This research contributes to advancing road safety practices by harnessing the capabilities of digital twin technology to proactively manage and mitigate the risks associated with overgrown roadside vegetation.**

**Keywords -**

**Roadside Vegetation; Road Safety; Digital Twin; Asset Management; Traffic accidents; Visibility obstruction; Non-Pavement Assets; Data-driven methodology; Vegetation Removal; Transportation Infrastructure**

## 1 Introduction

This paper is about a digital twin-based approach to control the overgrowth of roadside vegetation. Digital twins are "an up-to-date digital representation of a system's physical and functional properties" [1]. Roadside vegetation overgrowth refers to the excessive and uncontrolled growth of plants, shrubs, or trees along roadsides. More than 400 casualties, including three deaths, have been reported in national figures provided by the Department for Transport, UK, where overgrown vegetation was given as a contributory factor [2]. It occurs when vegetation surpasses desirable or safe levels, impeding driver's visibility, encroaching onto road surfaces, obstructing traffic signs, and posing safety hazards [3]. Consequently, there is a higher risk of wrong turns or missed exits, increasing the potential for accidents.

The existing approach to managing vegetation overgrowth relies heavily on manual methods, where visual inspections are the primary means of identifying and addressing overgrowth along roads [4]. This manual approach extends to the labour-intensive trimming process, and the information needed for effective vegetation control remains undefined. The reliance on manual methods for managing vegetation overgrowth along roads, as highlighted by visual inspections, presents challenges in efficiency and effectiveness. Firstly, the time required for visual inspections can lead to delays in identifying overgrowth issues promptly. This delay can result in increased vegetation encroachment, potentially escalating safety risks for road users. Secondly, the labour-intensive nature of the trimming process, stemming from the manual identification of overgrowth, can contribute to higher operational costs. KPIs related to cost-effectiveness and resource optimization are adversely affected as a consequence.

Additionally, the lack of well-defined information needs further hinders the development and implementation of targeted strategies for vegetation control, making it challenging to measure and improve KPIs related to the precision and efficacy of control measures. This situation underscores a critical demand for a paradigm shift in vegetation control methodologies. There is an urgent requirement to transition from predominantly manual methods to an automated and efficient system that addresses specific information needs.

The research design followed a structured methodology, first analysing current roadside vegetation control processes through expert interviews and a literature review. Identified drawbacks were scrutinized, and information requirements were established by analysing control parameters. Then, a Digital Twin-based solution was proposed to address these requirements and overcome identified drawbacks. A real-world case study demonstrated the solution's applicability, validating its effectiveness in roadside vegetation control. This approach ensures a thorough investigation integrating expert insights, critical analysis, and practical validation.

The expected contributions include an investigation into current control methods and their limitations, the definition of information requirements for vegetation control, and the illustration of how these requirements can be met through a Digital Twin technology-based solution. The study aims to provide valuable insights and a practical solution for more effective roadside vegetation management.

The paper is organized as follows: It commences with an introduction in Section 1, followed by background information in Section 2. The proposed concept and solution are presented in Section 3, and the research methodology is outlined in Section 4. Subsequently, Section 5 delves into the findings, emphasizes limitations, and proposes directions for future research. Ultimately, conclusions are drawn in Section 6.

## 2 Background

There are several advantages of roadside vegetation, which multiple studies have highlighted [5]. Key to these are improvements in air quality, temperature regulation, and noise reduction [6]. However, roadside vegetation along road networks can bring some drawbacks, including:

- **Reduced Visibility:** Overgrown vegetation can limit the visibility of road signs, signals, and other essential traffic control elements, increasing the risk of accidents to users and wildlife [7].
- **Infrastructure Damage:** Tree branches can damage road infrastructure, such as speed camera systems and road lights, increasing maintenance costs.
- **Obstructed Sightlines:** Tall or dense vegetation can obstruct sightlines at intersections, driveways, and pedestrian crossings, making it difficult for drivers to anticipate and react to potential hazards [8].
- **Encroachment on Road Space:** Uncontrolled growth of vegetation may encroach upon the road space, narrowing lanes and reducing the overall capacity of the road network.

Most of these pose risks to public safety and cannot be ignored; therefore, roadside vegetation maintenance must happen continuously to avoid such incidents.

The current body of literature concerning the automated detection and removal of overgrown vegetation is notably limited. Hyyppä et al.'s study [9] showcases the potential of utilizing autonomous vehicle-based perception data to transform map updating processes, particularly in the context of city tree registers. The research findings highlight that, through appropriate post-processing, autonomous perception data can accurately estimate key parameters, such as the diameter at the breast height of city trees, showcasing lower errors compared to specially planned mobile mapping laser scanning surveys. This emphasizes the critical role of time-based filtering for precise point cloud analysis in autonomous perception data. Another relevant study by Harbas et al. [10] introduces a method for detecting roadside vegetation in traffic infrastructure maintenance using visible spectrum images captured by standard colour cameras on vehicles. The study underscores the effectiveness of Fully Convolutional Neural Networks in real-world applications. However, it is noteworthy that existing studies have primarily concentrated on detecting the presence of roadside vegetation cover rather than specifically detecting their overgrowth, which poses a risk of obstruction.

The integration of digital twin and computer vision technologies has the potential to revolutionize conventional roadside vegetation control methods, as demonstrated in other road management applications [11, 12, 13]. By combining these technologies, a virtual counterpart capable of capturing real-time vegetation data and its impact on visibility is created, offering a more accurate representation of the roadside landscape. Computer vision algorithms integrated within the digital twin framework enable autonomous identification and precise assessment of overgrown vegetation, leveraging visual data from sources like surveillance cameras or drones [14, 15]. This integration represents a paradigm shift in roadside vegetation control, introducing a dynamic, data-driven, and precise approach compared to traditional methods.

Therefore, three primary gaps have been recognised, reflecting the analysis of the state of practice and research presented. Firstly, the existing documentation of practices for controlling overgrowth lacks specific and detailed information. Secondly, the technology-agnostic information requirements for vegetation control processes are not defined. Lastly, research on applying innovative technologies in this domain is scarce.

Recognizing this potential, the paper proposes a digital twin-centred strategy, aided by computer vision technique, to manage overgrown roadside vegetation and meet the identified information needs. The research aims to: (a) investigate existing methods for controlling roadside vegetation, identifying their limitations, and (b) assess the information requirements for vegetation control, illustrating their fulfilment through a solution based on Digital Twin technology.

To achieve the above objectives, the following specific research questions should be answered:

- RQ1: What is the current method (in practice) of controlling roadside overgrown vegetation?
- RQ2: How efficient and effective is this method in the current era of technology?
- RQ3: What are the technology-agnostic information requirements for vegetation control?
- RQ4: How can Digital Twin technology help effectively control vegetation overgrowth?

The subsequent section delves into the proposed concept and solution.

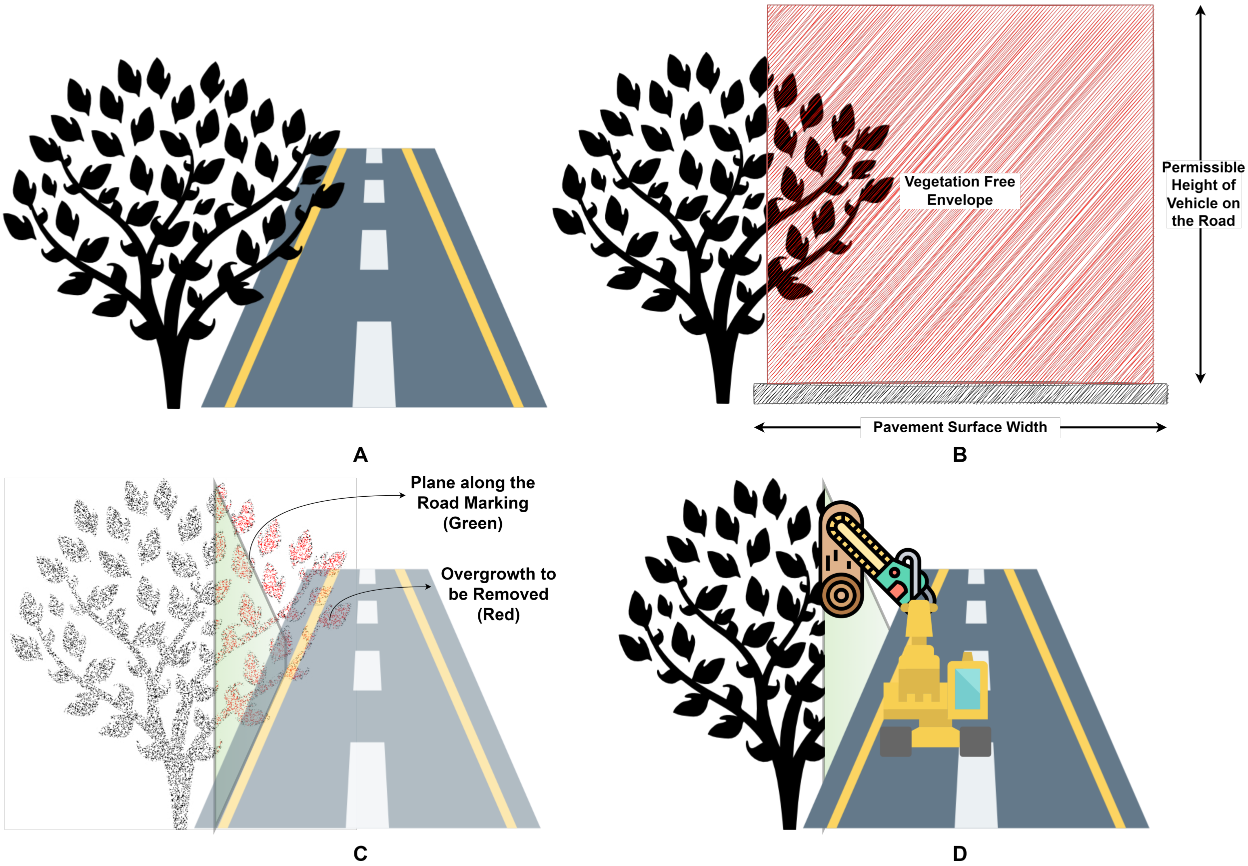



Figure 1. (A) Roadside overgrowth from driver's perspective, (B) vegetation-free envelop, (C) The segmented overgrowth in a digital twin environment as cut by the plane along road marking, (D) the vegetation clearing autonomous vehicle accomplishing the task

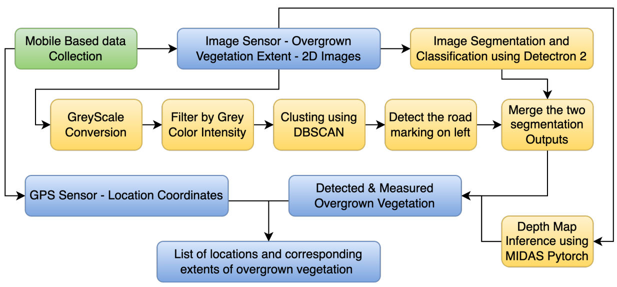



Figure 2. Proposed Solution for overgrowth detection

## 3 Proposed Concept and Solution

This work is confined to presenting and validating a proof of concept that addresses the identified information requirements for detecting vegetation overgrowth using digital twin technology. It is important to note that the actual removal of vegetation falls outside the scope of this study. The technology-agnostic information requirements for vegetation control are identified in Table 1. The following concept is developed to fulfil these information requirements.

Figure 1 shows the proposed concept for controlling roadside vegetation. Image (A) shows the view from the driver's perception; the tree is overgrown and growing over the pavement. The image (B) presents a sectional view of the pavement. Ideally, there should be a vegetation-free envelope to allow for safe passage of traffic, as highlighted in red. The size of this envelope is determined by the permissible height of the vehicle on the road as well as the road width calculated from the exterior ends of road markings.

The first task is determining the instances along the road network where the vegetation overgrowth breaches this envelope. To obtain this, the idea is to detect roadside vegetation using a segmentation algorithm and then segment it using a plane along the roadside marking. Therefore, detecting roadside vegetation and roadside markings

Table 1. Technology agnostic information requirements for controlling roadside vegetation overgrowth

| Sl. No. | Information Requirement | Description | Example |
|---|---|---|---|
| 1 | Location of Vegetation Overgrowth | Identification of overgrown areas and their specific locations. | GPS coordinates |
| 2 | Size/Dimensions of Overgrowth | Measurement of the size and dimensions of overgrown vegetation. | Square meters, Length x Width |
| 3 | Appearance of Overgrowth / Type of Vegetation | Description of the overgrown vegetation's appearance and type. | Tall grass, Shrubs, Trees |

is important. Figure 1 (C) shows utilising a plane along the road markings in a digital twin visualisation to generate a vegetation-free envelope. The vegetation on the plane's (green-coloured) right is segmented as excess vegetation and measured in the next step.

Once measured, the information of this excess overgrowth, the image's GPS location, and the original image are stored on the cloud as a job order for the robots or human-operated machine. Machines will utilise this information to locate and cut the overgrown trees, as shown in Figure 1 (D).

Figure 2 presents the pipeline to demonstrate this concept. The image data is obtained and then classified into pavement and non-pavement assets. This is done by applying a computer vision-based algorithm which classifies the various assets. In this study, we have applied panoptic segmentation inference with Detectron 2 [16] and their FPN-101 (Panoptic Feature Pyramid Network) model [17], which was pre-trained on the COCO dataset [18]. Integrated seamlessly into our system architecture, the panoptic segmentation pipeline processes real-time or periodic image data captured by roadside cameras or sensors. Through this integration, the Detectron 2 model generates semantic segmentation masks and instance-level detections, facilitating a thorough analysis of roadside vegetation and other objects, thereby enhancing road safety assessments.

As this neural network segments the whole road, including the roadside markings/sidewalks, as one entity, we need to detect the road edge using the line markings. For that, we use a separate road-marking detection algorithm. First, we convert the original image frame to a greyscale image, partition the image around the detected road and filter this by grey colour intensity since road markings feature high brightness. Once that is done, we cluster them using the DBSCAN algorithm [19] as it does not require specifying the number of clusters in advance and can deal with the noisy input. Then, we detect the largest left marking, corresponding to the left road edge, and merge this marking with the segmented image obtained from Detectron 2 in the previous step.

We then apply depth map inference on the cut input frame with a pre-trained model from MIDAS Pytorch [20]. This enables us to have the scene in 3D. Finally, with the road marking edge and vegetation depth detected, we obtain overgrown vegetation points above the road. As a result, the relative dimensions are measured to estimate the overgrown size.

Our hypothesis is that fulfilling this digital twin-based method's information requirements is much more efficient than the current method of practice regarding timeliness, safety and quality.

## 4 Research Methodology

Figure 3 presents the research methodology. First, the existing process of controlling roadside vegetation was outlined by interviewing five domain experts (each with at least ten years of on-field experience) from different highway agencies and reviewing the existing literature on vegetation control. Next, this process was analysed, and the drawbacks were outlined. The information requirements for vegetation control were also identified by critically identifying and studying the control parameters required for the survey and removal tasks. A DT-based solution presented in the previous section is proposed to target these information requirements and address the drawbacks. The applicability of this solution was demonstrated using a real-world case.

We collected 200m road length data to demonstrate the

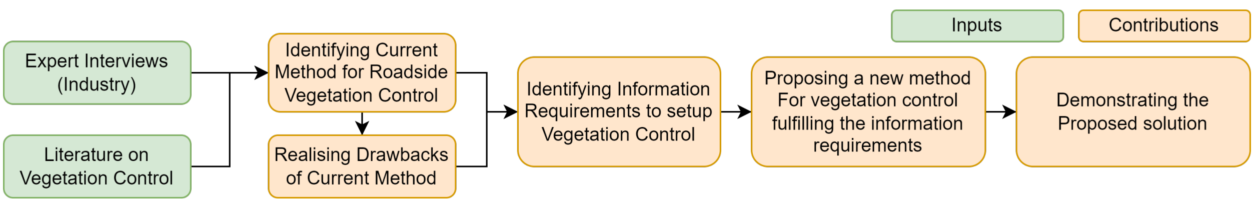



Figure 3. Research Methodology

proposed approach using an iPhone 12 Pro Max mobile camera sensor as a .MOV video file. We later processed it by extracting image frames from the video. Our method assumes that the road marking is alongside the road to construct the vegetation-free envelope. Next, all the steps presented in Figure 2 were applied to this data. The final relative encroachment width for overgrown vegetation was estimated in percentage to the road width.

# 5 Results and Discussion

## 5.1 Current Process and Drawbacks

The current process of controlling roadside vegetation is shown in Figure 4. The process starts with collecting data about the roadside vegetation status, i.e., locations at which the vegetation has overgrown along the road, the size of the overgrowth, and the type of vegetation. This is frequently done by routine surveys by pavement inspectors alongside a particular stretch of road through the visual inspection. Sometimes, the information is also conveyed by the public (road users) who might encounter such instances. The access growth is also realised by analysing recent accidents or near-miss reports.

This information is passed to the road asset owners with an approximate location (generally referred to as near a landmark) of the detected overgrown and sometimes supported with mobile camera images. Next, the road management authority takes the necessary action by sending workers to the locations to remove the overgrown vegetation and clear the path to traffic. Finally, the confirmation of the task completion is provided by the pavement inspector, who goes to the location and verifies.

There are various drawbacks to the current roadside vegetation control process. As observed, these are highlighted below:

- Subjectivity and Reliance on visual inspection: The current process heavily depends on routine surveys conducted by pavement inspectors using visual inspections, introducing a subjective element that may lead to inconsistencies and inaccuracies in vegetation status assessment.

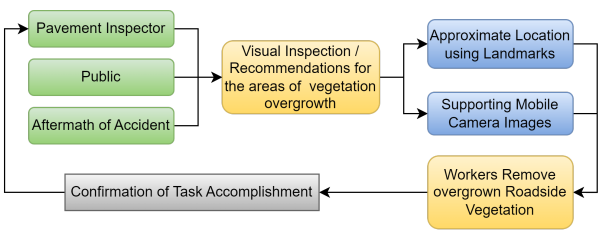



Figure 4. Current Process of Controlling Roadside Vegetation

- Delayed Detection: The current process may lead to delayed detection of overgrown vegetation, as it relies on periodic inspections or incident reports. This delay can contribute to heightened safety risks and a longer response time to mitigate potential hazards.
- Ambiguous Location Information: Providing approximate location details, often described as near a landmark, may introduce ambiguity and inefficiencies in pinpointing the exact locations of overgrown vegetation. This ambiguity can hinder the timely and precise execution of removal tasks. Also, using robots/automated machinery in the removal phase requires exact coordinates of the overgrowth, which is impossible with the current method.
- Resource-Intensive Verification Process: Confirming task completion involves a pavement inspector physically visiting the location, representing a resource-intensive verification step. This manual confirmation may lead to delays and increased operational costs.

## 5.2 Results using the Proposed Process in Real-world

Figure 5 (A) shows the original image, and (B) shows the segmented and classified image with Detectron 2. It can be seen that the algorithm detects roads, trees, grass and sky in the image frame. However, we can see that the road markings are explicitly not detected. For the road marking detection algorithm, the stepwise results are shown in Figure 5, where (C) is a greyscale image, (D) shows a cutout for the road portion, (E) shows results of filtering grey intensity, (F) shows clusters formed by DBSCAN and (G) shows detection of the largest left marking. The results after merging the segmentation obtained by detection 2 in Figure 5 (B) and road marking obtained in Figure 5 (G) are shown in Figure 5 (H). Next, Figure 5 (I) shows the depth map obtained from the MIDAS Pytorch algorithm. The detection of overgrown vegetation inside the vegetation-free envelope is shown in (J), highlighted with navy blue. Finally, we provide the approximate distance the tree takes over the ground in pixels and the percentage of the road width at approximately the same depth as shown in Figure 6b. It can be seen that the extent of the detected overgrowth is about 44% of the road width. With the location obtained from the mobile GPS sensor, the extent of this overgrowth and the original frame, this information can be shared with any automated or human-operated system to remove the overgrowth.

The concept of a vegetation-free envelope emerges as a promising strategy for ensuring the safe passage of traffic. By defining this envelope based on the permissible height of vehicles and road width, the proposed solution aims to mitigate potential hazards caused by overgrown roadside vegetation. However, further analysis and empirical studies are required to assess this approach's real-world

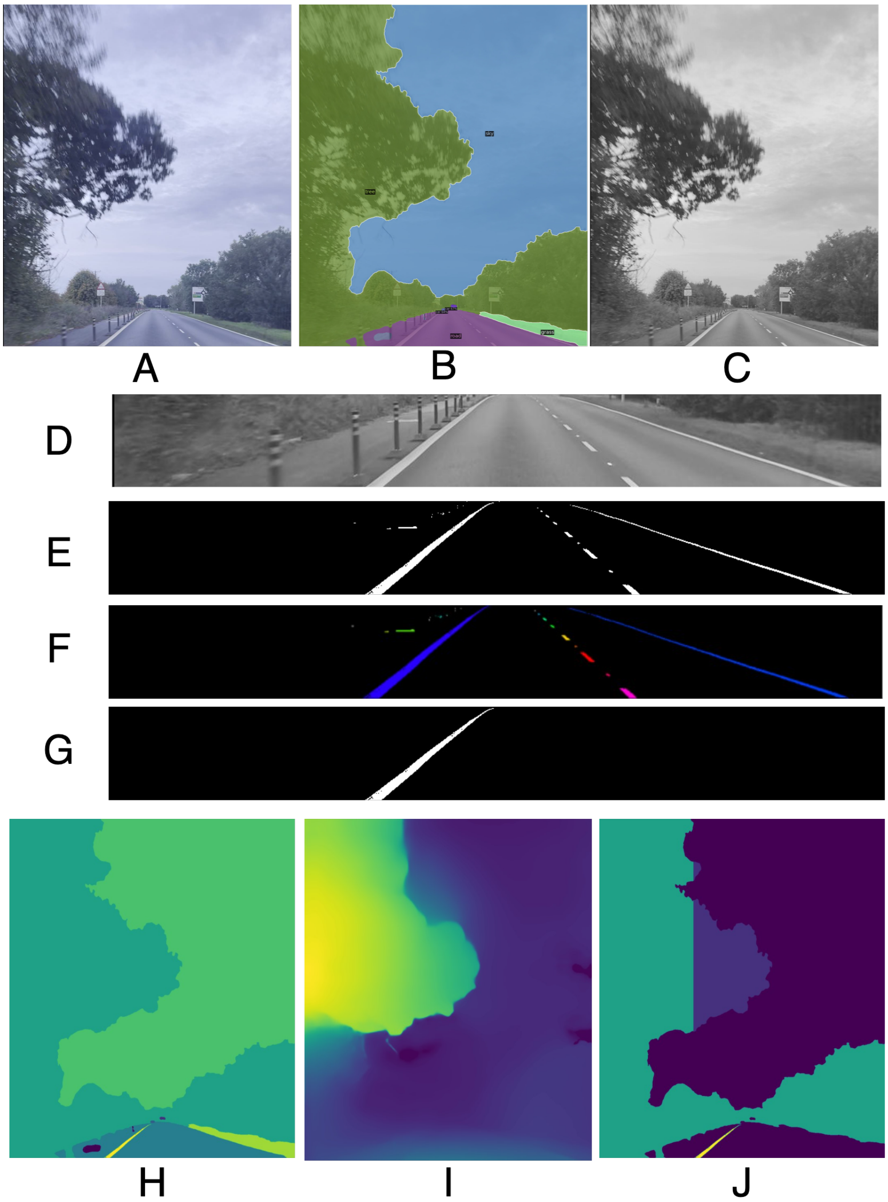


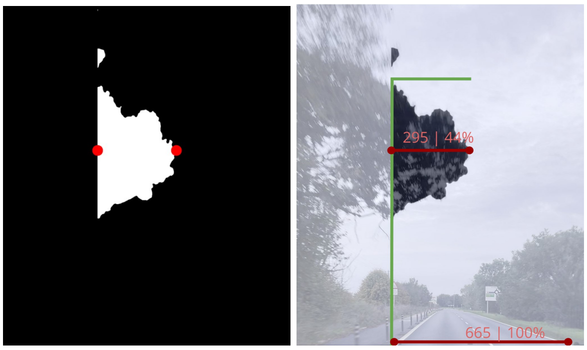

Figure 5. Stepwise Results for the Vegetation Overgrowth Detection

effectiveness and identify any possible limitations or scenarios where it may fall short.

The choice between data from public vehicle sensors and specialised survey vehicles for updating the road digital twin raises accuracy, frequency, and cost considerations. Utilising data from public vehicles offers a large-scale, crowd-sourced approach, but questions about data reliability and coverage arise. On the other hand, specialised survey vehicles provide targeted and potentially more accurate data but at an increased cost. Striking the right balance between these approaches is crucial for maintaining an up-to-date and reliable road digital twin.

The study made a dual contribution. Firstly, it delved into the investigation and documentation of the existing control methods for roadside vegetation overgrowth (RQ1) while also analysing their performance (RQ2). Secondly, it defined the information requirements for vegetation control (RQ3) and showcased how these requirements can be met through the proposal of a Digital Twin-based solution (RQ4).

It is essential to acknowledge the limitations of the current study. Relying on road markings for envelope definition may pose challenges on roads without clear markings. In this study, we assume that the road markings are present to construct the limits of a vegetation-free envelope, which may not be the case for all types of roads. In




(a) (b)

Figure 6. Detected overgrown vegetation, vegetation edge points in red and the vegetation-free envelope borders in green.

some cases, the road markings may be damaged or eroded; in that case, we will detect the pavement edge and use it to construct the vegetation-free envelope. In future, we also aim to monitor the condition of the other road assets like lamps, road signs, road markings, etc and integrate the same method to develop a combined comprehensive digital twin framework for road maintenance. In regions with different climatic conditions or vegetation profiles, adjustments to the detection algorithms and parameter tuning may be necessary to achieve optimal performance.

Compared to previously available literature [10, 9], our study specifically proposes a solution for controlling overgrown roadside vegetation rather than vegetation in general. We can also combine [10] generic approach with our method to further improve the performance of our method. Additionally, our method helps evolve conventional documentation and practices by comparing the effectiveness of these traditional methods with ours.

## 6 Conclusions

The practical implications of this study are substantial, as the examination and analysis of current roadside vegetation control approaches and identifying their limitations provide valuable insights for practitioners and policymakers. Understanding the inherent information requirements in vegetation control enhances the decision-making process for those involved in deciding the technology to be deployed for survey and removal. Introducing a novel Digital Twin technology-based solution addresses the limitations of traditional methods and signifies a practical advancement. Incorporating our approach into current road management practices entails adopting digital twin technology to address maintenance requirements, facilitating real-time monitoring of roadside vegetation, and facilitating data-driven decision-making. Over the long term, this integration will enhance infrastructure resilience, improve user responsiveness, reduce accidents, lower maintenance expenses, and enhance overall road safety.

The societal implications of this study are twofold, primarily centring on the direct enhancement of road user safety. Implementing the study's findings can optimize vegetation control processes, improve visibility on roads, and diminish the likelihood of accidents arising from overgrown vegetation. Additionally, the study underscores the importance of improved infrastructure management. This contributes to transportation infrastructure's overall efficiency and resilience, fostering smoother mobility and minimizing societal disruptions. The advancement in infrastructure management elevates safety standards and fosters the development of a more sustainable and dependable transportation network.

In the future, the data collection can be fully automatic by collaborating with connected autonomous vehicle providers and will require no additional effort for DT updation. Also, a potential future research direction is predicting the overgrowth based on the growth rate of the type of vegetation detected. This can help recognise the frequently vulnerable areas to take proactive action. Also, in some cases where autonomous vegetation-trimming robots like [21] can be deployed, it can make the process completely automated.

In summary, the presented digital twin-enabled methodology offers a promising avenue for transportation authorities and infrastructure managers to address the challenges posed by overgrown roadside vegetation. By leveraging cutting-edge technology, this approach enhances safety and contributes to the evolution of smart and resilient transportation systems. As technology advances, the integration of digital twins in road infrastructure management is poised to play a pivotal role in shaping the future of transportation safety and efficiency.

## 7 Acknowledgement

Funded by the European Union

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 101034337. The authors would like to acknowledge the support of the academic and industry partners: Kristen MacAskill (University of Cambridge), Mike Hunter (Georgia Tech), Jeremy Morley (Ordinance Survey), Stefano Cavarazzi (Ordinance Survey), Yogesh Patel (Ringway), Matt Peck (Atkins), Nick Wang (SAP), Arnulf Hagen (SAP), Simon Hayton (Keltbary), Michael Pelken (Keltbary), Tom Tideswell (Kier), Jordan Flint (Kier), Jonathon Simons (AECOM), and James Locke (Arcadis). Their expertise and guidance have significantly enriched the content of this paper.

## References


[1] Rafael Sacks, Ioannis Brilakis, Ergo Pikas, Haiyan Sally Xie, and Mark Girolami. Construction with digital twin information systems. *Data-Centric Engineering*, 1:e14, 2020.

[2] Amy Downward. Overgrown hedges 'a danger to drivers'. On-line `https://www.shropshirestar.com/news`, Accessed: 20/12/2023.

[3] Overgrown trees, branches and plants are a hazard for drivers. On-line: `https://www.edriving.com/three60/`, Accessed: 20/11/2023.

[4] Ann M Johnson et al. Best practices handbook for roadside vegetation management. Technical report, Minnesota. Dept. of Transportation. Office of Research Services, 2008.

[5] Richard TT Forman and Robert I McDonald. A massive increase in roadside woody vegetation: goals, pros, and cons. 2007.

[6] Kristina Hill, Richard Ray Horner, Ray Willard, and Washington Olympia. Assessment of alternatives in roadside vegetation management. 2005.

[7] Jeffery W Van Treese II, Andrew K Koeser, George E Fitzpatrick, Michael T Olexa, and Ethan J Allen. A review of the impact of roadway vegetation on drivers' health and well-being and the risks associated with single-vehicle crashes. *Arboricultural Journal*, 39(3):179–193, 2017.

[8] M Bassani, L Catani, A Salussolia, and CYD Yang. A driving simulation study to examine the impact of available sight distance on driver behavior along rural highways. *Accident Analysis & Prevention*, 131:200–212, 2019.

[9] Eric Hyyppä, Petri Manninen, Jyri Maanpää, Josef Taher, Paula Litkey, Heikki Hyyti, Antero Kukko, Harri Kaartinen, Eero Ahokas, Xiaowei Yu, Jesse Muhojoki, Matti Lehtomäki, Juho-Pekka Virtanen, and Juha Hyyppä. Can the perception data of autonomous vehicles be used to replace mobile mapping surveys?-a case study surveying roadside city trees. *Remote Sensing*, 15(7), 2023. ISSN 2072-4292. doi:10.3390/rs15071790. URL `https://www.mdpi.com/2072-4292/15/7/1790`.

[10] Iva Harbaš, Pavle Prentašić, and Marko Subašić. Detection of roadside vegetation using fully convolutional networks. *Image and Vision Computing*, 74: 1–9, 2018.

[11] Ou Zheng. Development, validation, and integration of ai-driven computer vision and digital-twin systems for traffic safety diagnostics.

[12] Yongkang Liu, Ziran Wang, Kyungtae Han, Zhenyu Shou, Prashant Tiwari, and John HL Hansen. Sensor fusion of camera and cloud digital twin information for intelligent vehicles. In *2020 IEEE Intelligent Vehicles Symposium (IV)*, pages 182–187. IEEE, 2020.

[13] Diana Davletshina, Varun Kumar Reja, and Ioannis Brilakis. Automating construction of road geometric digital twins using context and location aware segmentation. 2024. URL `https://ssrn.com/abstract=4767693`.

[14] Varun Kumar Reja, Koshy Varghese, and Quang Phuc Ha. Computer vision-based construction progress monitoring. *Automation in Construction*, 138:104245, 2022. doi:10.1016/j.autcon.2022.104245. URL `https://doi.org/10.1016/j.autcon.2022.104245`.

[15] Varun Kumar Reja, Shreya Goyal, Koshy Varghese, Balaraman Ravindran, and Quang Phuc Ha. Hybrid self-supervised learning-based architecture for construction progress monitoring. *Automation in Construction*, 158:105225, 2024. doi:10.1016/j.autcon.2023.105225. URL `https://www.sciencedirect.com/science/article/pii/S0926580523004855?via%3Dihub`.

[16] Yuxin Wu, Alexander Kirillov, Francisco Massa, Wan-Yen Lo, and Ross Girshick. Detectron2. `https://github.com/facebookresearch/detectron2`, 2019.

[17] Detectron2 model zoo and baselines. On-line: `https://github.com/facebookresearch/detectron2/blob/main/MODEL_ZOO.md`, Accessed: 20/11/2023.

[18] Tsung-Yi Lin, Michael Maire, Serge Belongie, James Hays, Pietro Perona, Deva Ramanan, Piotr Dollár, and C Lawrence Zitnick. Microsoft coco: Common objects in context. In *Computer Vision–ECCV 2014: 13th European Conference, Zurich, Switzerland, September 6-12, 2014, Proceedings, Part V 13*, pages 740–755. Springer, 2014.

[19] Martin Ester, Hans-Peter Kriegel, Jörg Sander, Xiaowei Xu, et al. A density-based algorithm for discovering clusters in large spatial databases with noise. In *kdd*, volume 96, pages 226–231, 1996.

[20] René Ranftl, Katrin Lasinger, David Hafner, Konrad Schindler, and Vladlen Koltun. Towards robust monocular depth estimation: Mixing datasets for zero-shot cross-dataset transfer. *IEEE Transactions on Pattern Analysis and Machine Intelligence (TPAMI)*, 2020.

[21] A new path to safely managing vegetation. On-line: `https://www.sarcos.com/robotics-applications-and-use-cases/vegetation-management/`, Accessed: 20/11/2023.