Joint CSCE Construction Specialty & CRC Conference 2025
Conférence conjointe spécialisée en construction de la SCGC et CRC-2025

Montreal, Quebec
July 28-31, 2025 / *28-31 juillet 2025*

Estimation of Road Widths to Infer Disaster Response Vehicular Mobility in Alleys Using GIS-based Road Polygon Data

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ABSTRACT: Rapid access of disaster response vehicles to disaster sites is critical for minimizing human casualties and property damage. However, physical constraints, such as narrow roads, hinder the ability of vehicles to meet critical response-time requirements. Although light detection and ranging (LiDAR) sensors can precisely extract road width information, their cost limits deployment in a broad range of urban areas, including narrow alleys. To address these challenges, this study estimates road widths using road polygon data from web-based mapping services to construct a road width dataset for the entire Seoul Metropolitan area. Public geographic information system-based road polygon data were used to calculate road widths at specific coordinates. OpenCV-based morphological image processing, including erosion, dilation, and skeletonization, extracted road widths by filtering nonroad elements, identifying centerlines, and measuring distances from centerlines to boundaries using polygon distance functions. For validation, a LiDAR mobile mapping system generated point-cloud data in narrow alleys of Seoul, based on which road widths were measured in 151 sampled areas. Comparison with LiDAR-based point-cloud measurements (ground truth) verified the reliability of the estimated road width dataset, yielding a high correlation (0.775, $p < 0.0001$) with a mean absolute error of 0.633 ± 0.574 m and a mean absolute percentage error of 14.56%. This approach offers a user-friendly way to allow fast retrieval of road width information without onsite investigation. Considering disaster response vehicle specifications and estimated road widths, this study ensures reliable mobility assessments across urban roads. This study supports continuous monitoring of disaster-prone alleys and infrastructure improvements to reduce vulnerability by replacing traditional field surveys.

1. INTRODUCTION

The rapid accessibility of emergency response vehicles in urban environments is a critical factor in minimizing casualties and mitigating property damage. Empirical studies have demonstrated that response time directly correlates with survival rates and damage severity in disasters such as fires, earthquakes, building collapses, and medical emergencies. However, physical constraints, such as narrow alleyways, impede the mobility of emergency vehicles, particularly in older residential areas and densely populated commercial districts, thereby exacerbating response delays and operational inefficiencies. These infrastructural constraints hinder the direct access of emergency vehicles, frequently necessitating alternative routes, thereby reducing the efficiency of disaster response and potentially exacerbating overall damage.

In metropolitan cities such as Seoul, a substantial proportion of the road network comprises narrow alleyways that restrict considerably the maneuverability of emergency vehicles. Fire trucks, ambulances, and police vehicles typically require a minimum road width of >3.45 m to operate efficiently; however, many alleyways fall below this threshold or barely meet the requirement, thus impeding smooth passage. As a result, emergency response personnel must identify alternative routes or conduct interventions from alleyway entrances, which can cause severe delays. Notably, in fire incidents, prolonged response times lead to an exponential increase in structural damage and cause decreases in survival probabilities. Buffington and Ezekoye (2019) have systematically analyzed the correlation between emergency vehicle response-time delays, fire damage escalation, and survival rate reduction.

To address these challenges, systematic field surveys have been conducted to measure road widths. However, owing to practical constraints, a comprehensive evaluation of the entire urban road network remains difficult. Road width analysis based on field measurement data necessitates a full-scale survey of each road segment, requiring substantial human resources and specialized equipment, which limits efficiency considerably. Furthermore, roads with restricted accessibility are often excluded from surveys, leading to potential data omissions. According to an analysis by the Korea Research Institute for Human Settlements, approximately 5–27.13% of the total road area in major urban regions consists of “de facto roads,” highlighting the limitations of local governments in accurately assessing overall urban road environments. De facto roads are unofficial pathways used by both vehicles and pedestrians, commonly found in areas with narrow alleys and irregular road networks.

In response to these limitations, recent advancements in spatial data analysis and image processing technologies have presented promising solutions to these challenges. Habib et al. (2018) demonstrated that a light detection and ranging (LiDAR)-based mobile mapping system, utilizing multisensor LiDAR configurations and point-cloud data analysis, effectively quantified road widths. Similarly, Ravi et al. (2019) proposed a methodology for road width estimation employing LiDAR-based mapping techniques. Nevertheless, the large-scale deployment of these technologies remains challenging owing to increased operational costs and computational demands. Additionally, Kim and Park (2024) analyzed LiDAR reflectance distortions under various meteorological conditions, revealing potential performance degradation. As autonomous driving technology advances, research on precise road environment analysis and road width estimation has been actively conducted. Ma et al. (2024) investigated methodologies for recognizing road attributes and lane structures to support path planning and motion control in autonomous vehicles. Additionally, Liu et al. (2023) reviewed vision-based road detection technologies for autonomous vehicles, demonstrating the applicability of various algorithms, technical frameworks, and datasets in route planning and decision-making. Their findings further validate the increasing availability of spatial data, such as road shapefiles, thereby enhancing the feasibility of efficient road width extraction.

In this context, Dey and Aithal (2025) conducted a study utilizing web-based mapping services and satellite imagery to estimate road widths based on image processing techniques. This research represents an effort to automate road width measurements using spatial data, demonstrating its cost efficiency and faster analytical capabilities compared with traditional surveying methods. However, existing studies primarily focus on structured road networks with consistent widths, while research incorporating irregular and narrow roads, such as alleyways, remains limited. In particular, the accuracy of spatial data-based road width estimation techniques in constrained environments has not been sufficiently validated. Furthermore, the consistency of road shape data in accurately reflecting actual road widths has not been fully validated. Therefore, to utilize spatial data-based approaches effectively, systematic validation and additional research are needed to ensure the reliability of road width estimation in constrained environments, such as narrow alleyways.

This study aims to estimate the road width of urban alleyways using geographic information system (GIS)-based road polygon data that can help analyze its impact on emergency vehicle mobility. Specifically, road width is computed at designated coordinates using GIS-based road polygons, and OpenCV-based image processing techniques, including morphological operations—such as erosion, dilation, and skeletonization—are applied to enhance extraction accuracy. Additionally, validation is conducted using LiDAR-based point-cloud data to propose a more robust alternative to conventional field survey methods.

2. RESEARCH METHODS

Accurately measuring road widths in narrow alleys is essential for quantitative analyses of urban road environments. Road width measurements constitute a crucial component of road infrastructure analysis, emergency vehicle accessibility assessment, and urban planning. However, to our knowledge, no comprehensive road width databases currently exist, and existing point-cloud-based measurement methods, such as LiDAR, entail increased operational costs and methodological limitations, making its implementation in large-scale areas challenging. This study proposes an automated road width extraction method utilizing GIS-based road polygon data provided by web-based mapping services, as illustrated in Figure 1.

This study constructs an urban-scale road width dataset by leveraging road polygon (.shp) data from web-based mapping services, such as Naver, Kakao, and Google Maps. The dataset is designed to extract rapidly road centerline and width parameters following the input of specific geospatial coordinates. The methodology employs a series of morphological operations, including erosion, dilation, and skeletonization, to refine the extracted road features. To validate the reliability of the proposed method, the extracted road width estimates are compared with ground truth data obtained through LiDAR-based mobile mapping systems.

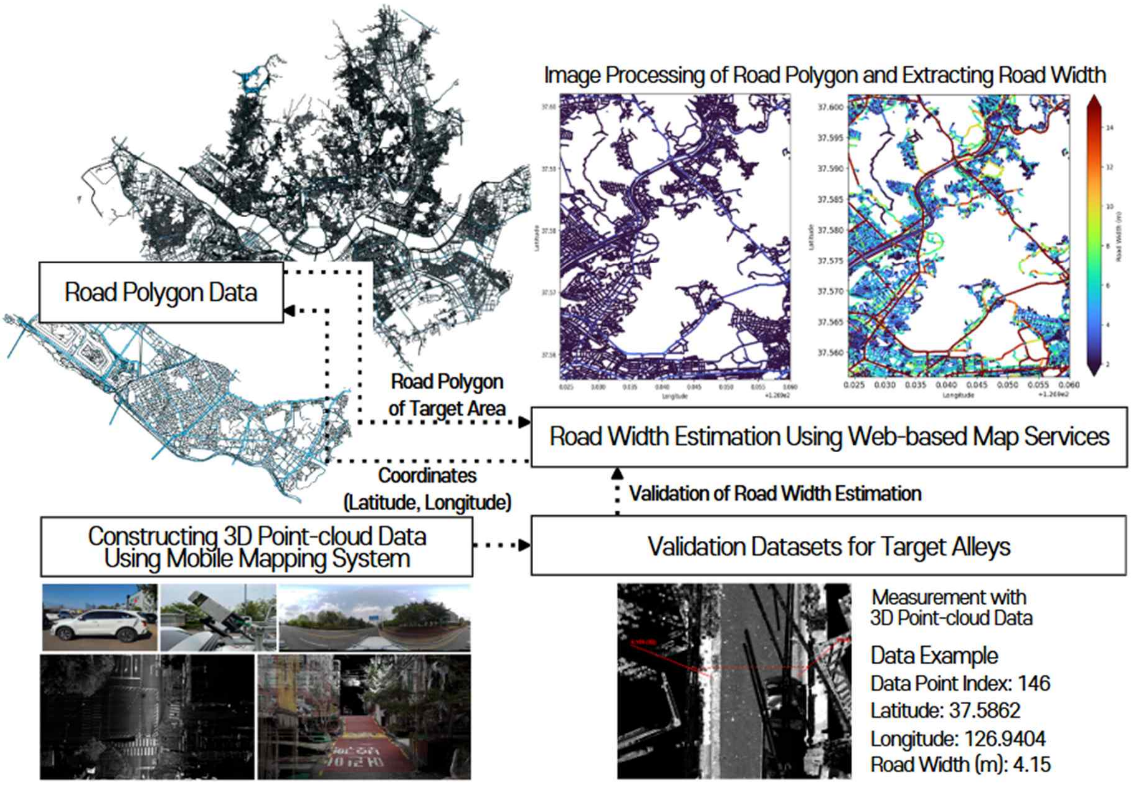

Figure 1: Research Framework Used in This Study

2.1 Road Width Data Acquisition and Processing

LiDAR-based methods utilizing point-cloud data are the most precise methods for estimating road widths in urban areas. However, the computational demands associated with LiDAR data processing render it impractical to generate a comprehensive road width dataset for large metropolitan areas such as Seoul. Currently, only a few datasets, such as Nuscenes (Caesar et al., 2020) and the KITTI vision benchmark suite (Geiger et al., 2012), incorporate point-cloud data for urban environments. However, these datasets primarily focus on broad road networks, limiting their applicability for detailed analyses of narrow alleyways. To overcome these limitations, this study adopts a file-based road width extraction approach, as outlined in Figure 2. This approach integrates web-based mapping services with image processing techniques to enhance efficiency in road width estimation. The mapping services utilized in this study include Google Maps (www.google.com/maps/), Naver Maps (navermaps.github.io/maps.js.ncp/), Kakao Maps (apis.map.kakao.com/), and the public mapping service Vworld (https://www.vworld.kr/v4po_main.do) provided by the Ministry of the Interior and Safety. As road polygon datasets from these services are independently compiled, their reliability was assessed before their use in this study.

The collected GIS-based road polygon (.shp) data were preprocessed using Python and QGIS through a series of steps. First, the road width at a given location was estimated by acquiring georeferenced images via mapping service APIs based on the latitude and longitude coordinates (x_0, y_0). Second, a color-based segmentation algorithm was applied to distinguish road areas from nonroad areas. This step ensured that only relevant parts of the image were used for further processing. Second, a color-based segmentation algorithm was applied to distinguish road areas from nonroad areas. This step ensured that only relevant parts of the image were used for further processing. Third, morphological processing techniques, such as erosion and dilation, were employed to eliminate noise and remove grid lines. Erosion helps in eliminating small artifacts, while dilation expands the road boundaries to fill gaps, improving the accuracy of the extracted road features (Anjanayya et al., 2023). Following this, skeletonization was applied to refine the road geometry by extracting its thinnest possible representation. This process facilitates precise centerline extraction, which is crucial for accurate width estimation. Lastly, the road width was calculated by determining the distance from each centerline point to the nearest road boundary using a distance-to-polygon function. This distance was then doubled to derive the final road width measurement in meters.

By applying this method across the entire road network, a comprehensive dataset containing road width information $\{ (x_i, y_i, w_i) \mid i = 1, ..., n \}$ was established, where w represents the road width at each geospatial coordinate. The dataset encompassed 9.35 million road center points across Seoul. Upon input of specific spatial coordinates, the system was designed to return promptly the nearest road center point in conjunction with its corresponding width measurement.

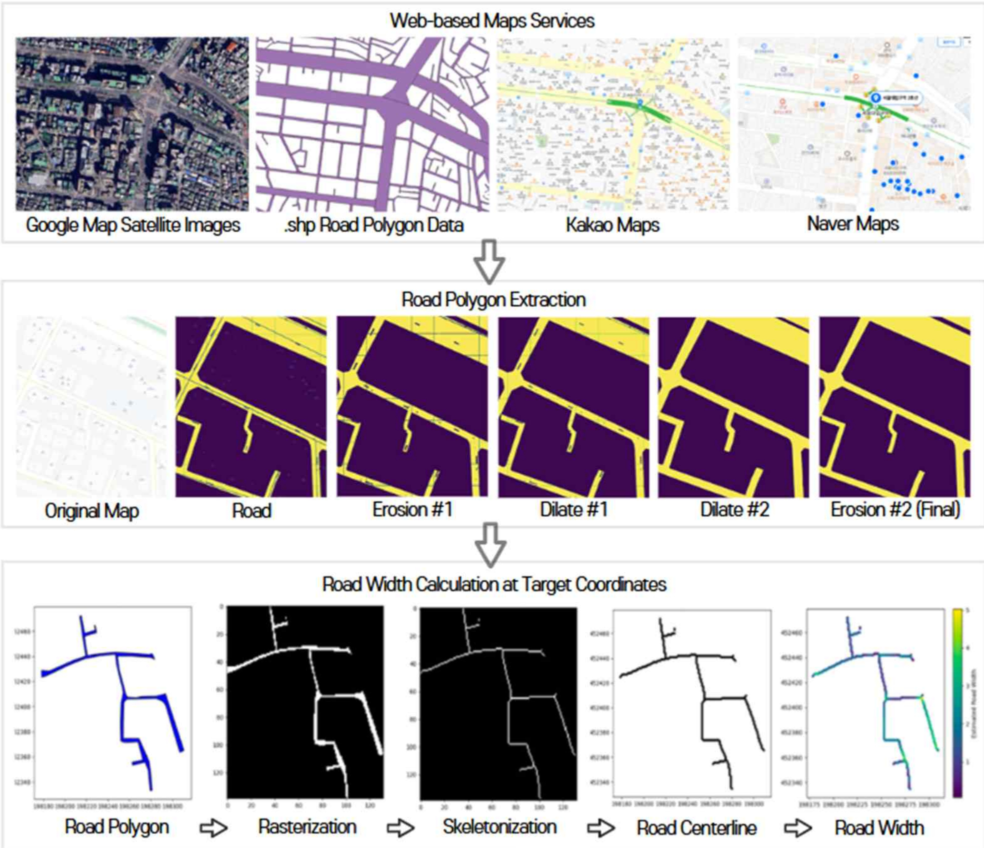

Figure 2: Estimation of Road Widths from Web-based Maps

2.2 Ground Truth Measurements for Road Width Evaluations Using Point-cloud Data

To verify the accuracy of the proposed method, road width measurements derived from the extracted road polygon data were compared against ground truth values of actual road widths obtained using LiDAR point-cloud data. For precise ground truth acquisition, an MMS equipped with a CL-360 LiDAR sensor and a high-resolution iSTAR Pulsar camera were deployed to collect point-cloud data. The survey focused on narrow alleyways within the study area, capturing data at 6443 locations. Each measurement site included geospatial coordinates (latitude and longitude), high-resolution imagery, and point-cloud data. Given the substantial processing time required for comprehensive LiDAR-based road width estimation, a representative sample of 151 road sections was selected for detailed analyses.

The collected point-cloud data was processed to compute road width by analyzing distances between key structural elements consisting of the alleyways (e.g., building facades and walls). The process for calculating the road width is illustrated in Figure 3. The established ground truth dataset was used to validate the accuracy of the proposed road width estimation method using a GIS-based road polygon (.shp). The performance of the method was quantitatively evaluated by calculating statistical metrics, including correlation coefficients and the mean absolute error (MAE), which are discussed in subsequent sections.

Figure 3: Validation of Road Width Measurements Using Light Detection and Ranging (LiDAR) Point-cloud Data

3. RESULTS AND DISCUSSION

3.1 Evaluation of GIS-based Road Width Measurements in Narrow Alleyways

This study evaluated the estimated road width data obtained from various road shapes provided by Google Maps, Naver Maps, Kakao Maps, and a government-provided mapping service. A quantitative analysis was conducted to assess the agreement between the road width data from each mapping service and the ground truth measurements. The results indicated that while all mapping services exhibited similar trends, the road width dataset provided by the government-provided mapping service demonstrated the highest accuracy for Seoul data. Given the observed consistency across mapping services, the government-provided map-based road width dataset may serve as a viable reference; however, alternative mapping services may be more suitable depending on specific regional characteristics and can be applied accordingly.

To validate thoroughly the estimated road width dataset, this study conducted a comparative analysis using 151 measurements from LiDAR-based point-cloud data, specifically focusing on narrow alleyways. Figure 4 illustrates the distribution of road width measurements obtained from LiDAR-based point-cloud data (ground truth) and GIS-based road width data (estimation). The figure shows the frequency of road widths across the 1–9 m range, with a concentration in the 4–5 m range, aligning with the characteristic road widths of narrow urban alleyways within the study area. This distribution provides a visual representation of the variability in road widths and underscores its potential utility as a key reference for road design and urban planning within the studied area.

Figure 5 presents a comparative analysis of LiDAR-based and GIS-based estimated road widths across 151 samples, illustrating the fluctuations and deviations between the two datasets. When estimating the road width of narrow alleyways from a GIS-based road width dataset, the results can be affected by slight variations in latitude and longitude. Therefore, to minimize the impact of incorrect estimation, the road width was determined using the median value from five points within a very small range of latitude and longitude around the alleyway location. The results showed that the MAE was 0.633 ± 0.574 m (mean ± standard deviation), and the mean absolute percentage error (MAPE) was 16.31%, demonstrating that the GIS-based estimates exhibit an average deviation of approximately 0.6 m from the actual road widths. These findings suggest that the proposed method provides a practically acceptable level of accuracy for assessing road widths in narrow alleyways. As illustrated in Figure 6, the correlation coefficient between the GIS-based estimated road widths and the actual road widths was 0.775 ($p < 0.0001$), indicating a significant correlation between the two datasets.

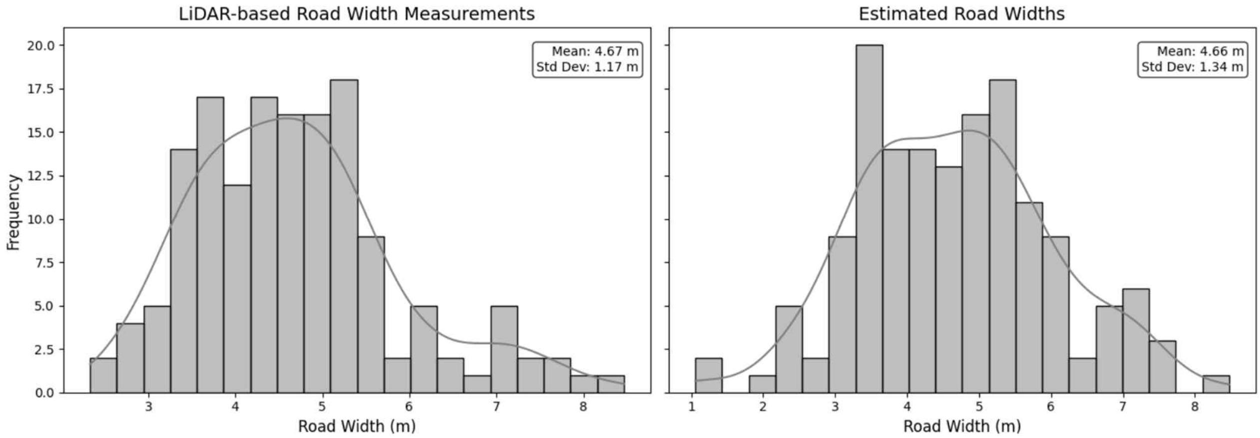

Figure 4: Histogram of LiDAR-based Road Widths (Left), and Estimated Road Widths (Right)

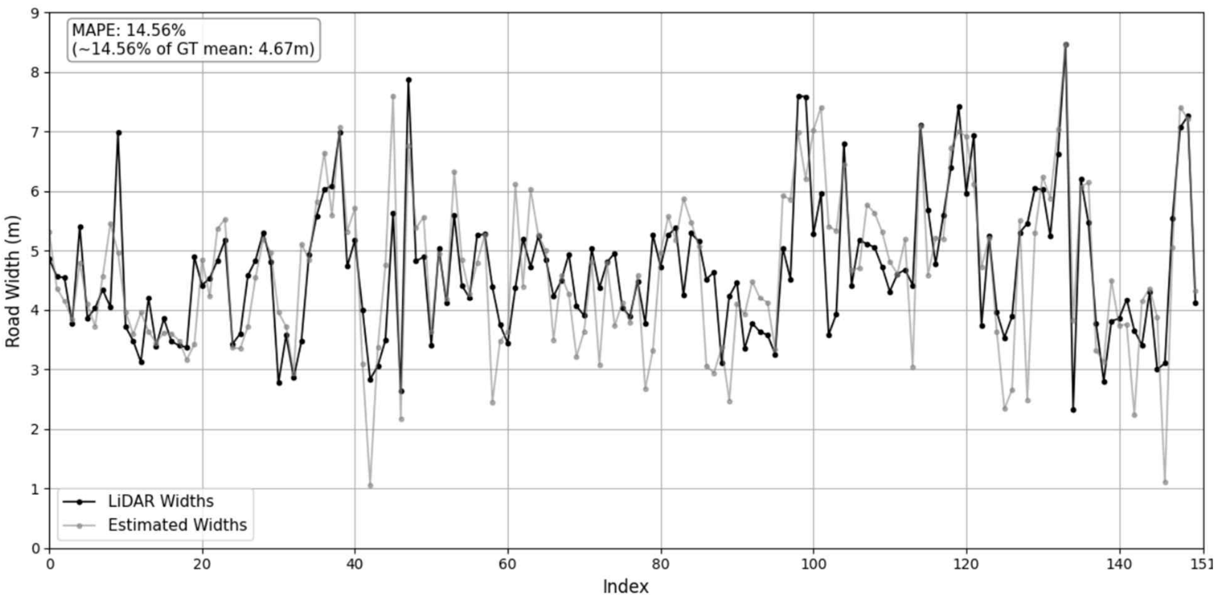

Figure 5: Comparison of Estimated and LiDAR-based Road Widths

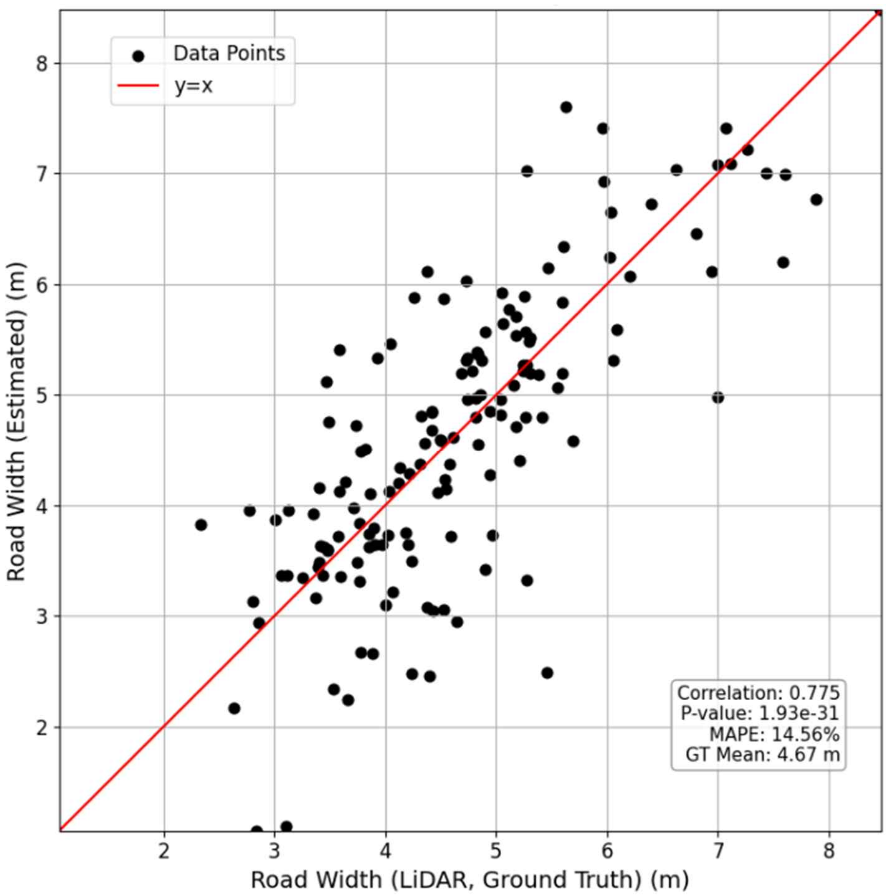

Figure 6: Scatter Plot of LiDAR-based and Estimated Road Widths

3.2 Discussion of Results

The analyzed results demonstrated a high-correlation coefficient (0.775, p-value < 0.0001) with an MAE of 0.633± 0.574 m, and a MAPE of 14.56%. An average error of approximately 0.6 m is within an acceptable range considering the various environmental factors in narrow alleyways, such as obstacles, parked vehicles, and structural protrusions that affect road widths in these alleyways. This level of accuracy was sufficient to capture localized variations in road widths affected by these factors.

For emergency vehicle accessibility assessment and disaster response planning, it is more critical to determine whether a road segment is passable rather than to measure the road width with extreme precision. In real-world emergency scenarios, a conservative decision-making approach is typically applied, where ambiguous road segments are classified as difficult for vehicular entry, while distinctly accessible or inaccessible areas are identified explicitly. For example, Seoul classifies narrow alleyways into three categories—accessible, difficult, and inaccessible—for disaster response vulnerability assessment and management. While the accuracy of this study can improve, it is sufficient for this classification of accessible, difficult, and inaccessible.

Additionally, the road width estimation results from the four mapping services yielded similar values. This suggests that the process of loading and processing road polygon data is largely consistent across services, allowing for reliable road width estimation with minor region-specific adjustments. Considering these analytical insights, the proposed methodology demonstrates its potential for effectively estimating road widths in narrow alley environments. This study contributes to key decision-making processes in emergency vehicular operations and offers practical implications for urban road network management and accessibility analysis.

3.3 Contributions and Applications

LiDAR technology has been extensively adopted to enhance inference accuracy in road perception tasks. However, conducting comprehensive LiDAR-based surveys for entire urban alley networks presents major challenges owing to high costs and operational inefficiencies. To overcome these challenges, this study presents an efficient approach for systematically building road width databases for target areas by utilizing GIS-based road polygon data, as shown in Figure 7. By implementing this approach, road centerlines and width parameters can be rapidly extracted by inputting specific spatial coordinates, enabling flexible scalability across large-scale road networks. Furthermore, leveraging web-based mapping services eliminates the need for additional hardware, allowing the generation of road width information solely from existing GIS data, making it a cost-effective and accessible alternative.

Thus, the proposed methodology provides an efficient framework for systematically generating road width information across diverse urban environments, including narrow alleyways. This approach holds tremendous potential for applications in urban planning, road infrastructure management, and emergency vehicle accessibility assessment, offering a practical solution for addressing critical challenges in road width estimation.

The methodology proposed in this study can be utilized to prioritize systematically infrastructure improvements by analyzing disaster-prone areas, aging residential zones, and underdeveloped urban regions. From an urban planning and infrastructure management perspective, this research provides a practical framework for optimizing accessibility in areas where narrow road widths pose substantial constraints. The developed road width estimation technique contributes to the enhancement of the completeness and accuracy of spatial data, thereby improving the reliability of existing road databases.

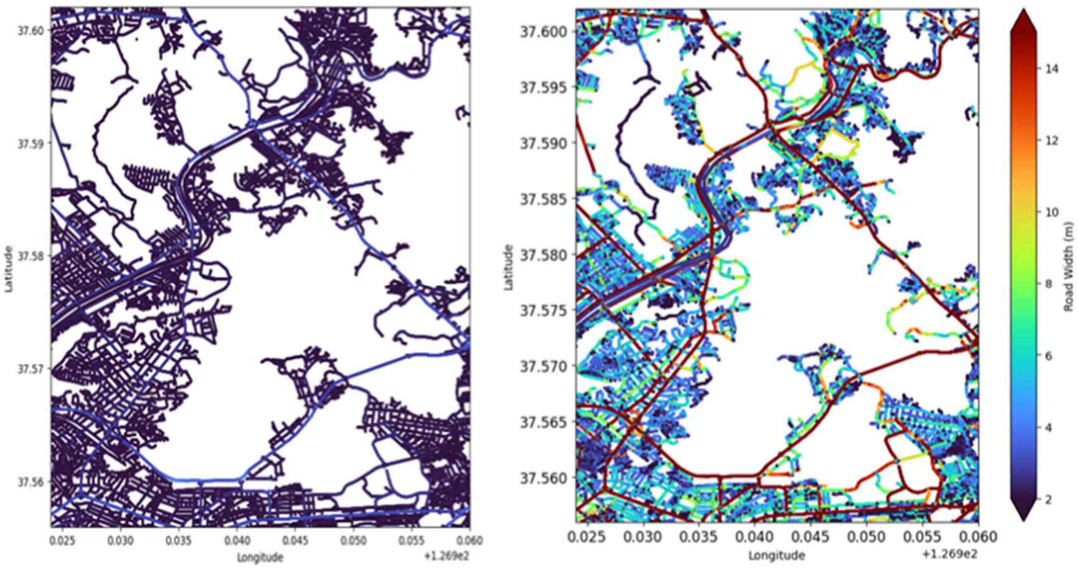

Figure 7: Heatmap Visualization of Road Widths Using Mapping Data in the Target Area

3.4 Limitations and Future Work

The GIS-based road width measurement conducted in this study was influenced by the accuracy of road polygon data provided by web-based mapping services and the variability of road environments. While road width information from mapping services is typically reliable, certain discrepancies may exist at specific locations. For instance, when comparing road width obtained using the distance measurement tool function of the Naver mapping service with validation data derived from LiDAR, the MAE was found to be 0.6198, with a standard deviation of 0.7849, and a MAPE of 0.1503. These error values are comparable to or greater than those observed in the current study. This suggests that as the spatial resolution and geometric accuracy of road shape data improve, the accuracy of the proposed road width estimation method is also likely to increase, potentially resulting in further reductions in error rates. Moreover, in highly complex urban environments, the accuracy of road width estimation may be compromised due to various obstructions, such as structural obstacles and illegally parked vehicles. These limitations can be mitigated by further refining and training object detection models using CCTV data as well as other image-based sources, such as aerial imagery and streetscape images, to estimate actual navigable widths considering obstacles. In addition, enhancing data precision through the integration of high-resolution aerial imagery and advanced spatial information analysis techniques can also contribute to improved accuracy.

4. CONCLUSIONS

This study proposes a GIS-based method for estimating road widths in narrow alleyways using web-based road polygon data. The approach facilitates mobility analysis and accessibility assessment for both vehicles and pedestrians. To validate accuracy, a comparative analysis with LiDAR-based point-cloud data from 151 locations demonstrated a strong correlation ($r = 0.775$, $p < 0.0001$) with an MAE of 0.633 m and an MAPE of 14.56%. While some errors indicated that there is room for improvement, the classification of alley accessibility into feasible, difficult, and restricted zones ensures sufficient accuracy for practical management and decision-making.

The proposed methodology is particularly beneficial for emergency response vehicle accessibility analysis and optimal route planning. Fire trucks, ambulances, and other emergency vehicles often face mobility constraints in narrow alleyways, where road width accuracy is crucial for rapid disaster response. This GIS-based estimation method provides essential decision-support information for evaluating emergency vehicle accessibility and optimizing response routes. Additionally, it contributes to urban road network management and disaster response planning, offering a practical solution to enhance emergency preparedness in constrained urban environments. Further refinement, considering the complexity of urban settings, could improve the overall accuracy and applicability.

ACKNOWLEDGMENTS

This research was supported by the National Research Foundation of Korea (NRF) grant funded by the government (Ministry of Science and ICT) (RS-2023-00210164). This work is also supported by the Korea Agency for Infrastructure Technology Advancement (KAIA) grant funded by the Ministry of Land, Infrastructure and Transport (Grant KAIA001434041G0003186).

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