



Title	Evacuation route selection based on tree-based hazards using LiDar and GIS
Authors(s)	Laefer, Debra F., Pradhan, Anu
Publication date	2006-04
Publication information	Laefer, Debra F., and Anu Pradhan. "Evacuation Route Selection Based on Tree-Based Hazards Using LiDar and GIS." American Society of Civil Engineering (ASCE), April 2006. https://doi.org/10.1061/(ASCE)0733-947X(2006)132:4(312) .
Publisher	American Society of Civil Engineering (ASCE)
Item record/more information	http://hdl.handle.net/10197/2307
Publisher's version (DOI)	10.1061/(ASCE)0733-947X(2006)132:4(312)

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Evacuation Route Selection Based on Tree-Based Hazards Using LiDAR and GIS

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ABSTRACT

Falling trees pose a great hazard to the safe and uninterrupted use of the road transportation system, during storm events. The present process of manually identifying potentially hazardous trees is laborious and inefficient. This paper presents a novel methodology for automating the tree threat identification process by using airborne laser altimetry data and a Geographical Information System (GIS). This methodology has the potential to be used for selecting the best possible evacuation routes based on tree hazards. The proposed method harnesses the power of spatial analysis functionality provided by existing GIS software and high-quality, three-dimensional (3D) data obtained from an airborne laser scanning system. This paper highlights the benefits related to using (a) height calculation of tall objects, (b) identification of hazardous objects, and (c) object identification from irregular 3D Light Detection And Ranging (LiDAR) point data over the currently employed manual methods.

KEYWORDS: Geographic Information Systems, Roadside Hazards, Highway Maintenance, Trees, Transportation Management, Highway Safety, Lasers, Evacuation

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INTRODUCTION

Wooded areas flank the primary and secondary road networks in many states. During severe weather incidents, fallen trees knock down power lines, endanger telephone lines, and block roadways. Besides disrupting traffic flow, such incidents endanger the lives of drivers and emergency crews, hinder service restoration, and impede effective emergency response. To avoid this, trees that may be a threat should be identified, and measures should be considered to prevent them from falling on overhead lines and thoroughfares. Before preventive measures can be considered, however, these trees must be identified. A manual approach to such a problem is not viable, because of the time and resources necessary for the initial assessment and the need for periodic updates. New technologies offer the possibility of automating such an identification process. With advances in Geographical Information System (GIS) and Remote Sensing (RS), an automated hazard identification tool can be developed for the aforementioned problem that is more economical, efficient, reliable, and safer than a manual approach. The ideal application of such an evaluation is in the selection of the most reliable evacuation routes. The goal of this research is to describe the development of such algorithms and the resources necessary to automate identification of trees that may endanger transportation routes.

BACKGROUND

Hurricanes, other strong winds, and ice storms cause tremendous damage across the United States (US) including flooding, wind-based destruction of property, and blockage of major road networks from fallen objects. The direct cost of such incidents can be in the billions of dollars, as was the case with hurricane Floyd in 1999 in eastern North Carolina (\$5.45 billion in damage costs) [Herbert et al. 1997], as well as indirect costs for economic losses due to closed businesses and lost productivity. The blockage of roads due to fallen trees and utility lines during severe weather is a significant problem (Draper 2003). According to the North Carolina Division of Emergency Management, after hurricane Isabel, Bertie County alone required tree debris removal from all roads in the county except three, totaling 780 km of road from which 52,865 cubic meter or 43,245.27 kg of debris was removed, at a cost of \$1.6 million, over the course of 84 days (Canty 2004). Beyond economics, posing a great risk to motorists, and interfering with utility service, roadway obstacles also disrupt traffic flow, and thus hamper evacuation and rescue operations.

The problem of tree-based hazards is well recognized, and each year millions of dollars are spent annually to identify and cut or trim such trees (Act 2003). In most states, identification of potentially hazardous tall objects has, to date, been done manually by road crews on an ad hoc basis. The task is significant. In North Carolina (NC) alone, there are 125,580 km of state maintained roads, not including 34,680 km of county and city roads (NC-DOT 2003) covering an area of 136,523 km² (State Library of NC 2004). Across the US, the national interstate system alone is comprised of 75,150 km of highway (FHWA 2003). As such, a manual approach to hazardous tree identification is cost prohibitive as well as time-consuming, especially since the effort would require periodic updates because of tree growth and road expansion. Thus, an automated process that is fast and potentially cost-effective, during initial identification and later updating, is critically needed.

At the most elementary level, for an automated tool to be effective it should be able to (a) identify the roads of interest, (b) locate tall objects, (c) calculate the heights of potentially hazardous objects along the roads, and (d) compare the height of the object to its distance from the roadway. The success of such an automated tool depends on both the quality of available data and a robust application that analyzes and processes the given data. As highly detailed data must be collected along the entire length of road network, data gathering becomes the most time-consuming and expensive part of the process. Light Detection And Ranging (LiDAR), a recent advancement in RS technologies, offers the potential of automated and expeditious data collection, and GIS provides a means to analyze and process such data.

LiDAR and Its Characteristics

LiDAR is an active remote sensing technology that is used to collect topographic data (NOAA 2003). The data are collected with aircraft-mounted lasers capable of recording elevation measurements at a rate of 5,000 to 50,000 pulses per second. The difference in time is measured from when a laser pulse is emitted from a sensor to when the target objects in the path of the laser reflect back the pulse. Using the speed of light, these time measurements can be converted into distance or range (Lim et al. 2001). The LiDAR instruments collect elevation data. To make these data spatially relevant, the positions of the data points must be known. Thus, a high-precision global positioning system (GPS) antenna, mounted on the aircraft, is used to determine the spatial positions of the data points. The end

product is accurate, geographically registered longitude, latitude, and elevation from the mean sea level (x, y, z) positions for every data point (Baltsavias 1999). Latitude, longitude, and elevation are typically presented in a plane co-ordinate system.

LiDAR is capable of providing both horizontal and vertical information at high spatial resolutions and vertical accuracies. Airborne-based LiDAR data are accurate to +/-15 cm for vertical measurements and +/- 1.5 m (worst case scenario) for horizontal distances (Flood 1999), although the system is marketed as having an accuracy of an order of magnitude better in both directions (ALTM 2003). The extent of LiDAR point density is dependent on flying height and system dependent factors such as platform velocity, sampling frequency, and field of view (Axelsson 1999). The point density needs to be adjusted according to the application so that sufficient information is harvested, while not collecting excessively detailed data. LiDAR technology has been used in many areas of applications such as (a) generation for a variety of GIS/mapping related products, (b) forestry, (c) coastal engineering, (d) flood plain mapping, (e) disaster response and damage assessment, and (f) urban modeling (Airbornelasermapping 2003).

A current limitation of LiDAR is that it does not store any topological, shape, or size information of the geographical features scanned. A LiDAR dataset is simply a collection of somewhat randomly distributed 3D points. As it does not provide feature information, clever and efficient algorithms are required for feature identification depending upon the desired application. Identification of tree hazards requires such an algorithm. LiDAR provides only qualitative data, thus software capable of analysis is also required. GIS possesses such capabilities.

GIS and Its Characteristics

GIS can be defined as a computer-based tool set for collecting, storing, retrieving, transforming, and displaying spatial data from a discipline-specific domain for a particular set of purposes (Burrough and McDonnell 1998). Although computer aided design (CAD) software can perform similar functions, the true strength of GIS lies not its ability to store and process data but in its spatial representation and spatial analysis (Rasdorf et al. 2000). Spatial analysis involves examining the geographic patterns in data and observing relationships between geographical

features. The actual methods for spatial analysis can be simple – just making a map after an analysis – or more complex ones, involving models that mimic the real world by combining many data layers. Thus, GIS is a software capable of performing complex spatial analysis operations (e.g. proximity analysis and buffering) on geographic data that would otherwise be too repetitive, expensive, and inaccurate to perform by hand (Longley et al. 2001).

GIS has established itself as an enabling technology to solve many transportation problems (Fletcher 1987, Nyerges and Dueker 1988). This specialized domain of GIS, particularly suited for transportation applications, is known as Geographic Information System for Transportation (GIS-T). GIS-T refers to the principles and applications of applying geographic information technologies to transportation problems (Miller and Shaw 2001). GIS-T is one of the leading GIS application fields and has been used in a wide variety of transportation areas such as infrastructure planning, design and management, transportation safety analysis, travel demand analysis, traffic monitoring and control, public transit planning and operations, environmental impact assessment, hazard mitigation, and intelligent transportation systems (Dueker and Kjerne 1989, Ries 1993). The core purposes of GIS-T are to (a) develop and enhance the GIS design to meet the growing needs of transportation applications and (b) facilitate and improve transportation studies (Miller and Shaw 2002). For road safety hazard management, GIS can help to identify hazards posed by specific man-made or natural objects. This paper describes the process of identifying hazardous trees that may endanger transportation routes.

EXISTING HAZARDOUS TREE IDENTIFICATION METHODS

Because of budget restrictions, across the US there is no generalized, method to identify hazardous trees, despite the acknowledged expenses that they generate. As an example of what is presently done, in the State of North Carolina, the Department of Transportation (NCDOT) has no formal procedure in place to identify hazardous trees. Instead, they are identified in ad hoc manner in several ways as outlined below (Watkins 2003):

1. On any given day, each county has approximately 7 to 20 separate crews working on specific tasks. During this time, the crews are instructed to identify all roadway hazards, including trees. When a potential hazard is located, it is reported to the Highway Maintenance Supervisor. Once the Highway Maintenance Supervisor

receives the report, a physical investigation is conducted to determine, if the tree is on the NCDOT right of way and the urgency of the potential hazard. The tree may then be scheduled for trimming or removal, based on this information.

2. Each autumn, every county has a snow day. During this time, the snow truck operators drive their assigned section of roads. These operators are also asked to look for roadway hazards and to report them to the Highway Maintenance Supervisor.
3. Every two years, a pavement condition rating is conducted. This consists of pavement inspectors driving each paved road and rating the pavement. Again, if a hazard is spotted, the Highway Maintenance Supervisor is notified.
4. Lastly, the general public calls to report roadway hazards.

The process of hazardous tree identification is in part empirical as the 1996 AASHTO Roadside Design Guide is generally used to determine ideal clear zone distance criteria (AASHTO 1996). These distances are not, however, always practical (AASHTO 1996, Michigan DOT 2004). A survey of 20% of the DOTs, focusing mainly on states with large tree growth and severe weather problems, established that most states were highly reactive in their approach and did not have the resources to do more than respond to calls from the public or from maintenance workers, who happened to notice a potential hazard (Table 1). A few states such as Virginia and Oregon have a handful of foresters and/or arborists, but they also operate on a hazard call basis. Wisconsin has a more extensive pavement management system than most states (COMPASS 2003). The program is entitled COMPASS, but tree hazards are not included. However, each section of roadway does have a patrol that is entirely devoted to driving up and down designated routes on a daily basis to look for all types of hazards (Stark 2004). The other exception to the call and respond system is the state of Florida (Allen 2004).

Florida's Department of Transportation (FDOT) has developed a formal procedure as a part of a highway maintenance program. Every 3 years, a computer program is used to randomly generate 3 segments (each 1/16 km in length) for a given section of highway, if it is less than 16.1 km long, in terms of its paving type and general characteristics. For those road sections over 16.1 km in length, 30 segments are randomly selected. Highway maintenance crews are assigned to those segments for general hazard assessment but do have specific tree related

activities defined. The distance of each tree from the road is measured, along with the tree's diameter, and its height is surveyed from the road in order to measure distances of trees from the road. FDOT claims that this process has a reliability factor of 95% (Allen 2004).

An alternate approach to casual visual observation to manually identify the heights of the tree is to use a hypsometer. A hypsometer is a device used to measure angles and distances to points on the tree, from which height is derived. Geometric or trigonometric principles are embodied in the use of hypsometers. Correct use of a hypsometer depends on the state of the tree (leaning or vertical) and the position of the observer (observer's eye upslope or down slope, with respect to the base of the tree). The necessary information and measurements are recorded in a field book. Alternatively, total station surveying devices can also be used to measure the height of a tree, as long as the tree height does not exceed the ability to position a reflector. To employ total station surveying, substantial cost would be incurred to setup and shoot all the trees along a road. Except for Florida, none of the DOTs surveyed reported using such procedures.

Most of the states reported that the majority of the tree problems experienced were on the secondary road system as (1) the clear zone was not as large as that for interstate system, (2) the areas tended to be flanked with more trees, and (3) available resources per kilometer were less. Manual methods for these thoroughfares are prohibitively expensive, when one considers the length of the road system, periodic tree growth, labor costs, and tree density adjacent to roadways.

PROPOSED METHODOLOGY

The research described herein adopts a unique technique to identify and assess potentially hazardous tall objects: (a) buffer calculation, (b) elevation characterization, (c) shortest distance determination, and (d) feature identification. To achieve these four tasks, the proposed method employs a LiDAR dataset, a centerline GIS data set of the road network, and multi-spectral imagery.

Study Area, Data Characteristics and Software used

An area of 3,050 m x 3,050 m in Edgecombe County of North Carolina was chosen for analysis (Figure 1).

The area was selected primarily due to the availability of all the required data for the project: LiDAR data, centerline road data, and multispectral aerial imagery. Bounding co-ordinates of the given area are as follows:

Southwest Northing: 231,648 m

Southwest Easting: 725,424 m

Northeast Easting: 728,472 m

Northwest Latitude: 234,696 m

(a) LiDAR Data

LiDAR data was collected and processed by the North Carolina Floodplain Mapping Program, as part of a statewide effort to modernize FEMA Flood Insurance Rate Maps (FIRM) in response to the extensive damage caused by Hurricane Floyd in 1999 (NCFPM 2003). Although created for a specific use, namely the engineering aspects of floodplain delineation, the data were also developed to address the elevation requirements of the broader geo-spatial data user community.

The LiDAR data was collected January through March in 2001 and is represented as point data containing the co-ordinates of X, Y, Z in an ASCII file format. The projection is NAD83, North Carolina State Plane, and the original data units are in feet. The bare-earth data are required to have a vertical RMSE of 20-cm for coastal counties and 25-cm for inland counties, computed after discarding the worst 5% of the checkpoints to account for un-cleaned artifacts (NCFPM 2003).

(b) Road Data

The centerline road data were collected and produced by NCDOT. In a centerline GIS road data set, the center of the road is captured as an identifiable feature and presented in a vector-based format. The projection is NAD83, North Carolina State Plane, and the original data units are in feet.

(c) Multispectral Aerial Imagery

This imagery was obtained from the Department of Marine, Earth and Atmospheric Science at North Carolina State University (NCSU) and was corrected for across-frame anisotropic reflectance, georeferenced, and orthorectified using ERDAS Imagine. The projection is also NAD83, North Carolina State Plane, and the original data units are in feet.

Environmental Systems Research Institute (ESRI) ArcInfo™ 8.2 was primarily used for the spatial analysis, while ESRI ArcMap™ 8.2 was used for the visualization, tabular querying, and manipulation. The following provided functions were employed:

- Buffer
- Pointdistance
- Table Querying and Manipulation
- Identify

The algorithm flowchart for the proposed automated methodology is shown in figure 2. The first step is the buffer calculation.

Buffer Calculation

Airborne LiDAR systems are capable of producing extremely detailed information of even small scanned areas (Baltsavias 1999), but to achieve a high level of detail requires substantial processing time. An effective measure to counter such resource intensiveness, while not losing the desired level of detail, is to reduce the dataset size. Since data points beyond a certain distance from the centerline of a road do not contribute to the analysis, as any potential falling hazard exceeds the distance to the road, these points can be excluded. In order to select the relevant data points, a buffer zone can be created around the road network; should fringe lane data be available, instead of centerline data, an even more accurate evaluation is possible. Only points that lie within the defined buffer zone are selected. A comparison of 2 data groups (figures 3 and 4) presents the benefits of a buffer zone. In figure 4, only

points within a 120m buffer zone (60m from each side of the center of the road) are included. In this simple example, the number of data points was reduced by 83%, which decreased computation time by 67% compared to the time needed to process the non-buffered data. The criterion for a 120m buffer zone was based on the assumption that the maximum height of any tree is 60m; this parameter is easily changed to reflect local vegetative growth patterns.

Comparative Elevation Calculation

Once a buffer zone is established, the LiDAR points within the buffer zone need to be analyzed. A LiDAR dataset can be procured in two different categories. One dataset represents a reflective surface elevation model [also known as Digital Surface Model (DSM)], which contains elevation data from the ground, as well as from vegetation, tree canopy, and other features such as buildings. The other dataset represents “bare earth” ground points, which excludes additions to the terrain. Such a dataset is also called the Digital Terrain Model (DTM). The difference between the elevation values from the DTM and DSM datasets represents the height of any natural or man-made objects such as trees, utility poles, or buildings that are situated on the bare ground. Height information above bare ground surface is important to determine the potential hazard posed by any tall object within the buffer zone. The height column is the elevation difference for LiDAR points 0001-0004, whereas the distance column reflects the respective shortest distance value to their nearest road segments. The development of the bare earth model is a complex and error prone process, as it relies on the quality of the input data.

Shortest Distance Calculation

After the height calculation is completed, the shortest distances between the LiDAR points (within the buffer zone) and their adjoining road are calculated by subtracting half the road distance from the centerline position location (Table 2). GIS based applications can determine the shortest distance between a point feature and a line or polygon feature. In this project, ArcInfo™ from ESRI is used to perform the shortest-distance calculations. The distance between the LiDAR point and its adjoining road centerline is stored as attribute data for the corresponding LiDAR point (Table 2).

Vulnerability Analysis

The objective of the vulnerability analysis determines those LiDAR points that represent potentially hazardous trees. After the shortest distance calculation is conducted, the elevation of an individual LiDAR point above bare earth elevation is compared with its shortest distance to the road edgeline [Eqn. 1]. If the elevation of any LiDAR point represents a height that is greater than its calculated, shortest distance to the adjacent road, the object representing the corresponding point may pose a threat to the road, should the tall object fall perpendicular to the road. Figure 5 depicts a fallen tree of height H_i at distance L_i from the roadside. In this example, H_i is greater than L_i , thus the fallen tree blocks a portion of the road.

$$\textit{If height above bare earth} > \textit{shortest distance to adjacent road, then object hazardous} \quad (1)$$

$$\text{if } H_i > L_i, \text{ then object} = \text{hazard}$$

Table 3 shows that in this data subset only points A and D are at elevation values greater than their shortest distance values. Points A and D, thus, represent potentially hazardous objects.

The potential threat of a tree depends not only its height and its distance from the road but on whether it is elevated or depressed. With the relatively simple approach proposed, there is an overestimation of the hazard, based on tree projection. A more precise calculation would require cross-section elevation. Although the cross-section elevation can be generated from bare earth LiDAR data, the analysis is relatively complicated as it would have to be repeatedly done for every section, where a tree is present. This would substantially increase processing time and provide only a marginal increase in accuracy that would still have to be verified through field inspection, prior to any tree removal or intervention technique. Thus, the relatively simple approach presented here can be considered more economical.

Risk Assessment Prioritization

Hazard identification is the first step to risk assessment prioritization. The next step is determination of the level of threat that a specific hazard presents by establishing how much of the road a fallen tree may cover (Figure 5a). The vulnerability (V_i) ratio (eqn 3) can be considered as the total percentage of road width crossed by the fallen objects, where R_i is the width of the road (Figure 5b).

$$V_i = (D_i) / R_i \quad (2)$$

$$\text{where } D_i = H_i - L_i \quad (3)$$

which is the maximum distance over which the tree can cover the road. The percentage of the road pavement that might be impacted should actually be considered the sweep over which the tree may fall (eqn 4) [Figure 5b] subtracted by the non-pavement portion (eqn 4) to assess the full area of vulnerable pavement (eqn 5). This procedure serves as a preliminary screening of how traffic on a particular road would be impacted. More sophisticated evaluation measures could be made by expanding the algorithm to make the risk status related to the significance of the road closure. For example, the traffic volume could be considered, and whether or not alternate routes exist could be incorporated as part of the evaluation process. Such a feature, however, is beyond the scope of this paper.

Based on trigonometric geometry, the total area over which the tree may land is

$$A_T = H_i^2 (\theta/2) \quad (4)$$

where A_T is the total area over which the tree may land and θ is the angle of sweep (Figure 5b). The area of the pavement that is vulnerable (A_p) is calculated by subtracting the area of the surface that is not paved (A_s) from the total area (eqns 4-6).

$$A_s = L_i^2 \tan(\theta/2) \quad (5)$$

$$\text{where } \theta = 2 \arccos(L_i/H_i) \quad (6)$$

$$A_p = A_T - A_s \quad (7)$$

Such critical areas can be easily identified and calculated with the aid of GIS software. Using such a relationship, the areas potentially impacted per kilometer of road could be summed, and a rating system could be developed to compare that area impacted with a usage based parameter. Alternatively, the relationship could be coupled with a criticality evaluation, based on alternatively available routes and the likelihood of those alternative routes being blocked. Such assessments could become the basis for more informed evacuation route selection.

Feature Identification

The proposed vulnerability analysis locates threat-posing LiDAR points. Yet, the physical, real-world objects constituted by those points still remain indeterminate. Since a LiDAR dataset is simply a collection of points, the set lacks the capability of storing information about the shape or attributes of the object represented by the group of points. In order to identify the shape and dimension of objects, an algorithm is required. At present, many such algorithms are being developed both by commercial and academic institutions for similar pursuits. For instance, to generate three-dimensional (3D) reconstructions of buildings in urban areas, Haala and Brenner (1999) proposed the combination of multispectral imagery and laser altimeter data (LiDAR) in an integrated classification. Multispectral aerial imagery is defined as the remotely sensed data that captures the reflectance of topological features such as buildings, vegetation, land, etc, (based on their chemical compositions) in multiple regions of the electromagnetic spectrum. This process helps to distinguish specific natural and man-made objects, based on their reflectance values in the electromagnetic spectrum. To generate similar outputs, Mass and Vosselman (1999) suggested two other algorithms for extracting building models from raw LiDAR data based on the invariant moments of LiDAR points to extract building models in conjunction with an analysis of deviations between point data and model (Mass and Vosselman 1999).

The main objective of all of the aforementioned algorithms is to extract features, especially those related to geometry, from the LiDAR points. The scope of the above referenced published work encompassed only the objectives related to achieve 3D visualization with no particular, identifiable, engineering application proposed.

Based on these general concepts, the work presented here is a comparatively streamlined methodology, without complex implementation or excessive computation.

The approach employs multispectral aerial images to classify the threat-posing LiDAR points into various features such as trees and utility poles, similar to the work done by Haala and Brener (1999). As the spectral bands of trees, utility poles, and other tall objects are distinct, the LiDAR points belonging to trees or utility poles can be distinguished with the automated overlaying of a multi-spectral aerial image atop the LiDAR points. The data from both LiDAR and multi-spectral aerial image are required, since the utility poles and trees have small surface coverage. After the groups of points are classified into different categories, the points that represent a single feature need to be identified as belonging to a single item. The approach uses buffering to group LiDAR points belonging to a hazard area. Earlier in the analysis, the buffer region is defined in order to restrict the number of LiDAR points to minimize computational time. The main objective of this grouping of the LiDAR points belonging to one particular feature is to count the number of clusters of hazard-posing objects for intervention prioritization. Since a feature can be represented by multiple points, the grouping of LiDAR points is required to avoid counting the same feature multiple times. In order to achieve this, a second buffering process is implemented. A buffer region of a certain distance is created around the threat-posing LiDAR points. If a point shares a common buffer zone with another point, it can be considered that these two points belong to a same feature (Figure 6). The selected buffer depends on the average diameter of the utility pole or tree crown. For instance, by using a 1.5 m diameter tree crown for a buffer analysis, 279 separate LiDAR clusters were identified as belonging to threat-posing objects, within the study area in Edgecombe County of North Carolina. Thus, multiple LiDAR points belonging to a single cluster are discarded. By reducing the number to more accurately reflect the true number of groups of hazardous objects, better intervention prioritization can occur (Figure 7).

RESULTS

In December of 2003, two inspectors were sent to the study area to conduct visual hazard identification assessments. The inspectors followed current NCDOT procedures by slowly driving along each side of the road and visually estimating whether or not a particular object was sufficiently tall and sufficiently close to the road to pose a hazard. The close spacing and small diameters of the trees made precise identification particularly difficult. Inspector A

identified 349 separate objects, while inspector B counted 372. The two inspections yielded results that were within 10% of each other. The automated procedure resulted in only 279 objects. The manual procedure has the following shortcomings.

1. Most conspicuously, the proximity of the inspector to the trees appeared to substantially overestimate the number of hazards.
2. Because of tree density, cluster identification was not possible. All objects received equal weight. Therefore, no prioritization could be made. Areas with 1 or 2 trees were listed as hazardous as those with 6 or 8; further system refinement could include algorithms to identify how many hazardous items exist along a specified road length.
3. The precise location of the tree could only be accurately documented for later inspection by resetting the vehicle's odometer for each length of road.
4. The potential number of lanes that might be blocked should the object fall perpendicular to the road was impossible to assess, whereas the automated system can do this through eqn 3.
5. The inspectors must drive slowly along busy or partially obstructed roadways, thereby, potentially generating a hazard and endangering the inspectors and other drivers.

Currently, the automated process is more expensive than manual process. To conduct the overview of approximately 3.2 km of road required allocation of a vehicle and two inspectors for 1.5 hours. Based upon NCDOT pay rates (NC-DOT-PAY 2003) and a Means' cost analysis (RSMMeans 2003) for two workers (\$9/hour/person) and a vehicle (\$20/hour), the total was \$38 per hour assuming coverage for both sides of the road. The cost for the given study area is \$57. In contrast, the cost of procuring LiDAR data is approximately \$386-\$772 per square kilometer for 1 to 2-meter postings (NOAA 2004). Thus, for the given study area of 3.050 km x 3.050 km with an average cost of \$579 per square kilometer, the total cost for the automated data procurement is approximately \$5,386. Although the current cost of automated data would be prohibitive, the expense can be offset, when the data is being collected for other efforts as in the case of North Carolina Flood Mapping Project (NCFPM 2003). As such procedures become routine and the cost of technology decreases, this automated approach may eventually serve as a cost effective method by itself.

One unique feature that this method offers is to be able to more effectively identify more reliable evacuation routes: specifically routes, which encompass the fewest number of potentially hazardous trees. Additionally, flyover data need not be collected every year. By integrating growth trends for local vegetation, the values for H_i can be automatically augmented annually, thereby precluding the need for frequent flyovers for data collection. With annual tree growth projected, a correction can simply be built into the calculation equation (eqn 2).

$$H_n = H_i \times (1 + G)^n \quad (8)$$

where G equals an average growth factor based on local vegetation and environmental conditions, n is the number of years since the flyover was conducted, and i is the point of interest. Here H_n would be substituted, wherever H_i was previously used.

CONCLUSIONS

An automated tree-hazard prediction methodology that utilizes GIS and high quality remotely sensed data offers substantial advantages over existing manual process in terms of safety, speed, and efficiency. In this study, LiDAR data was used to obtain the heights of the trees, which circumvented the need for time consuming field inspection. This method avoids the extensive use of labor in surveying long lengths of highways. In addition, LiDAR is a safe way for data collection, as the data collectors are not exposed to roadway traffic hazards. In North Carolina, LiDAR data was collected as part of flood mapping program, thus its simultaneous use for establishing road inventory data collection, basemap creation, and hazard object identified allowed data availability and usage at nearly no cost. Since the identification process is automated and computationally efficient, the process is many times faster than manual approach and can be achieved in a systematic and automated fashion. Thus, the deployed method demonstrates the capability of 3D LiDAR data combined with GIS-based software to identify potentially hazardous tall objects adjacent to major roads. Such a system can render substantial help to optimize evacuation route selection.

ACKNOWLEDGEMENTS

The authors thank Dr. John Stone of North Carolina State University (NCSU) and the Southeastern Transportation Center at the University of Tennessee at Knoxville for their generous support of this project. The authors also thank Dr. David Bloomquist of the University of Florida at Gainesville for suggesting automation of tree-based hazard analysis. The data were obtained from Ms. Sarah Wray, the North Carolina Emergency Agency, the North Carolina Department of Transportation, and the Department of Marine, Earth and Atmospheric Science at NCSU.

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TABLE 2. Attribute Table of LiDAR Points for Height and Distance Identification

TABLE 3. Vulnerability Analysis

TABLE 1. Tree Identification Methods Employed by Various DOTs

State	Actions Undertaken
Maine	Respond to calls by public or staff (Brune 2004)
Georgia	Respond to calls by public or staff (Frazier 2004)
Oregon	Respond to calls by public or staff (Lepschat 2004)
Michigan	Focus on dead tree removal; previously had a forestry crew but no longer; now most further rely on maintenance staff (Heme 2004)
California	Sight distance policy focusing on branch trimming (Brown 2004)
Virginia	20 feet clear zone, mostly branch trimming based on calls (Cline 2004)
Alabama	60 feet clear zone; replace trees on back slopes with grass and flowers (Newsome 2004)
North Carolina	Annual inspection as part of larger hazard identification program (Watkins 2003)
Florida	Randomized sampling program every 3 years (Allen 2004)
Wisconsin	Daily segmented patrolling as part of larger hazard identification program (Stark 2004)

TABLE 2. Attribute Table of LiDAR Points for Height and Distance Identification

Shape	Location Identification	Height, H_i (m)	Distance, L_i (m)
Point	0001	56.36	49.23
Point	0002	22.54	57.68
Point	0003	35.21	62.35
Point	0004	19.32	15.26

TABLE 3. Vulnerability Analysis

Shape	Identification	Height, H_i (m)	Distance, L_i (m)	$H_i - L_i$ (m)
Point	A	56.36	49.23	+7.13
Point	B	22.54	57.68	-35.14
Point	C	35.21	62.35	-27.29
Point	D	19.32	15.26	+4.06

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FIG. 5a. Measurement of Tree across the Road.

FIG. 5b. Impact of the Downed Tree.

FIG. 6. Proposed Buffer to Account for Tree Crowns.

FIG. 7. Hazard Posing Tree with Defined Crown Diameter and Background Removed.

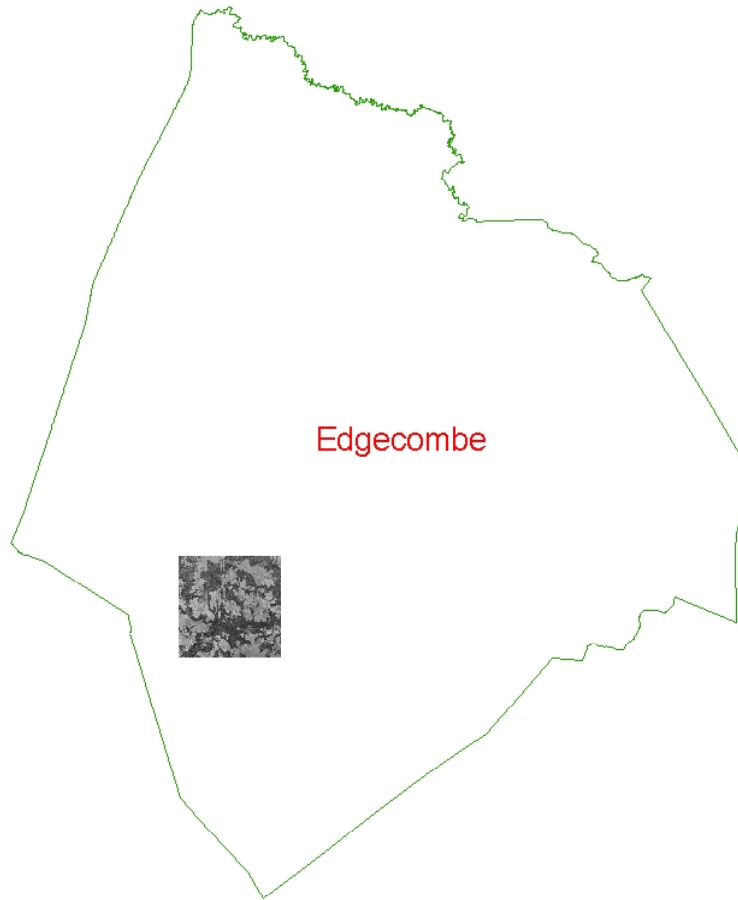


FIG. 1. Study Area (Figure to Scale).

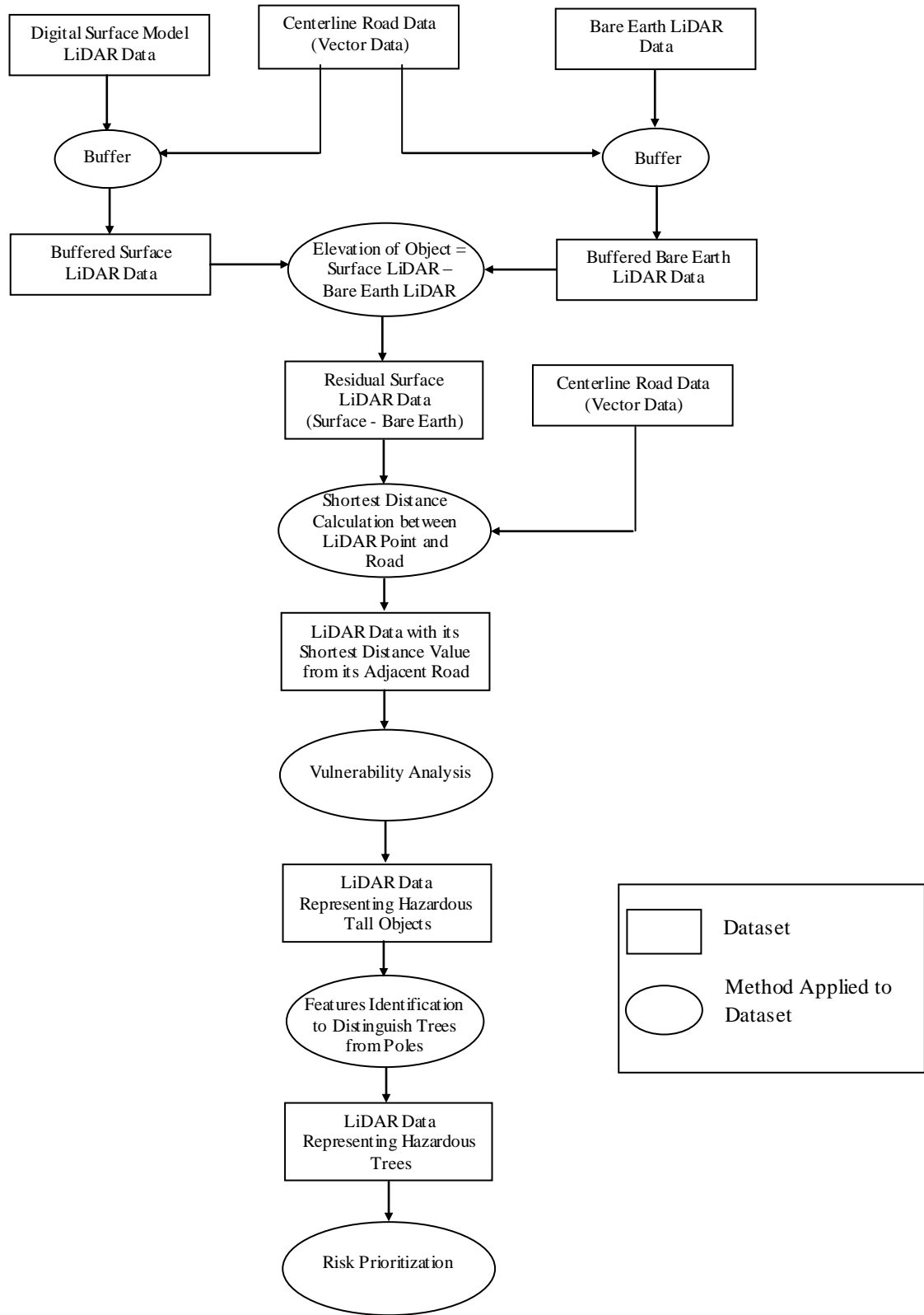


FIG. 2. Algorithm Flowchart.

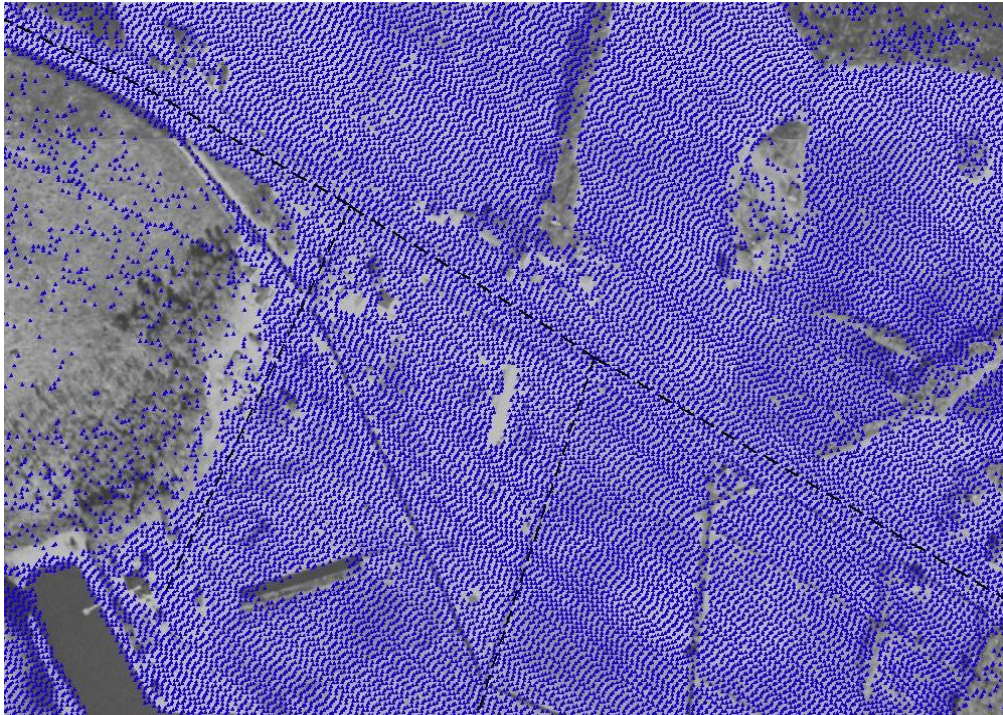


FIG. 3. LiDAR Points and Road Segments without Buffer Zone.

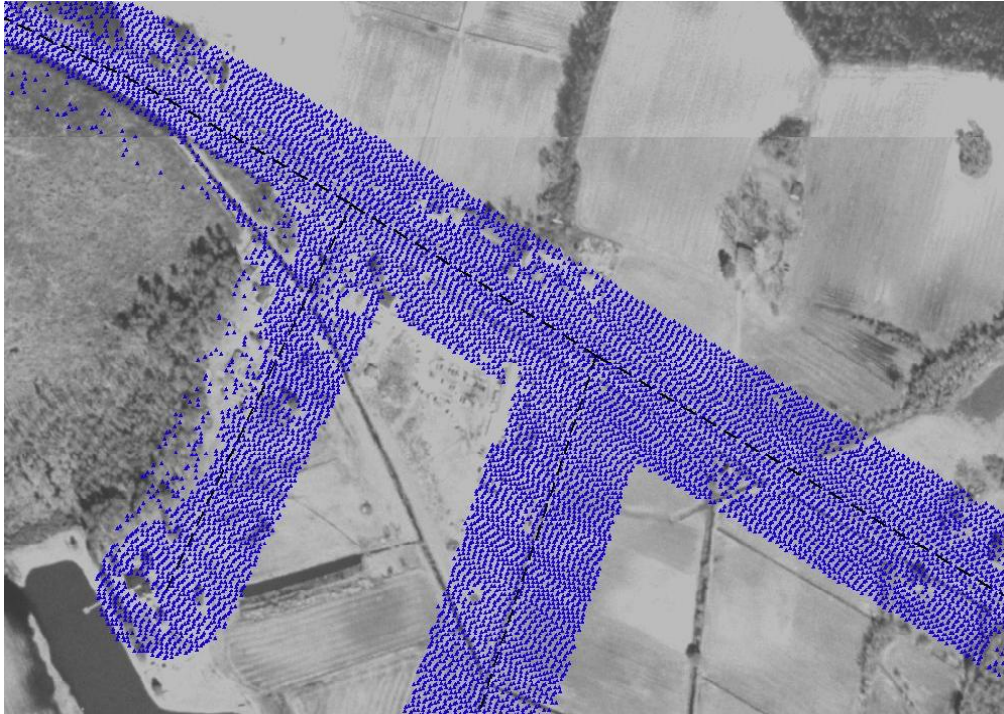


FIG. 4. LiDAR Points and Road Segments with 120 m Buffer from Road Centerline.

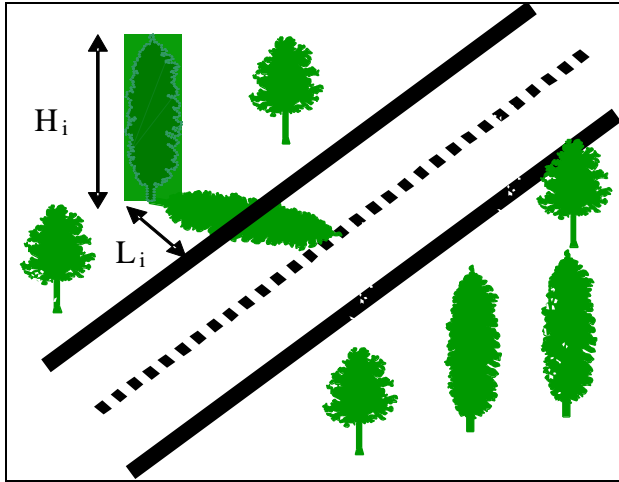


FIG. 5a. Measurement of Tree across the Road.

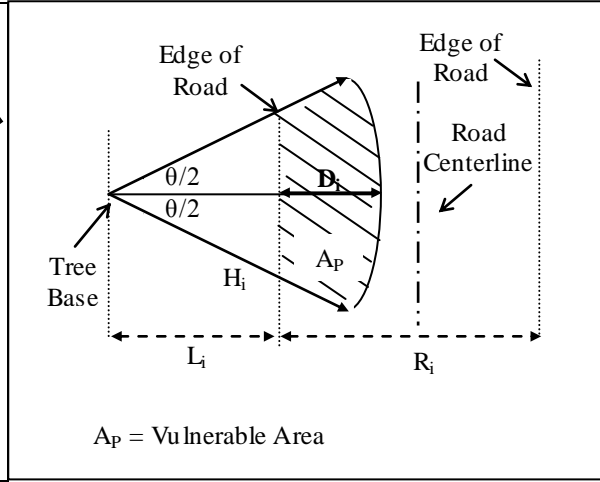


FIG. 5b. Impact of the Downed Tree (Plan View).

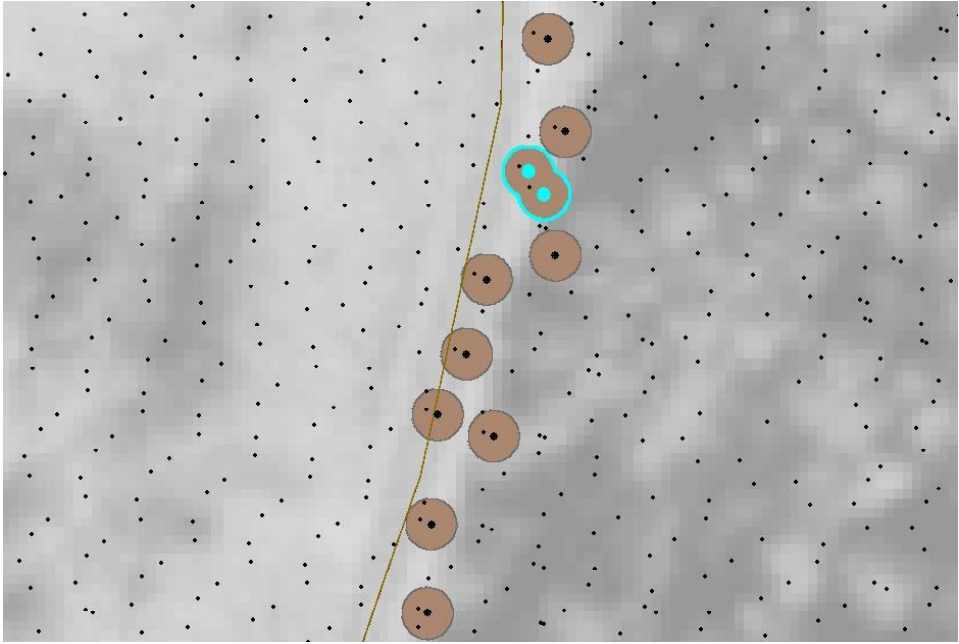


FIG. 6. Proposed Buffer to Account for Tree Crowns.

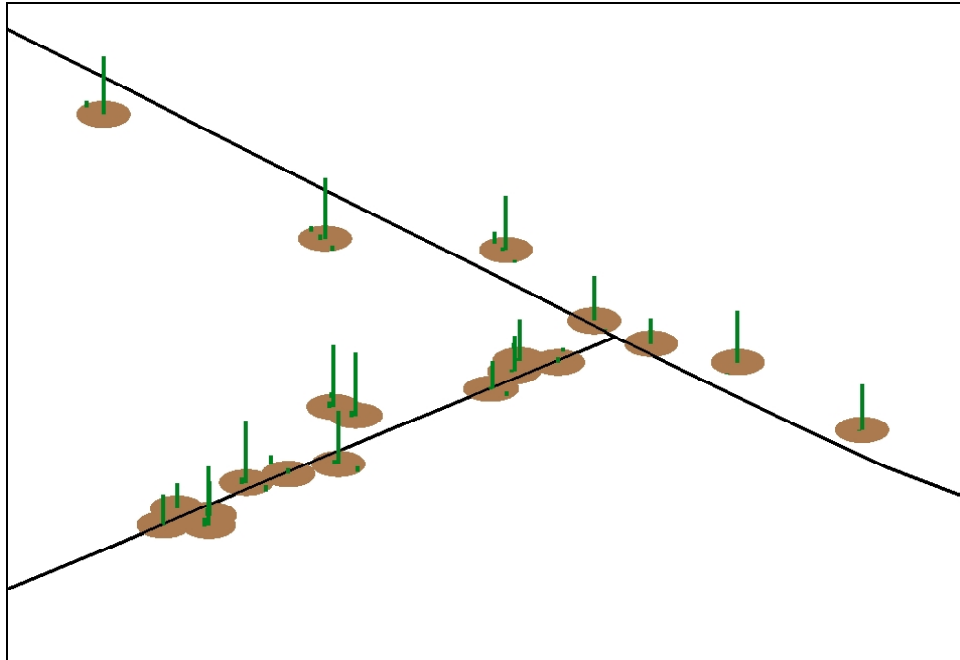


FIG. 7. Hazard Posing Tree with Defined Crown Diameter and Background Removed.

Evacuation Route Selection Based on Tree-Based Hazards Using LiDAR and GIS

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