SATELLITE REMOTE SENSING AND TRANSPORTATION LIFELINES: SAFETY AND RISK ANALYSIS ALONG RURAL SOUTHWEST ROADS

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ABSTRACT

The availability of high resolution commercial remote sensing has contributed to a revolution in the application of satellite Earth Observation (EO) methods to the analysis of transportation networks. Other geospatial technologies, including GIS and the GPS, sharply enhance the utility of EO data in identifying potential road hazards and providing an objective basis for allocating resources to reduce their risks. In combination, these powerful information technologies provide substantial public benefits and increased business opportunities to remote sensing value-added firms.

This paper reports on research aimed at developing a set of methods designed to assist road departments in rural jurisdictions (local, county, state) improve the trafficability of the roads under their management. We are developing and testing these methods in the U.S. Southwest, where thousands of kilometers of unimproved and graded dirt roads cross Native American reservations. This generally arid region is nevertheless subject to periodic summer rainstorms and winter snow and ice, creating hazardous conditions for the region's transportation lifelines.

Data sources include Ikonos imagery and digitized aerial photographs of rural roads in Northeast Arizona and Southeast Utah, as well as digital terrain models from the U.S. Geological Survey. We have analyzed several risk factors, such as slope, road curvature, and intersections, by means of multi-criteria evaluation (MCE) both on unimproved and improved roads. In partnership with the Hopi Indian Nation in Arizona, we have acquired and analyzed GPS road centerline data and accident data that validate our methodology.

The methods we have developed will lead to less expensive means of analyzing the risks and hazards along paved and unpaved roads of the American Southwest. They are also transferable to international settings, particularly in similarly arid climates.

INTRODUCTION

The proliferation of government and commercial satellite remote sensing systems over the past several years (Stoney, 2001) has led to an opportunity to use Earth observations (EO) data in many new ways. The advent of high-resolution commercial systems capable of imaging Earth's surface at 1 meter resolution or better, is rapidly advancing the application of satellite EO methods to transportation networks (Jensen and Cowen, 1999). These high-resolution image products will undoubtedly enhance our ability to model complex patterns in transportation; patterns that might otherwise remain unnoticed by local officials lacking such tools and technologies. Other geospatial technologies, including GIS and GPS, sharply enhance the utility of EO data in identifying potential road hazards and providing an objective basis for allocating resources to reduce or eliminate them (Launen, 1993; Bajikar, 1997; Czerniak and Reilly, 1998; Miller and Wu, 2000; Goodchild, 2000). In combination, these powerful information technologies provide substantial economic benefits and increased business opportunities to remote sensing value-added firms. In particular, recent advances in Geographic Information Science and decision support have resulted in a set of new techniques for efficient integration of different GIS and remotely sensed data layers to map composite risk along certain sections of roadway. The use of multi-criteria evaluation (MCE) and fuzzy sets allows users to assign different weights to risk factors leading to more realistic portrayal of overall or composite risk. The combined use of MCE and fuzzy sets can help decision-makers determine which risks are most important, provide insights into value judgments, and ultimately decide where hazard mitigation strategies should be employed. Such mitigation strategies might include placement of signage, road widening, barrier placement, slope stabilization, or other engineering techniques used to reduce risks along roadways.

This paper reports on research aimed at developing a set of methods designed to assist road departments in rural jurisdictions improve the trafficability of the roads under their management. We are developing and testing these methods in the U.S. Southwest, where thousands of kilometers of unimproved and graded dirt roads cross Native American reservations. Adverse weather can reduce trafficability and even cause portions of these roads to become impassable, limiting access of emergency vehicles. Because of the steep terrain and lack of dense ground cover (discussed in the following section), flash floods resulting from sudden, intense rains are also common. Low lying road portions may become flooded with rapidly rising waters, making some roads dangerous or impossible to traverse. The resulting rutted surfaces remain long after the surface dries, increasing the danger of navigating these roads. Improved roads may become impassable as a result of mudslides or subsurface erosion. Not only do such conditions severely reduce road safety, they make it difficult for local residents, often widely dispersed, to reach their jobs and schools. Not surprisingly, road safety and trafficability are therefore among the most important public issues cited by residents. Therefore, any tool or set of tools that could allow local transportation planners to effectively *predict* where accidents might occur and take corrective would be of enormous value.

This project is one component of a larger effort to improve safety and reduce hazards in U.S. transportation networks: the National Consortium on Research in Transportation (NCRST) (http://www.ncrst.org). As part of this larger effort, a consortium of three universities—the University of New Mexico, the University of Utah, The George Washington University, and York University of Canada—along with members of the staff of Oak Ridge National Laboratories, is focused on exploring the issues of safety, hazards, and disaster assessment in transportation lifelines (http://www.trans-dash.org).

THE PHYSICAL SETTING

The Hopi Reservation is located on western edge of the Colorado Plateau within the northern half of the State of Arizona, and is surrounded by the much larger Navajo Reservation (Figure 1). The Hopi lands cover approximately 630,000 ha. Elevation ranges from approximately 1600-2000 m and the topography is characterized by a series of broad mesas (or plateaus) separated by shallow canyons and broad, gently sloping valleys. Generally, slopes on the Reservation range from steep to gentle, averaging about nine percent. Along the edges of the reservation's mesas, slopes steepness may exceed 200 percent (approximately 62 degrees).

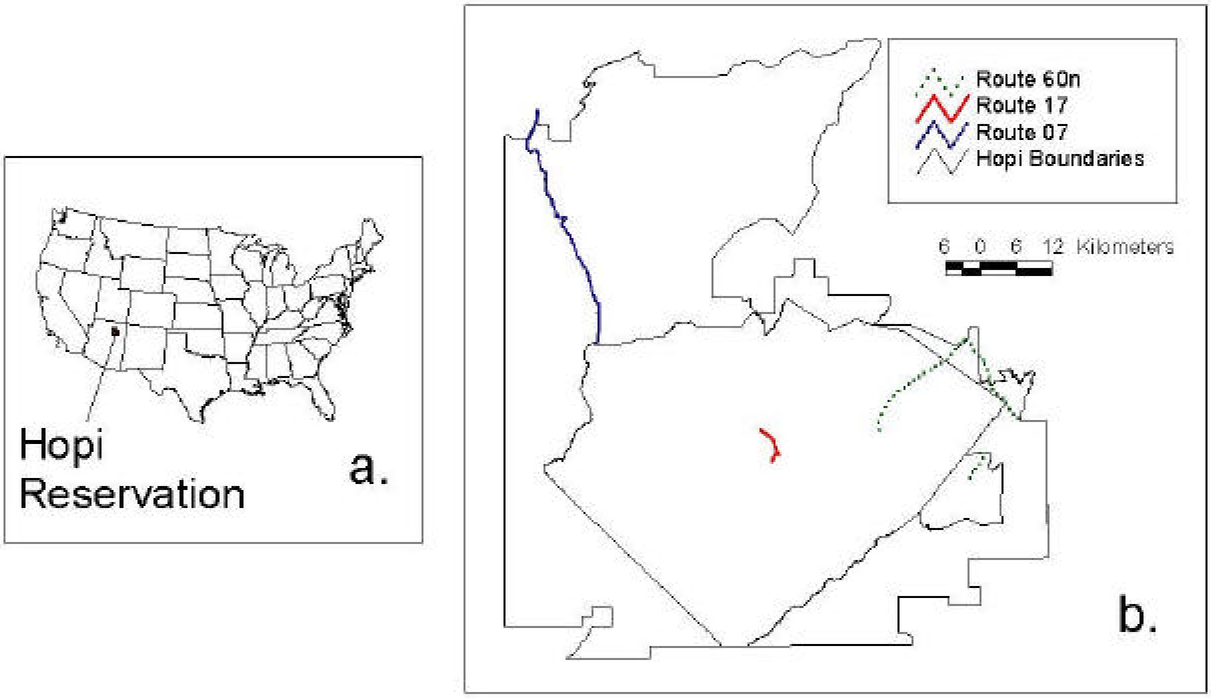

Figure 1. Maps of the Hopi Reservation: a. Location in the USA; b. Road segments analyzed.

The climate is continental/temperate with hot summers and cold winters. Average daily high and low temperatures range from 5^{o}/-6^{o}C in winter and 32^{o}/15^{o} in summer. The region is semi-arid, receiving an average of approximately 200 mm of rainfall per year. Consequently, vegetation cover tends to be quite low. Thunderstorms are frequent in the summer months, although spatial variability of rainfall can be extremely high. Snow and ice are rare in the winter months and therefore do not tend to represent major hazards.

Soil scientists have recognized some 40 different soil classes on the Hopi Reservation. The soil distribution is complex and governed mainly by the extensive sedimentary parent materials (principally sandstones and shales) and topography. Soils with sandy-loam texture are most common, although soils with significant clay content are often found in areas of gentle slope, near intermittent water-courses (known locally as “washes”) in the valleys.

Three classes of roads cut across the Hopi Nation: paved highways maintained by the state of Arizona; graded dirt roads, which are maintained by the Bureau of Indian Affairs, an agency of the U.S. Department of the Interior; and a large network of informal roads, some of which receive occasional grading. Dirt roads are readily passable for much of the year although moderate to heavy rainfall in areas of clay soil greatly reduces tire traction, thus rendering many dirt roads impassable for brief periods (usually several hours). As mentioned above, sudden downpours can also wash away road surfaces, thus cutting off important transportation lifelines on the Reservation. Other notable hazards include variations in road width due to the placement of drainage structures (culverts) and cattle guards, high curvature (i.e., sinuosity), rock-fall and slide hazards in areas of steep slope, and intersections. Each of these variables is being treated as a risk factor in our analysis of transportation risks associated with the roads on the Reservation.

RESEARCH METHODOLOGY

The Hopi Nation has made significant investments in remote sensing, GIS, and GPS technologies. Further, the Nation has a federal requirement to develop a long-term plan for its road system. Staff members of the Research and Planning Office and Lands Office are also skilled in GIS and GPS and use them as integral parts of their efforts. Our research partners in these offices have supplied us with an initial set of georeferenced data layers, including a set of digital orthophotos (1 meter spatial resolution), and a moderate resolution (10-meter) digital elevation model (DEM). Although we would have preferred to use Ikonos panchromatic and multispectral data for the first phase of this research, the relatively high cost of these data has prevented their use. Instead, we are using the digital orthophotos of the area prepared by the U.S. Geological Survey. These data have the distinct advantage that they cost less than $10 per 3.75-minute quadrangle. However, the digital ortho quarter quads (DOQQ), as they are called, have the distinct disadvantage that because they are derived from periodic aerial surveys, they do not reflect the most recent changes in the road network. In fast growing areas like many of the U.S. suburbs they very quickly fall out of date. Thus, for many applications, recently acquired high-resolution satellite data are preferable. Nevertheless, for research purposes, they are excellent substitutes for the more expensive satellite data. Table 1 lists the baseline data sets used in our analyses thus far.

From the DOQQs, we digitized washes and intersections using raster-based GIS software (Idrisi32). The main advantage to using this particular software is its advanced decision-support capabilities for use in land allocation, suitability mapping, and risk assessment. Linear and point features were rasterized to a 10-meter grid, which corresponds to that of the DEM—the most spatially coarse of the data layers. We also utilized the GIS software to create derived layers depicting the distance from hazardous features, namely washes, intersections, steep slopes, and culverts. We evaluated the accuracy of features digitized from the DOQQs with a GPS in the field during an August 2001 visit to the Reservation. We used both a hand-held Garmin GPS as well as a RedHen Video Mapping System, which provides post-processing differential correction for position and elevation. Thus, we were able to evaluate the accuracy of the DEM, which is one of the most important layers given the highly variable, steep topography of the Reservation.

Since our initial goal was to map areas of high risk along roads, we utilized a set of procedures to standardize and combine data layers to create composite risk maps (Figure 2). Standardization of each data layer to a common set of values was performed using the Fuzzy module in the Idrisi32 software (Eastman, 2001). This module is designed to assign each pixel in an image to a fuzzy set by evaluating any of a series of fuzzy set membership functions. The main advantage to this approach for our work is that it avoids setting hard or arbitrarily established thresholds between different levels of risk. It also facilitates subsequent integration of data layers in the generation of composite risk maps, which take into account the major risk factors for which we have data, i.e., slope, clay content, washes, culverts, intersections, and cattle guards.

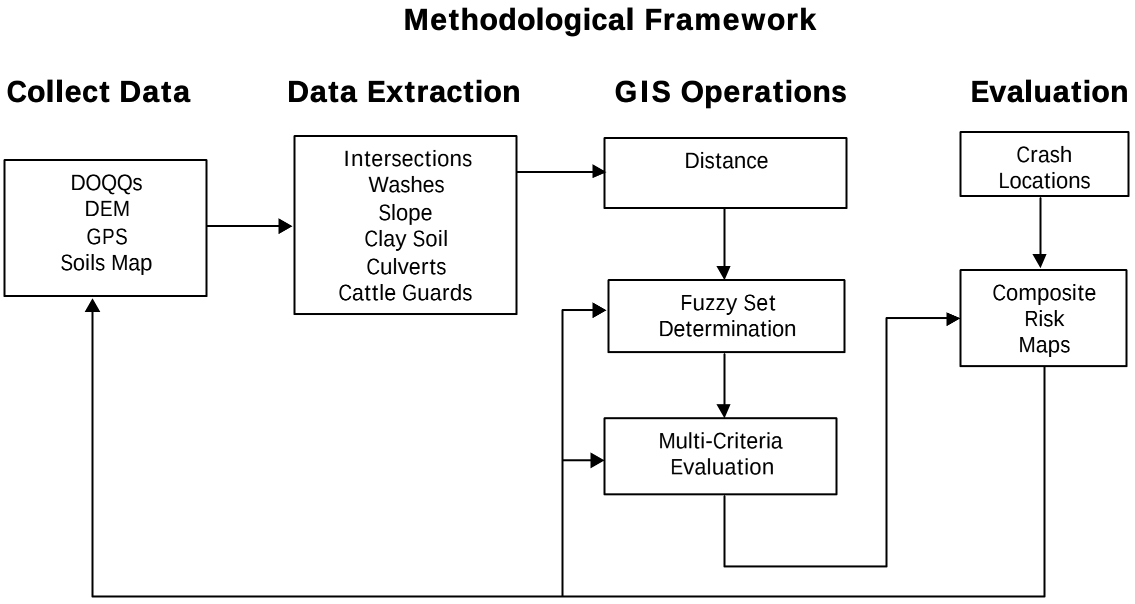

Figure 2. Flow chart depicting the different steps for creating composite risk maps.

Thus far we have utilized both linear fuzzy functions and J-shaped fuzzy functions (these can be further specified to be either monotonically increasing or decreasing functions), which are controlled by four breakpoints ordered from low to high on the measurement scale. A J-shaped function sets point a and d where the function is 0.5 and in the process, makes the J-shape function asymptotic to 0 and 1, points of absolute minimum and maximum risk. In the case of a monotonically increasing function, the first point marks the location where the membership function begins to rise above 0. The second point indicates where it reaches 1 (i.e., 100 percent probability of class membership). Output was scaled from 0 (zero probability of class membership) to 255 (100 percent probability of class membership) for each layer in our analyses. In the case of slope, for example, we evaluated steepness using a monotonically increasing function with the first breakpoint set at 10% (slopes are beginning to become "steep") and b, c and d set at 25% (slope has become a full member of the class "steep slopes").

In the case of the other risk factors identified (clay content of soil, washes, culverts, intersections) we applied a monotonically decreasing linear Fuzzy membership functions with breakpoints at 10 and 30 meters. This logic assumes that risk decreases greatly with distance from feature such that distances beyond 30 meters present zero risk (i.e., probability of class membership equal to zero). Finally, in the case of soils with significant clay content, we possess only Boolean information (i.e., present or absent) for each pixel rather than an interval-scale measurement such as percent clay. We therefore assigned values of 255 to all pixels with clay and zero to all pixels without significant clay.

Integration of the data to create composite risk maps along roads was carried out using the Multi-Criteria Evaluation (MCE) module, also in Idrisi32. Like the Fuzzy module, the MCE procedure allows for the combination of factors using a variety of functions. We utilized the linear-weighted function, which is analogous to a weighted mean, with factor weights determined arbitrarily. Factor weights are very important because they determine how individual factors will tradeoff relative to each other. In the case of a linear weighted combination, the higher the factor weight the more influence that factor has on the final composite risk map. We conducted a factor weight sensitivity analysis by varying both the factor weights and the type of fuzzy function used for each risk factor thus creating a final set of twenty or so MCE composite risk maps. Once this step was completed, each MCE composite risk map was then compared to a set of accident data points from the same road networks used in the analysis. These accident points were collected by the Hopi Tribal police and converted into a GPS/GIS database by Dalton James at the Hopi Tribal Office. T-tests were used to assess the statistical significance of risk values at crash versus non-crash locations.

RESULTS

Before assessing how the different MCE results depict risk, we identified a subset of normally distributed risk scores so that we could apply a parametric tests to values given for crash and non-crash locations. The MCE output ("MCE test") layers, factor weights and fuzzy functions are shown in Table 1 below.

MCE test	Layers involved	Fuzzy Functions	Factor weights
1J	1; 2; 3; 4; 5	L,L,L,L,J	0.2; 0.2; 0.2; 0.2; 0.2
1L	1; 2; 3; 4; 6	L,L,L,L,L	0.2; 0.2; 0.2; 0.2; 0.2
2J	1; 2; 3; 4; 5	L,L,L,L,J	0.25; 0.15; 0.1; 0.2; 0.3
3J	1; 2; 3; 4; 5	L,L,L,L,J	0.3; 0.2; 0.15, 0.25; 0.1
3L	1; 2; 3; 4; 6	L,L,L,L,L	0.3; 0.2; 0.15, 0.25; 0.1
4J	1; 2; 3; 4; 5	L,L,L,L,J	0.1; 0.25; 0.2; 0.3; 0.15
4L	1; 2; 3; 4; 6	L,L,L,L,L	0.1; 0.25; 0.2; 0.3; 0.15
6J	1; 2; 3; 4; 5	L,L,L,L,J	0.2; 0.1; 0.3; 0.15; 0.25
11	1; 3; 4; 5	L,L,L,J	0.25; 0.25, 0.25, 0.25
14	1; 3; 4; 5	L,L,L,J	0.2; 0.3; 0.3; 0.2
18	1; 3; 4; 5	L,L,L,J	0.1; 0.4; 0.4; 0.1

Abbreviations: L = linear function; J = J-shaped function;
1 = slope steepness; 2 = distance from culverts; 3 = distance from intersections; 4 = curvature; 5 = distance from washes (J-shaped function); 6 = distance from washes (linear function).

Table 1. MCE composite risk maps with normally distributed scores (values from 0-255). Test 4J is shown in Figure 3 below.

Figure 3 shows the results of our analysis for Route 17, which is one of three road segments we analyzed. As in all risk maps generated, this particular example produces data scaled from zero (no risk) to 255 (maximum risk). This composite risk map along with several others depicts good correspondence between crash locations (white dots) and areas of high risk, although in some instances crash location was displaced somewhat from the areas of highest risk, which coincide with the location of several risk features such as intersections, curves, etc. Several factors may explain this displacement including error associated with the crash site data (obtained through interviews with emergency personnel), post-collision momentum, or other hazards unaccounted for in our analysis (e.g., temporary obstructions in the roadway).

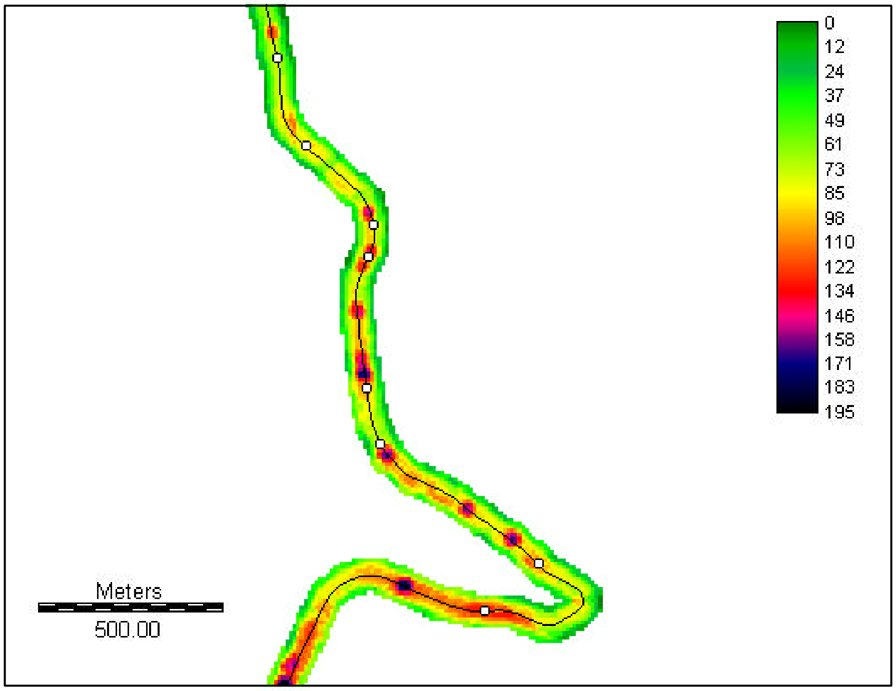

Figure 3. Results of one MCE-based risk map (test 4J, input parameters given in Table 1 above) for an area within 50 meters of the road centerline of Route 17 (shown in black). High values (blue-to-black tones) indicate areas of high risk, while the green tones signify low risk. The white dots show the approximate location of crashes that had occurred along this segment of road on the Hopi Reservation in northern Arizona.

The data depicted in graphs below (Figure 4) reveal statistically significant differences in the MCE-based scores of crash and non-crash locations for risk maps 1L, 3L, 6J and 18. Figure 4 also shows that the mean and standard errors were smaller for non-crash locations than for crash locations, as we expected. However, not all tests produced statistically significant results. We noted that those tests in which more factor weight was applied to proximity to intersections and road curvature tended to produce statistically significant differences in MCE scores for crash and non-crash locations. This result suggests that these factors are most important and may need to be addressed in future hazard mitigation strategies employed on the Hopi Reservation.

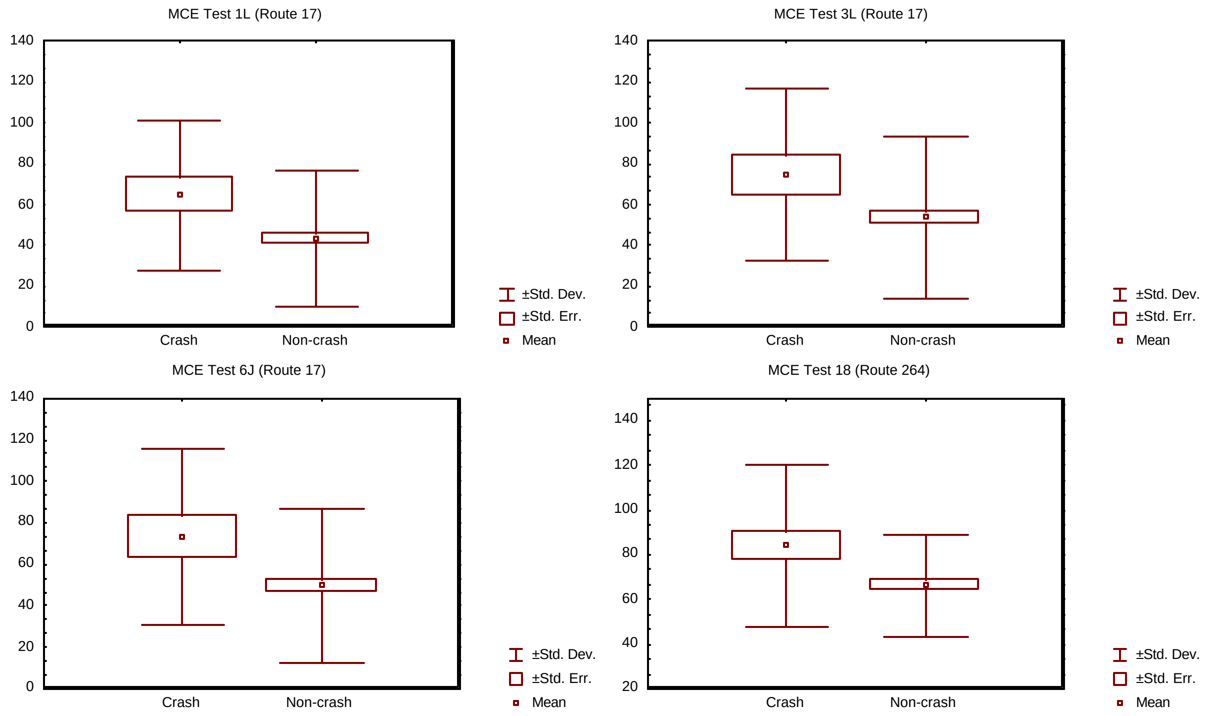

Figure 4. Examples of statistically significant results (determined through t-tests) for four MCE risk maps.

CONCLUSIONS

Recent advances in Geographic Information Science and decision support have resulted in a set of new techniques for efficient integration of different GIS and remotely sensed data layers to map composite risk along certain sections of roadway. In particular, the use of multi-criteria evaluation (MCE) and fuzzy sets allows users to assign different weights to risk factors leading to more realistic portrayal of overall or composite risk. Although driver error often contributes greatly to the occurrence of any particular crash event, analysis of crash locations indicates that natural and man-made hazards help to explain why crashes are more frequent in some locations than in others. Our analysis has shown that static features along roadways such as intersections, culverts, etc., which can be mapped with high precision, pose particular risks. Road curvature and slope interact and these too appear to account for the presence of accidents on the reservation. The approach demonstrated here clearly has potential for helping transportation planners and engineers design mitigation strategies that seek to reduce risk along rural roadways. The adoption of this technology will be greatly reinforced by the emergence of new high-resolution satellite imagery (e.g., IKONOS and QuickBird) that may be used to rapidly update expanding transportation networks and hazard points along roadways.

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