



Using a Cosmic Ray Neutron Rover to Measure Unpaved Road Moisture for Improved Maintenance and Safety

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Research Needs

Unpaved or gravel roads are an important component of the U.S. transportation system. Nationally, 33% of all roads are unpaved, while 64% of all roads in FTA Region 8 are unpaved (Bureau of Transportation Statistics, 2018). Unpaved roads are particularly relevant to underserved populations, as 75% of all tribal roads in the U.S. are unpaved.

Preservation of unpaved roads is difficult because they can transition from excellent to failing condition in less than a year (Saha and Ksaibati, 2017). The condition of unpaved roads is typically monitored through manual inspection (Shtayat et al., 2020). Indications of surface distress include rutting, pulverization, potholes, loose gravel, erosion, and corrugation. The

development of these features depends on the age and quality of the road material, vehicle types, traffic volume, and road moisture (Rada et al., 1989; Shtayat et al., 2020). While the triggers for road deterioration are typically related to vehicles, the rate of deterioration is accelerated by high moisture content (Lekarp et al., 2000).

The safety of unpaved roads is also an ongoing concern. The rate of fatalities on unpaved roads is more than twice the rate for paved roads (Ecola et al., 2018). While numerous factors contribute to this difference, one factor is reduced visibility due to lofting of fugitive dust. Dust from unpaved roads is largely comprised of particles smaller than 10 μm (PM_{10}), and unpaved roads contribute about 35% of this particulate matter in the air (Environmental Protection Agency, 2014). PM_{10} has significant health impacts. Positive correlations have been documented between PM_{10} and heart and lung diseases as well as carcinoma (Khan and Strand, 2018). The lofting of fugitive dust is strongly related to the moisture of unpaved roads, mainly through the moisture's role in determining adhesion of fine-grained particles (Struss and Mikucki, 1977; Parvej et al., 2021).

Although the preservation and safety of unpaved roads are both linked to road moisture, road moisture is rarely measured because rapid non-destructive measurement methods are not widely available. Instead, inspection of road surfaces is typically used to determine whether maintenance or dust suppression is needed. As a result, interventions are reactive rather than proactive, allowing road damage, safety risks, and health impacts to occur before action is taken.

Research Objectives

Recently, cosmic ray neutron (CRN) rovers have been developed to measure soil moisture. These devices can be mounted in vehicles and used to measure the soil moisture every minute as the vehicle travels. Although the rover's measurement is most sensitive to the moisture directly under the sensor (i.e., the road), CRN rovers have not been tested for measuring road moisture. The objective of this project is to evaluate the accuracy of a CRN rover for measuring the moisture of unpaved roads and thereby unlock a new tool for the development of proactive management strategies.

Research Methods

A nearly constant flux of cosmic rays enters the Earth's atmosphere and produces high energy and fast neutrons when interacting with the Earth's atmosphere and surface. The energy of these neutrons is moderated (producing slower epithermal and thermal neutrons) when the neutrons interact with hydrogen atoms (Desilets and Zreda, 2001; Zreda et al., 2008). Because most hydrogen in the environment occurs as water, the number of epithermal neutrons occurring at a given location depends on the quantity of water near that location.

A CRN sensor uses helium-filled tubes that are shielded to isolate and count the epithermal neutrons. The effects of stable pools of hydrogen such as atmospheric humidity, biomass, soil organic matter, and small water bodies can be accommodated by using correction functions (Tian et al., 2016) and/or location-specific calibrations. Once calibrated, the CRN sensor measures a weighted average soil moisture within the measurement footprint. Both the size of the footprint and the sensitivity to moisture at different distances are known from rigorous neutron transport models (Köhli et al., 2015). For low atmospheric pressure and humidity (common in Colorado),

the footprint has an approximate radius of 250 m, but moisture within 6 m of the sensor constitutes nearly half the weighted average. Several studies have demonstrated the accuracy of CRN sensors. Franz et al. (2012) calculated a root mean square error of $0.017 \text{ cm}^3/\text{cm}^3$ when comparing to 160 in-situ probes distributed across the footprint. Franz et al. (2012) also demonstrated that CRN sensors have a high sensitivity to near-surface soil moisture (<10 cm depth).

Typical CRN sensors require about an hour to count sufficient neutrons to produce a stable moisture estimate, so they are used to monitor the soil moisture at a fixed location through time. Mobile CRN rovers are also available. They use multiple and larger helium-filled tubes, which allow them to count adequate neutrons every minute. Thus, they can be mounted on a vehicle and moved to map the moisture over large spatial extents. The vehicle speed determines the spatial resolution in the direction of travel. The vehicle materials do not obstruct the neutrons and can be accommodated by the rover calibration (Schrön et al., 2018).

Few studies have directly considered the interaction of roads and CRN rovers. Schrön et al. (2018) used a theoretical neutron transport model to develop a correction that adjusts the neutron counts to remove the effect of the road and improve the estimates of the landscape soil moisture. They assumed the road moisture based on typical values for different road materials (gravel, asphalt, or concrete), and only the landscape soil moisture was estimated.

In the proposed research project, a CRN rover will be used to estimate unpaved road moisture by accounting for the landscape soil moisture. Because the rover's sensitivity to moisture at different distances is known (Köhli et al., 2015), the average road moisture within the footprint can be estimated if the landscape soil moisture within the footprint is known. The landscape moisture will be estimated by downscaling soil moisture from NASA's Soil Moisture Active Passive (SMAP) satellite. This satellite provides soil moisture at a 9-km spatial resolution with an accuracy better than $\pm 0.04 \text{ cm}^3/\text{cm}^3$ (Chen et al., 2017). These coarse-resolution estimates will be downscaled using the Equilibrium Moisture from Topography Plus Vegetation and Soil (EMT+VS) model (Ranney et al., 2015; Cowley et al., 2017). The EMT+VS model can downscale to 10-m spatial resolution based on a water balance of the soil layer and fine-resolution topographic and vegetation data. The resulting fine resolution soil moisture estimates have root mean squared errors ranging from $0.02 \text{ cm}^3/\text{cm}^3$ to $0.05 \text{ cm}^3/\text{cm}^3$ (Grieco et al., 2018).

Relevance to Strategic Goals

This project will advance the USDOT strategic goal of Safety. Most public roads in Region 8 are unpaved, and high moisture of unpaved roads increases road damage. By developing a rapid and non-destructive method to measure road moisture, interventions to protect unpaved roads can be evaluated at larger scales (longer road sections), thereby producing more informative results. Furthermore, the linkage between the protective intervention and the road damage can be better understood if the road moisture is known. Reduced visibility from dust lofting is a major safety hazard on unpaved roads, and dust lofting also reduces air quality and increases the risk of disease. Dust lofting is strongly linked to the road moisture. Current mitigation strategies are applied after dust lofting occurs because dust lofting cannot be readily predicted. If rapid measurements of road moisture are available, then the onset of dust lofting can be predicted, and these strategies can be implemented before the health and safety hazards occur.

Educational Benefits

Most of the requested funds will be used to support one or more students who will perform the hands-on tasks of the project. Support will include a stipend and tuition support and/or hourly wages. The students will gain a diverse range of experience through this project by collecting field data, analyzing soil samples in the laboratory, and numerically modeling road and soil moisture. The students will also be actively mentored by the PIs.

Outputs through Technology Transfer

Technology transfer to researchers and practitioners will be accomplished by presenting the key findings at one or more conferences. The conferences will be selected to maximize the visibility of the work for the target audience (transportation professionals who focus on hydrologic aspects of roads). We also anticipate that the results will be published as a peer-reviewed journal article in a widely viewed and cited journal. We will also contact the Tribal Technical Assistance Program at NDSU to collaborate on a larger subsequent proposal effort that specifically focuses on application of the rover technology for unpaved tribal roads.

Expected Outcomes and Impacts

The key outcomes from this project will be: (1) a method to estimate road moisture using a CRN rover and downscaled SMAP soil moisture, (2) an evaluation of the errors in the road moisture estimates, and (3) a comparison of road and landscape moisture values. Together these outcomes are expected to determine the feasibility of using CRN rovers for measuring road moisture. These results are expected to help guide future research studies that explore this topic in more diverse conditions. They could also be used to gain a better understanding of the conditions where surface distress and dust lofting occur and to develop more proactive strategies for preserving unpaved roads and improving health and safety. The outcomes will be documented in at least one presentation at a professional conference and at least one peer-reviewed journal article.

Work Plan

This project is expected to begin around Fall 2024 and be completed within a 2-year period. Four major tasks will be undertaken to achieve the project objective (Figure 1).

Figure 1. Timeline for completion of major project tasks.

Task	Year 1				Year 2			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1. Collect field data								
2. Estimate landscape soil moisture								
3. Estimate and analyze road moisture								
4. Document results								

Task 1: Collect Field Data. Field data collection will focus on a 5-10 km segment of a lightly traveled gravel road in Weld County, Colorado. The road will be selected in consultation with county officials, but to facilitate access to the adjacent landscape, we anticipate selecting a road that is mostly within the 6280-ha Central Plains Experimental Range (CPER). This facility is operated by the Agricultural Research Service for research purposes. The native soils are primarily sandy loams but range between clay loams and sand. Data collection will occur on ~10 dates that span the full range of moisture conditions from late spring to early fall 2025 (this period is selected to avoid snow and frozen ground). On each date, the rover will be held stationary at a central location that is far from the road while ~25 in-situ soil moisture measurements are collected within the measurement footprint using portable HydraProbes with built-in GPS (available at no cost to the project). These measurements will be used to develop and test the rover calibration (the rover is available at no cost to the project). Then, the rover will be driven along the road segment at about 20 km/h (using ~4 passes), which will produce data with a 30-m resolution in the direction of travel. Along the road segment, ~25 locations will be selected for field data collection on all dates. At each location, the road conditions will be documented, and samples of road material will be extracted and analyzed in the laboratory to determine their soil moisture. Water content will also be determined for the landscape adjacent to each location (in the rover's footprint) using the portable HydraProbes at multiple sites. Dry density will also be determined from soil samples to allow conversion of HydraProbe measurements from volumetric to gravimetric soil moisture.

Task 2: Estimate Landscape Soil Moisture. For each field date, SMAP Level 3 Passive Enhanced soil moisture will be obtained and downscaled using the EMT+VS model to estimate the landscape soil moisture. Elevation data at 10-m resolution will be obtained from the National Elevation Dataset, and 10-m vegetation data will be obtained from multispectral data from the Sentinel-2 satellite. The downscaled soil moisture will have 10-m resolution. A subset of the landscape soil moisture measurements will be used to calibrate the EMT+VS model, and the remaining measurements will be used to test the reliability of the downscaled soil moisture estimates. Processing of elevation and vegetation data will occur before field data collection, but model calibration and testing will occur after field data collection.

Task 3: Estimate and Analyze Road Moisture. As noted earlier, the rover's measurement is a weighted average of the road and landscape moistures. If the landscape moisture is known within the measurement footprint from Task 2, the average road moisture can be calculated. Moisture in drainage ditches adjacent to the road is not expected to strongly impact the rover measurement because the ditches are not under the rover (like the road), and they do not cover a large portion of the footprint (like the landscape). The accuracy of the road moisture estimates will be assessed by comparing to the field measurements of road moisture at all locations. The difference between the road and landscape moisture will also be examined using both the field data and the rover/downscaling results.

Task 4: Document Results. The results of this project will be documented using a final report, at least one professional presentation, and at least one peer-reviewed publication. Further details are provided in the technology transfer section below.

Project Cost

Total Project Costs:	\$90,000
CTIPS Funds Requested:	\$45,000
Matching Funds:	\$45,000
Source of Matching Funds:	Colorado State University

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