Predicting and Automating Weather-Driven Slip Risk in Autonomous Mining Truck Fleets

BUSINESS PROBLEM

Weather plays an important role in mining operations, where environmental conditions can significantly affect productivity, equipment wear, and operational safety. These effects are particularly important in autonomous mining operations because fleet behavior must be coordinated through centralized fleet management systems. Within Caterpillar's Command for Hauling (CfH) autonomous haulage system, responses to weather are manual and rely heavily on operator experience and domain knowledge.

DATA SOURCES

Weather Data - Solar radiation, soil temperature, soil moisture, temperature, humidity, and precipitation.

MineStar Logs - messages sent from trucks provide a time-stamped record of messages containing information on vehicle state, location, and events.

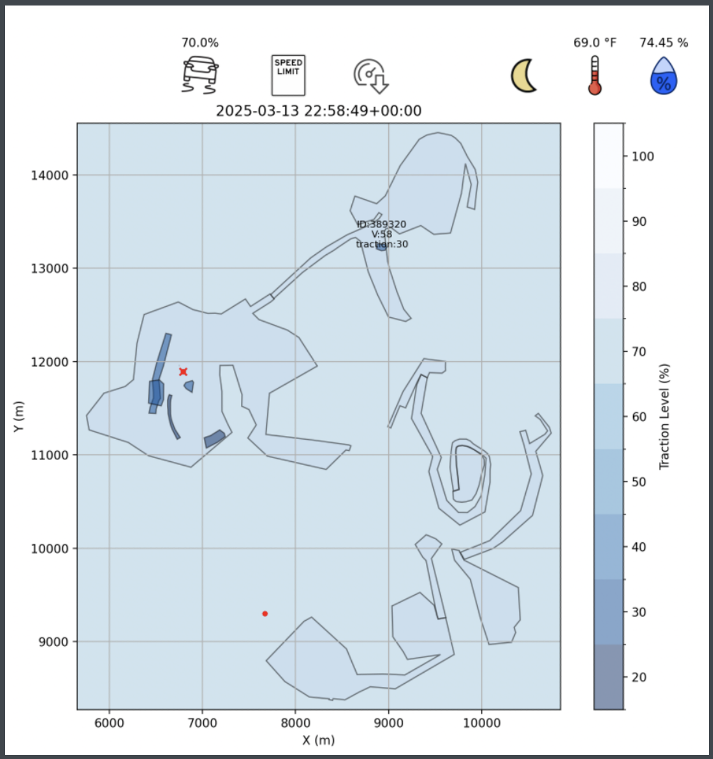
Zone Configuration Snapshots - Zones define operational constraints within geospatial polygons. Snapshots contain zone geometry and attributes.

Data Types and Format

Spatial

APPROACH

This thesis explores how data-driven methods can support and automate weather-related operational decisions within CfH. In particular, this work develops a predictive model to predict slip events for autonomous mining trucks using a combination of operational telemetry and environmental measurements. In addition to the predictive modeling contribution, this thesis presents an interactive data visualization tool designed to integrate multiple previously disconnected sources of operational data. This integrated view enables improved understanding of the impact of environmental conditions on operational behavior.



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IMPACT

As a first step towards automating weather-aware operational responses, this thesis introduced a predictive modeling framework for slip risk in autonomous mining operations, enabling proactive traction management based on environmental and operational telemetry. The contributions of this thesis include: development of a novel, unified, year-long dataset combining weather and operational data; reconstruction and visualization of effective traction levels and mine-site dynamics; development and evaluation of a predictive model for slip events; introduction of slip prediction as a foundational component for automated traction management; and analysis of feature importance, to better understand the primary drivers of slip risk. This work provides a strong justification for future work with weather-related modeling and autonomy for Caterpillar. For the first time, multiple data sources were integrated and used to observe weather and operational interactions at a mine site as the basis for a predictive model. The model shows promising results in using weather and operational data to predict slip risk, which has significant operational and technical applicability.

DRIVERS	To remain competitive, Cat must continually improve products and provide features to improve safety and efficiency. Weather still has a significant impact on operation and productivity - site conditions must be monitored and operating parameters manually adjusted. Automation could respond more quickly, consistently, and proactively.
BARRIERS	Aligning multiple data sources with different time and geospatial resolution was a key challenge that was overcome to achieve this project.
ENABLERS	Support from colleagues at Caterpillar made this possible - the opportunity to visit a mine was instrumental in better understanding the problem and access to mentors and resources made the data analysis possible.
ACTIONS	Data decoding and visualization tools were built as part of this project to enable large-scale data analysis. These tools were then used to build a predictive model to estimate the probability of slip events for autonomous mining trucks using a combination of operational telemetry and environmental measurements.
INNOVATION	For the first time, multiple data sources were integrated and used to observe weather and operational interactions at a mine site as the basis for a predictive model. This thesis also presented an interactive visualization tool designed to integrate multiple previously disconnected data sources. This integrated view enables improved understanding of how environmental conditions, operational parameters, and vehicle behavior interact during weather.
IMPROVEMENT	These contributions demonstrate how predictive modeling and integrated data visualization can support proactive, weather-aware fleet management for autonomous mining operations. This work represents a promising first step toward automated decision-support systems that enable safer and more efficient operation of autonomous haul truck fleets under changing environmental conditions.
BEST PRACTICES	Best practices and lessons learned from this process are to utilize data visualization as a method for data quality checks and hypothesis generation. Tools for decoding and visualizing data have been provided to the team at Cat as part of this project.
OTHER APPLICATIONS	This project showed promise in using weather data for prediction of slip events at one mine site, which can be generalized to other operational behaviors at other mine sites.