

Haul road roughness measurement using georeferenced truck vibration

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Date of submission to the Editor: 05/2019

Date of acceptance by the Editor: 08/2019

INTRODUCTION

A major component of any mining operation is transport of material from the working face to its next destination, be it processing facilities or waste dumps. The main form of transport for surface mine is truck haulage. Haulage of material can account for up to 50% of total mining costs (Hugo et al., 2007, Thompson 2018). This cost accounts for maintenance of equipment, fuel costs, labor costs, and road maintenance costs. The factor linking all these costs is the haul road. Mining haul roads differ from other off-highway or unpaved roads by being constructed of mainly in-pit material. This material is often sub optimal for road construction. Proper road construction uses a mixture of rock, sand, and fine particles that when layered correctly can reduce water from penetrating the surface of the road and allow water that does saturate the road a path to flow out. Moisture is a leading cause of road damage (Federal Highway Administration and United States Department of Transportation, 2015). Additionally, mine roads in open pit mines are constructed on bedrock. This further reduces the ability to dewater the roads by blocking the flow from under the road. For these reasons, mining haul roads are in constant need of maintenance.

Unmaintained roads can cause damage to trucks, injure operators, and reduce haulage efficiency.

Truck tires are a major concern, costing up to \$100.000 each puncture can not only incur costs for new tires, but downtime for the haul truck while repairs are made. Tires can make up to one third the operational cost for haul trucks. Outward facing surface is more likely to be damaged. A major risk is puncture from road debris (Kotchon et al., 2016). Not only are tires a concern, but other regular maintenance and operational costs can be increased due to poorly managed roads. (Hugo et al., 2008). The large size of haul trucks makes them especially susceptible to uneven roads. The distance from the ground to the engine or cabin can be 20 feet or more. This acts like a lever to magnify any unevenness between the tires.

Operators also suffer from poorly maintained roads. Operators are exposed to whole body vibrations in the cab. While the vibration may be higher during loading, drivers spend much more time during transport. Exposure to whole body vibrations combined with the constrained posture of sitting in a haul truck cabin can put the lumbar intervertebral disk at risk of failure. This leads to lower back pain, sciatic pain, and degenerative changes in the spinal system, including intervertebral disk disorders (Bovenzi et al., 1999). This can lead to costly workplace compensation claims and a reduced workforce. Maintained roads are associated with lower vibration and it is likely haul road maintenance will be an effective control for whole body vibrations. (Wolfgang and Burgess-Limerick, 2014)

Existing maintenance management systems rely heavily on visual assessment. This assessment is converted to a defect score that relates to rolling resistance through an empirical model. Frequent visual inspections of long road sections are required with this method (Hugo et al., 2008). Hugo goes on to suggest by using the haul trucks, the exact location of localized defects can be identified. Unlike paved road maintenance, the user and maintainer are the same for mining properties. Therefore, it makes sense to use existing trucks to monitor roads. (Hugo et al., 2008)

Previous research has attempted to equate rolling resistance to the quality of road through a quantitative measurement. Thompson explains by using a truck manufacturer's SAE engine power and speed curves, the engine efficiency and subsequently the rolling resistance can be back calculated. The rolling resistance represents the force the truck must overcome to move forward. This method directly relates to the fuel efficiency and cycle time but does not directly address operator health, equipment maintenance, or tire damage caused by excessive vibration.

To address the shortcomings of a rolling resistance only model, research has been conducted to add vibration measurements into the equation. In 2014, Wolfgang demonstrated road quality is a major contributor to vibration response and the vibration magnitude caused by the road roughness is highest in the vertical direction – the direction most damaging to the health of operators. Maintained roads are associated with lower vibration (Wolfgang and Burgess-Limerick, 2014). Another study showed it is possible to identify and reconstruct road defects using vibration data (Hugo et al., 2008). This research was successful at identifying specially constructed defects, but application to real road conditions where vibration response of multiple defects can overlap was not proven. Ngwangwa conducted a similar series of studies, both times using an artificial neural network. She again used specially constructed defects and had not addressed multiple defects in series. There was also limited control in this study over the velocity of the test vehicles, however it did identify speed plays a role in measured vibration. This research did outline the value in “identifying the general level of the road’s surface roughness” (Ngwangwa and Heyns, 2014, Ngwangwa et al., 2014).

In all cases, an increase in the amount of data and monitoring actual driving conditions on in-use haul roads would improve the understanding of road condition monitoring. This research proposes an existing technology on an entire mining fleet can be adapted to provide an adequate data stream to determine road roughness. A mining fleet was selected that has a system that records GNSS and vibration data as a small part of the technologies intended use. The GNSS and vibration data was isolated and annualized in three steps: 1) is the vibration reading of the accelerometer independent of the acceleration experienced by the truck from changing speed or direction, 2) how does the speed of the haul truck effect the vibration measurement and can the effect be eliminated, and 3) do different locations along the mine road have statistically different vibration measurements?

METHODOLOGY

Focus of this research is an easy transition from existing technology data being used in new ways. Thus, a mine for this case study was selected that operates a technology solution that reports GNSS location data and vibration data. As a preliminary study, 3 random haul trucks were selected. Data for each truck was collected from the previous week. This data was generated and stored without initially knowledge or consideration of this project. This demonstrates the method can be applied to historical data to use for model validation and verification in future projects.

The GNSS is a low precision device using a combination of GPS and GLONASS technology. The GNSS antenna is mounted at a height equal or above the haul truck canopy. This provides the best accuracy for location. The average horizontal accuracy is 0.51m, with a vertical resolution of 1.0m.

The vibration sensor is a LIS3LV02DL by STMicroelectronics. The sensor is mounted in the operator's cabin of the haul truck. It is secured with high power magnets to the frame of the cabin, but the orientation is not controlled between haul truck installations. The sensor calculates the root mean square measurement of the x, y, and z acceleration at 40 Hz and low pass filters the result at 0.8 Hz. (www.st.com) These values are averaged over 10 samples and reported at 1 second intervals with the GNSS location.

For this study, a series of regression analysis was conducted to determine if the data is capable of indicating differences in road condition. First, the acceleration of the truck was compared to the accelerometer reading to eliminate the source of vibration unrelated to road condition. Next, the velocity of the haul truck was compared to vibration to determine the effect of speed on the vibration reading. Finally, locations throughout the mine were compared to determine if different vibration levels appear in different areas of the mine.

RESULTS

An obvious source of error is the acceleration of the haul truck creating a detectable acceleration in the accelerometer. To determine if this will create issues in utilizing the vibration data a regression analysis was conducted.

The effect of vehicle acceleration on vibration did not meaningfully impact on observed vibration. The R-squared value (0.15) combined with the small parameter value 0.0011 show most of the variation is a result of noise or non GNSS sources of vibration. This pattern is easy to see in Figure 1.

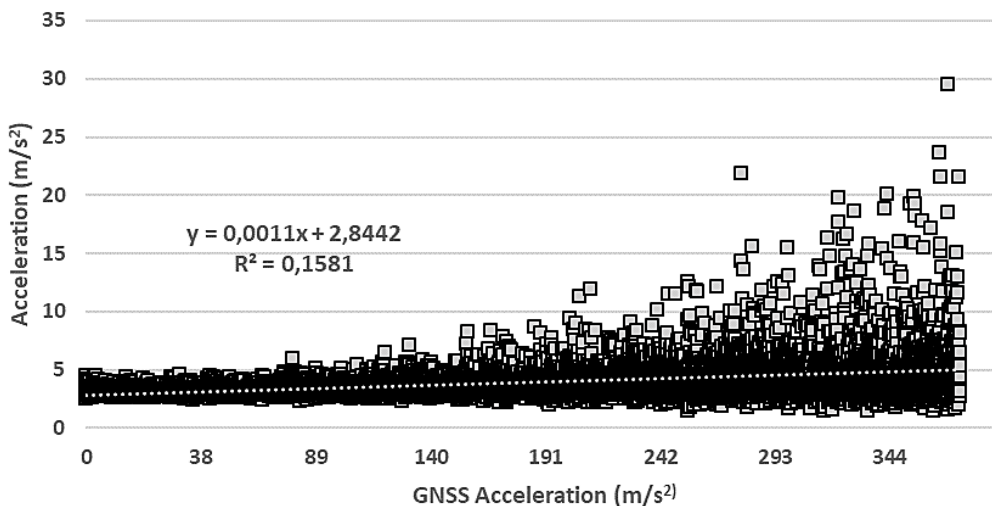


Fig. 1 GNSS Acceleration vs Accelerometer Measurement

A second source of error is the operational speed of haul trucks. In a theoretical example, a fast-moving non-accelerating truck hitting an incompressible bump will accelerate in the z direction faster than a slow-moving truck. This is an easy concept, but in reality, uneven ground and vehicle suspension can change the expected behavior.

The vibration at speed increments of 0.1 KPH was averaged and a regression analysis was conducted. It was observed different speed ranges had drastically different vibration patterns. This is likely due to the gear selection of the haul truck, slope, driving behavior, and number of available data points.

The haul trucks spent most of the time in two narrow speed ranges, 9-12 KPH and 20-23 KPH. The number of data points at each speed rounded to the nearest 0.1 KPH is shown in Figure 2.

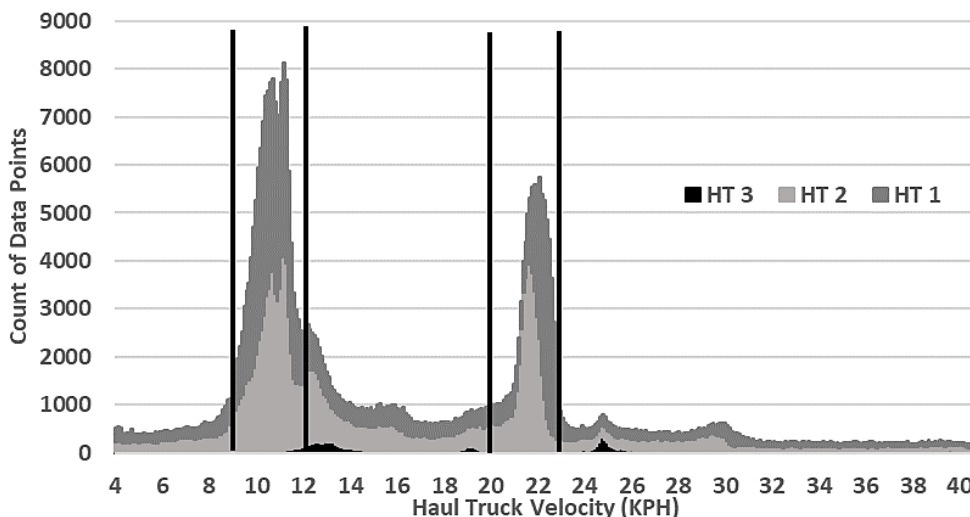


Fig. 2 Number of Data Points for Each Speed

The graph includes vertical lines indicating the observed speed ranges. The spike in values at the lower speed is due to the maximum speed attainable traveling loaded uphill; the second spike is due to a speed limit imposed for safety and dust control. Speed values below 4 KPH were discarded due to the low number of data points and high variability caused by external factors unassociated with haulage, e.g. loading, dumping, and pitching due to suspension. The regression analysis for speed and vibration was recalculated using a piecewise regression with the bins for speed at 4-9, 9-12, 12-20, 20-23, and 23+. It was found the average vibration for each speed bin was related to the speed (R-squared 0.65). The results of the piecewise function are found in Table 1.

Table 1 R-Squared Value of Speed and Vibration by Truck

	HT 1	HT 2	HT 3
Overall	0.651	0.668	0.694
4-9	0.337	0.630	0.714
9-12	0.007	0.008	0.543
12-20	0.699	0.664	0.661
20-23	0.658	0.509	0.249
23+	0.022	0.151	0.173

The value of average vibration for a given speed is shown in Figure 3, along with the regression line.

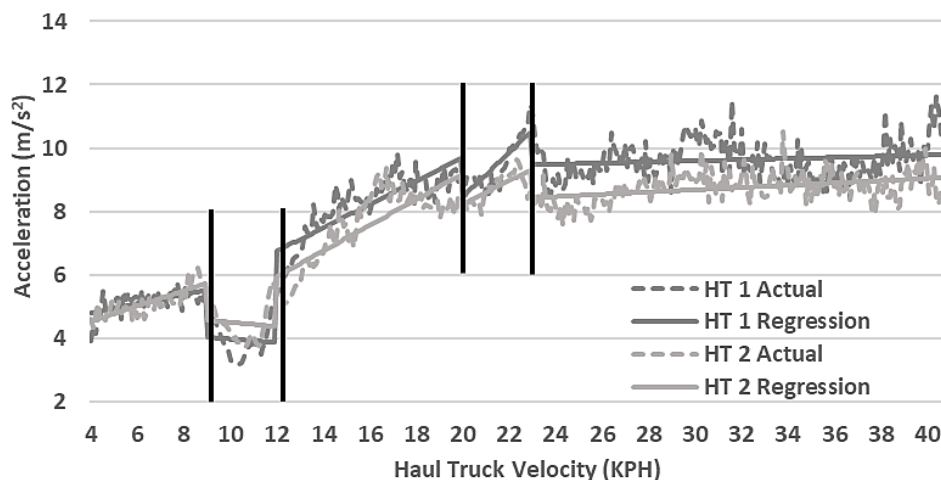


Fig. 3 Average Value of Speed and Vibration by Truck

Finally, the GNSS location for each vibration data point was plotted. Figure 4 shows the relative vibration level with lower vibration in a lighter color and high vibration in a dark color. Labels indicating the location in the mine are included to orientate and imply driving behavior at the different locations. The pit area has the highest vibration; the long-term ring road and spurs to fixed locations have lower vibration. Switchbacks and ramps have moderate vibration. This shows different locations in the mine experience statistically different vibration levels (p-value < 0.01).

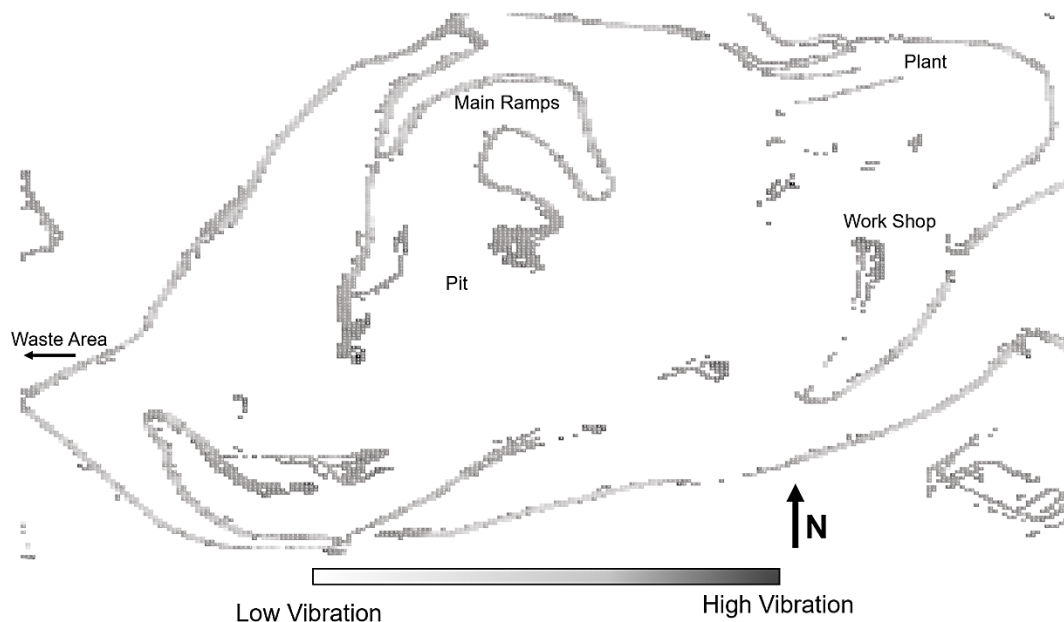


Fig. 4 Mine Map of Vibration Levels for Speeds Between 9-12 KPH

DISCUSSION

The results are promising for using this data source for further research. First, the acceleration of the truck calculated from the GNSS locations do not have a meaningful effect on the observed vibration from the accelerometer. Figure 1 shows the variance of vibration does increase with increasing GNSS acceleration. The vibration measurement has a lower bound of zero, so with increasing variance the mean will increase. Due to this effect, a small trend appears in the data. This should not be confused for correlation, but only as an effect of the data bounds. For the higher values of GNSS acceleration, haul trucks cannot achieve this rate of acceleration under normal operating conditions. The top readings of GNSS acceleration potentially result from abnormal tire to road surface interactions, like encountering large potholes, causing a chain reaction from the suspension to the vehicle frame to antenna. This high acceleration found in the GNSS data could be used as an indicator of road condition if vibration data is unavailable.

The second objective shows the speed of the haul trucks influences observed vibration. The r-squared values between 0.65-0.70 show much of the differences in acceleration is a result of speed. It was interesting that the range of speed associated with fully loaded hauling uphill (9-12 KPH) did not find a correlation between speed and vibration. Additional research should be conducted to find the effects of truck orientation and suspension loading on measured vibration. Finally, analyzing the data for the location in the mine allows mine management to see locations of high vibration. This will be useful to dispatch road maintenance crews to the highest needed locations. The results show the expected condition of the roads based on experience, with the pit areas having the roughest roads, main roads the smoothest, and switchbacks in the middle. However, the actual condition of the road was not measured for this study.

Future work is needed to confirm the observed vibration levels correlate to road roughness.

CONCLUSION

Poorly maintained haul roads can be a source of excessive vibration leading to operator injuries, damaged tires, and increased maintenance costs. This study demonstrates vibration data tied to location data can be used to identify locations in the mine that experience high vibration. First, the acceleration of the haul truck based on GNSS location was determined to not affect measured vibration with an accelerometer. The speed of the haul truck is a major component of observed vibration. However, in the small range of speed (9-12 KPH) where the truck is traveling up an incline fully loaded the speed is not a determinate of vibration.

For this speed range the effect of road roughness is the primary source of vibration differences. Locations in the mine exhibit different vibration levels that match expected road conditions with pit roads resulting in higher vibration measurements than ramps or ring roads. Further research is planned to further relate the vibration measurement to road roughness using onsite surveys of roadways and to monitor the change overtime to not only indicate current road condition, but also predict future locations to prioritize road maintenance.

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Abstract.

Vehicle vibrations caused by poor haul road conditions create multiple negative effects for mines, including slower cycle times, increased maintenance, and operator injury. Vibration levels in vehicles result in part from road roughness. Mine roads are mainly constructed from in-pit materials that are more likely to deteriorate overtime and require frequent maintenance to maintain a smooth surface. The decision for when and where road maintenance is conducted is primarily based on visual inspections. This method can provide subjective, inaccurate, and delayed response to adverse conditions. The recent increase in vehicle telemetry data allows instant access to several types of data; mainly being used for haul fleet dispatching, collision avoidance, and geologic surveying, telemetry data has yet to see widespread use in road maintenance dispatching. This paper examines current road roughness characterization techniques and current telemetry data streams. An initial case study was conducted using vibration and Global Navigation Satellite System (GNSS) telemetry data to determine road roughness. Data from three haul trucks under normal operating conditions were collected over the course of a week. The results of this case study demonstrate localized vibration levels can be used to objectively identify rough roads. This can be further developed to dispatch road maintenance crews leading to overall reduced mining costs and increased operator health. The researches propose continuing to full scale test using data from an entire fleet and longer timeframe.

Keywords: Haul Road, Vibration, Operator Health, Road Maintenance, Big Data