Simulation and sensitivity analysis of mobile proximity detection system stopping distance in Unity

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ABSTRACT

Proximity detection systems (PDSs) on underground mobile haulage equipment are intended to protect mineworkers from crushing, pinning, and striking accidents by slowing and stopping the vehicle before a collision occurs. However, highly variable and changeable environmental and vehicle conditions can drastically alter PDS performance, and the magnitude of these effects is not clear. Furthermore, overly conservative PDS configurations can interfere with other work, making it difficult to appropriately configure these systems. Researchers at the National Institute for Occupational Safety and Health (NIOSH) leveraged their existing "VR Mine" simulation and PDS expertise to examine these problems. This paper presents the results of a deterministic simulation exploring the sensitivity of vehicle stopping distance to a variety of environmental, vehicle, and PDS configuration variables. The simulation was uniquely created using the Unity game engine and the PhysX library to simulate the time-based relationships in order to leverage the visualization for improved communication of the results. Using this simulation, over ten thousand trials were run on a range of variables, such as slope, friction, vehicle type, load level, braking behavior, and PDS configuration. Values for the physical parameters were derived from a large number of sources including previous research, manufacturer specifications, field observations and measurements, and subject matter expert discussions. The model was validated with results from lab tests of a loaded and an unloaded vehicle on pavement. The results of this simulation will be used to develop guidelines on the implementation and configuration of PDSs based on mine environment and vehicle parameters. The visualization afforded by Unity will also be used in real-time virtual reality applications to communicate the results of the tests and compare different PDS configurations.

ABOUT THE AUTHORS

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Jacob Carr is the Team Leader for the Machine Safety Team within NIOSH PMRD. He earned his Bachelor's and Master's degrees in Mining Engineering from the University of Nevada, Reno in 2006 and 2008, respectively, and is currently pursuing a PhD in Energy and Mineral Engineering at Penn State. Jacob joined NIOSH in 2009 and has performed research on mine illumination, underground wireless communications, underground positioning systems, post-disaster refuge alternatives, electromagnetic interference, and proximity detection systems.

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INTRODUCTION

Crushing, pinning, and striking accidents involving mobile equipment are a major problem in underground coal mining that may be preventable. The Mine Safety and Health Administration (MSHA) identified at least 75 fatalities involving crushing, pinning, and striking accidents between 1984 and 2013 that were preventable with the use of proximity detection systems (PDSs) (MSHA, 2015a). Similar to emergency braking systems on automotive vehicles, PDSs are control systems that automatically decelerate and stop a mining vehicle to *prevent* a collision. However, because of the damp, dark, and dusty environment of an underground coal mine, all currently approved PDSs in the U.S. are electromagnetic-based. These systems use pulsed magnetic fields to locate wearable sensors called miner wearable components (MWCs) based on measures of the magnetic field strength with respect to the field generators mounted on the vehicles (Bissert, Carr, and DuCarme, 2016). PDSs typically limit a vehicle's motion using two zones around the machine: the yellow and red zones. If a mineworker enters the outer yellow zone, the PDS typically reduces and limits the speed of the vehicle or simply provides a warning. Upon entry into the smaller red zone, the PDS more rapidly decelerates the vehicle until it stops.

In 2015, MSHA mandated that all place-changing continuous mining machines be equipped with PDSs (30 CFR 75.1732) (MSHA, 2015a). Shortly after, MSHA (2016) proposed a similar rule to mandate that all mobile haulage vehicles in underground coal mines be equipped with PDSs. Though there has been no further action to regulate mobile haulage PDSs, these systems have the potential to save lives, and mine operators are beginning to adopt the systems. MSHA estimates that PDSs on mobile haulage vehicles (i.e. scoops, battery haulers, and shuttle cars) have the potential to eliminate up to 70 injuries and 15 fatalities over the next 10 years, and as of June 2015, mine operators have already equipped 155 of the 2,116 mobile haulage vehicles currently in use in U.S. mines (MSHA, 2015b).

The problem remains that as more mine operators implement these PDSs, the industry lacks the intuitive knowledge of how the rapidly changing and diverse mine conditions affect system performance. This can be especially problematic because researchers have found that some mineworkers may over-rely or under-rely on PDSs (Bellanca and Swanson, 2018), and research suggests that maintaining appropriate trust in automation is critical to workers' safety and productivity (Hoff and Bashir, 2015). Mineworkers have also expressed concerns about mobile PDS performance and the perceived unintended consequences, such as increased risk of musculoskeletal injuries and dust exposure (Bellanca et al., 2019a). Furthermore, some of the performance concerns have been documented in systematic PDS tests. De Kock and Bennett (2018) found that some of the PDSs were unable to prevent a collision in some of the scenarios tested using the manufacturer-recommended configurations. PDSs that are not appropriately implemented, maintained, and used can lead to additional and possibly greater safety risks. It is critical that mineworkers and mine operators have a complete and accurate understanding of PDSs and their capabilities.

Simulation and modeling can be an effective explanatory and communication tool to fill this gap in understanding. In fact, many vehicle dynamics simulations exist ranging in complexity of setup time, execution time, and outputs. Specifically, previous efforts to model mining vehicles have been directed towards complete autonomous driving and controls (Ridley and Corke, 2003; Kohlmeyer, 2011) and system design (Jobes, Bissert, Mahmoudian, and Li, 2016). However, without real-time display and visualization capabilities, the results of these solutions are difficult for nontechnical users to interpret. Furthermore, because of the proprietary nature and lack of availability of mining equipment, it is not feasible to implement the more complex models due to the lack of reasonable parameter values

(e.g., gear ratios). Commercial solutions such as TruckSim (Mechanical Simulation; Ann Arbor, MI) provide a better balance, but price and distribution limit dissemination and use across the mining industry.

The aim of this work is to build an intuitive picture of how mobile haulage PDSs performance changes in different conditions and with different PDS configurations. NIOSH researchers developed a real-time, virtual-reality-capable simulation in order to maximize knowledge transfer and minimize setup and execution time. This paper describes the initial validation and sensitivity analysis results of the simulation.

METHODS

Using previous research, manufacturer specifications, field observations and measurements, and subject matter expert discussions, NIOSH researchers created a discrete simulation to study how environmental, equipment, and PDS configuration variables affect the ability of PDSs to stop mobile haulage vehicles. Three of the most common underground coal mine haulage vehicles in the United States were modeled for this simulation study. The fourth vehicle was added as a representative utility vehicle (i.e. a scoop), because they are also covered by MSHA's proposed mobile haulage PDS rule. The specific scoop was selected because NIOSH researchers had direct access to test it for validation (described later in the Model Validation section). The four vehicles were modeled in the Unity game engine (Unity Technologies; San Francisco, CA) using the PhysX 3.4 (Nvidia; Santa Clara, CA) physics library. The simulation was created using the Unity as a part of NIOSH's VR Mine (Bellanca et al., 2019b) to take advantage of the native real-time visualization capabilities of the software while comparing dynamic behavior (Figure 1). This flexibility allows researchers to more easily visualize changes in vehicle performance and to facilitate the communication of results to the industry.

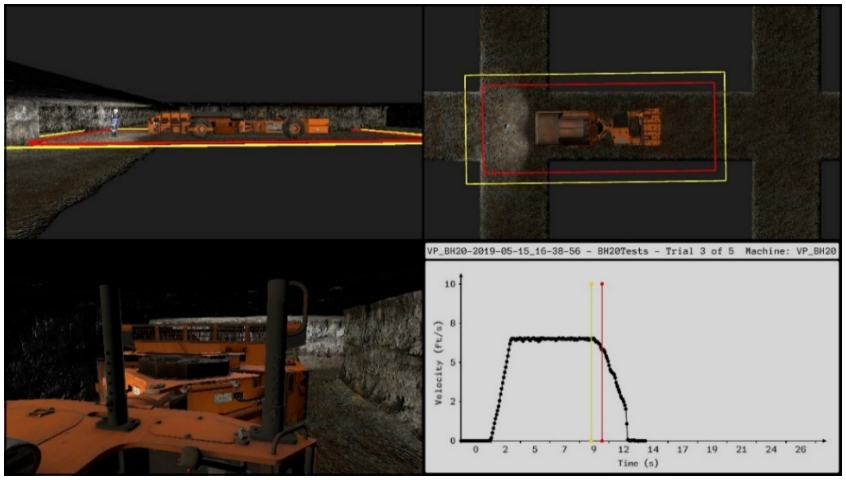

Figure 1. Screenshot of the visualization interface for the developed VR simulation tool.

Independent Variables

In order to quantify the environmental, equipment, and PDS configuration, NIOSH researchers identified 12 key variables. These variables were chosen because they are practically significant and vary over the use of the system. Table 1 lists these independent variables along with their minimum, maximum, and nominal values. Each of the continuous variables were tested with four modeled vehicles (Joy BH20, Joy 10SC32B, Bucyrus CH816C, CAI 4880), three PDS zone configurations (Extra Small, Small, and Large; Figure 2), and two braking models (Red Only, Yellow and Red). The continuous variables were incremented from the minimum values to the maximum values over 51 trials. Each variable was manipulated one at a time with the other variables held at their nominal values. Some of the nominal values are different for each vehicle in order to generate comparable conditions based on the vehicle limitations (e.g., initial speed). The test trials consisted of the vehicles driving straight towards a simulated mineworker wearing a MWC that would trigger the PDS on the vehicle. The distance of travel was selected such that all test conditions could successfully enter into the following states: ramp up to the initial speed, maintain the initial speed for 4–6 seconds, and enter into the PDS zones. The simulated ground was an irregular surface containing random bumps and divots varying by +/-1.5 inches that was generated in 3DS Max (Autodesk; San Rafael, CA) using the standard noise modifier that was otherwise flat.

Table 1. Sensitivity Analysis Variable Test Ranges

	Variable	Minimum	Nominal	Maximum
Enviro.	**Slope [degree]**	-10	0	+10
	Asymptote Force Ratio	0.05	0.45	1
	Asymptote Slip Ratio	0	0.3	1
	Extremum Force Ratio	0.05	0.35	1
	Extremum Slip Ratio	0	0.1	1
	Friction Multiplier	0.05	1	2
Equip.	**Initial Speed [ft/s]**	25%	Per Vehicle	200%
	Loaded Weight	Empty	100%	25% Overload
	Braking Torque [lbf/wheel]	25%	Per Vehicle	200%
PDS	**Delay [s]**	0	0.25	1
	Zone Configuration	Extra Small	Small	Large
	Braking Model	Red Only	Yellow & Red	Yellow & Red

Environmental Variables

Researchers based the environmental variables on previous research as well as on field observations. The simulation modulates slope in the direction of travel. Slope is important because it can change between different areas of a mine where a vehicle may travel across different mine sites. The friction is modeled using a time- and slip-based approximation of friction. Researchers based the nominal values for friction on loose gravel at low speeds as it is a common surface condition underground (Harned, Johnston, and Scharpf, 1969). The friction model was adapted from the default Unity game engine wheel collider using the underlying PhysX 3.4 library. In this model, the effect of friction is controlled by four variables: force and slip coefficients for the extremum and asymptote of the friction curve. The force coefficients represent the ratio of applied force that effectively acts on the vehicle, and the slip coefficients are the amount of slip of the wheel with respect to the ground (Unity, 2017). The asymptote represents the steady-state friction ratio, while the extremum capture the slow-speed effects including tire deformation and the transition between static friction and rolling friction. In order to look at the overall effect of increasing or decreasing friction, a friction multiplier was also manipulated as an independent variable, where all four values were multiplied by a constant in order to shift the curve up and down from the nominal level. Friction was included in the simulation because it can quickly change with the presence of water and mud that is common in underground coal mines.

Equipment Variables

Researchers also varied features of three aspects of the vehicles tested. Initial speed and loaded weight were taken from the manufacturer specifications (Table 2). Because the researchers were most interested in worst-case scenarios, initial speed was based on the maximum speed of each vehicle. Similarly, the loaded weight varies across the capacity of the vehicle with a nominal value of fully loaded. Speed and load are of interest because they may vary between vehicle operators and can be controlled through policy or intervention.

Table 2. Select Modeled Vehicle Parameters

Vehicle	Chassis Length [in]	Tire Radius [in]	Top Speed [ft/s]	Weight [lbf]	Load Capacity [lbf]	Tire Weight [lbf]	Braking Torque per Wheel [ft-lbf]*
Joy 10SC32B	354.0	20.0	7.0	55,000	30,000	507	2,493
Joy BH-20	453.3	25.0	6.5	78,000	40,000	1,525	4,419
Bucyrus CH816C	456.0	22.0	5.0	76,300	36,000	1,200	3,804
CAI 4880	341.0	17.5	5.0	35,750	20,000	500	1,418

* Derived from average red zone deceleration rate

Braking torque was included in the simulation because it is known to vary with the use and maintenance of the vehicle (e.g., worn brakes). In order to approximate the braking torque, the average red zone deceleration rate (i.e., the maximum deceleration of the vehicle) was calculated from field tests. NIOSH researchers visited three mine sites, where they instrumented a mobile haulage vehicle with a custom-built photo sensor to determine the PDS zone state and a GSS 20 radar (PEGASEM Messtechnik GmbH; Nördlingen, Germany) to measure speed. PDS zone state (i.e.,

yellow zone, red zone) was determined by the measured illuminance of the photo sensor placed in front of an LED that changes color based on the PDS state. The radar calculated speed internally using a proprietary algorithm. Deceleration rates were calculated from the speed as a point-to-point average from 0.5 s after the PDS detected entry into the red zone to 0.1 s from when the vehicle stopped. A delay of 0.5 s was chosen as a conservative estimate for any system delay. The end offset of 0.1 s was used to prevent the inclusion of any final slip or skid. The deceleration rate was averaged over 12 trials from each mine test, where a trial consisted of the vehicle driving at top speed towards a MWC mounted at 46" or 16" high. Each MWC height was used for six of the 12 trials. The average across the three mine sites resulted in an overall average red zone deceleration rate of 3.5 ft/s^2. This deceleration rate was then used to calculate nominal braking torque by computing the torque needed to achieve the average deceleration for each vehicle (Table 2). A summary of the results are presented in Table 3.

Table 3. Summary Field Measurements

Mine	Mobile PDS	Vehicle	Wheel Radius [in]	Average Deceleration [ft/s^2]
A	System A	Joy BH20	23.5	4.6
B	System A	Joy BH18	21.5	2.4
C	System B	Bucyrus CH816	21.5	3.6
			Average	**3.5**

PDS Variables

Lastly, the values for PDS configuration parameters—delay, zone configuration, and braking model—were identified and defined through field observations and discussions. These parameters were included in the model because they are directly related to the design and implementation of PDSs. PDS system delay is the time it takes the PDS to respond (i.e., start braking) after entry into the yellow or red zone is detected. Figure 2 depicts the categorical zone setups that were tested in the simulation: Large, Small, and Extra Small. These zone setups are approximations of measurements of zones observed at mine sites. For simplicity and because only a straight-on approach is currently being simulated, the PDS zone shapes are approximated as boxes. Actual zone shapes depend on the PDS and MWC tracking method, where one system allows custom zone shape configurations and another uses ellipsoid-like shapes around the vehicle. The two braking models that were included are Yellow and Red and Red Only. The Yellow and Red braking model applies 50% braking upon entry into the yellow zone and limits the speed to 2 ft/s while an MWC is detected in the zone. It also applies 100% braking upon entering the red zone. Red Only braking simply means that only entry into the red zone initiates 100% braking, while entry into the yellow zone merely gives a warning to the mineworker.

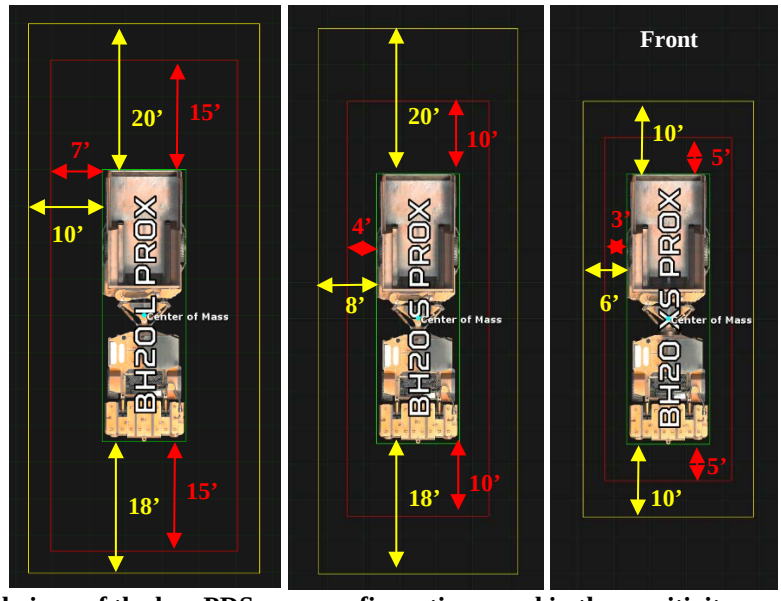

Figure 2. Overhead views of the box PDS zone configurations used in the sensitivity analysis: Large, Small, and Extra Small (left to right). These approximate values were taken from field observations of systems.

Model Development

For the simulation, researchers created a medium fidelity model that incorporates many of the physical properties of the vehicles including, geometry, weight, center of mass, motor torque, and brake torque (Table 2). The values were derived from manufacturer specifications and direct measurements, where the center of mass of each vehicle is assumed to be located horizontally at the center of the wheel base and vertically at the center of the chassis (not the geometric center).

Custom control logic was incorporated into the models to match observed PDS behavior in the field. Namely, the models include a proportional, integral, derivative (PID) speed controller to maintain the initial speed until the PDS was triggered (i.e. entry into the yellow or red zone) as well as to maintain the slow speed in the yellow zone (i.e., 2ft/s). The PID controller uses velocity differential as an input and clamped torque as an output. The PID controller was tuned for each vehicle, but resulted in the same constants. The control logic also handles the PDS system delay and braking behavior (i.e., whether the yellow zone slows down the vehicle or is just a warning) for each trial.

Model Validation

The simulation was validated by a series of validation trials using a CAI 4880 underground coal mining scoop. The vehicle was instrumented with the same photo sensor and radar as used in the field test as well as a laser tachometer (Monarch Instrument; Amherst, NH) to measure speed. Speed was calculated from the tachometer signal using 36 reflective markers affixed to one tire in 10° increments, where the timing of the pulse rate caused by each marker passing in front of the tachometer gives wheel rotation rate and is converted to speed with the wheel diameter. The MWC was placed in line with the centerline of the scoop at a distance adequate to attain full speed prior to entering the PDS zones. The PDS was configured to what is considered a poor configuration: the yellow and red zones were small (Extra Small configuration) and braking only occurred upon entry into the red zone (red zone braking). The tests were conducted on level ground. Eight trials were conducted in an asphalt parking lot without any load, and seven trials were conducted inside a large highbay building with concrete floors. For the indoor tests, two different load weights were used: 6,270 lb (3 trials), and 10,700 lb (4 trials). The loads consisted of a combination of concrete weights and sandbags that were placed in the scoop bucket. For each trial, the position of the MWC was surveyed using a Topcon QS3A robotic total station (Tokyo, Japan). After the scoop came to a complete stop, the front corners of the scoop bucket were surveyed in order to calculate the distance from the vehicle to the MWC.

To determine inputs to the simulation, the PDS zone timing and speed were analyzed for each trial to determine initial speed, PDS delay, and braking torque. The tachometer data was used to calculate speed instead of the radar, because the radar data was found to be unreliable at low speeds, likely due to the uniformity of the surface. Though the tachometer does not account for wheel slip, this was not observed to be an issue in the trial videos and not expected on high friction surfaces like asphalt and concrete (Harned, Johnston, and Scharpf, 1969). Initial speed was determined by averaging the speed for the two seconds prior to the PDS detecting entry into the red zone. PDS delay was then identified by finding the first sample after the red zone trigger with a lower speed than in the prior two seconds. Braking torque was calculated in the same manner as the field tests by basing the torque off the observed deceleration rate. However, using the tachometer, deceleration was computed as an average rate from the PDS delay to the stop point, where the stop point was defined as the first point that the vehicle speed less than or equal to 0.51 ft/s. Stopping distance was compared between the lab and simulation trials in order to validate the model. Stopping distance is defined as the distance traveled after entering the red zone until the stop point. Model agreement will also be evaluated qualitatively by comparing the speed curves.

Sensitivity Analysis

Two dependent variables were derived from the simulation to describe the performance of the PDS under the trial conditions: failure and distance to MWC. Failure is defined as any trial resulting in a collision, where a collision is defined as a distance to MWC of less than or equal to zero. Distance to MWC is defined as the minimum distance between the front plane of the vehicle and the MWC in the direction of travel over the trial. The minimum distance is being used to represent the worst case and eliminate any rocking of the vehicle. However, minimal distance is typically very close to the final resting distance of the machine. Distance to MWC was selected instead of stopping distance because speed data is not readily available to mine operators in the field, the primary audience of this simulation.

Distance to MWC is also used to analyze sensitivity. Sensitivity was calculated as a normalized change of distance to MWC over the normalized change in the variable (Equation 1) (Redl, Gfoehler, and Pandy, 2007), where D_{trial} is distance to MWC for the trial, D_{nom} is the nominal distance to MWC, $Offset_{min}$is the minimum D_{nom}, V_{trial} is the normalized variable value for the trial, and V_{nom} is the normalized nominal value for the test variable. The nominal distance to MWC is defined as the computed value under the nominal conditions for a given vehicle, PDS configuration, and braking model. The offset is used in the numerator in order to remap the performance values away from zero to prevent computational errors. The normalized nominal variable is the nominal variable value (e.g., slope in degrees, load in percent, etc.) normalized from zero to one with respect to the variable's test range (Table 1). To compare sensitivities, the maximum value is calculated for each vehicle, PDS configuration, and braking model.

$$Sensitivity = \left| \frac{\frac{(D_{trial} - D_{nom})}{D_{nom} - (Offset_{min} - 1)}}{(V_{trial} - V_{nom})/V_{nom}} \right| \quad (1)$$

RESULTS

Validation

Overall, the simulation is in good agreement with the lab validation data. Figure 3 displays how the average deceleration profiles for each of the loaded conditions are very similar and share the same characteristically linear deceleration. However, there appears to be a horizontal shift in the deceleration profile, where the simulation trials start to brake later than the lab trials. This is more apparent in the loaded conditions.

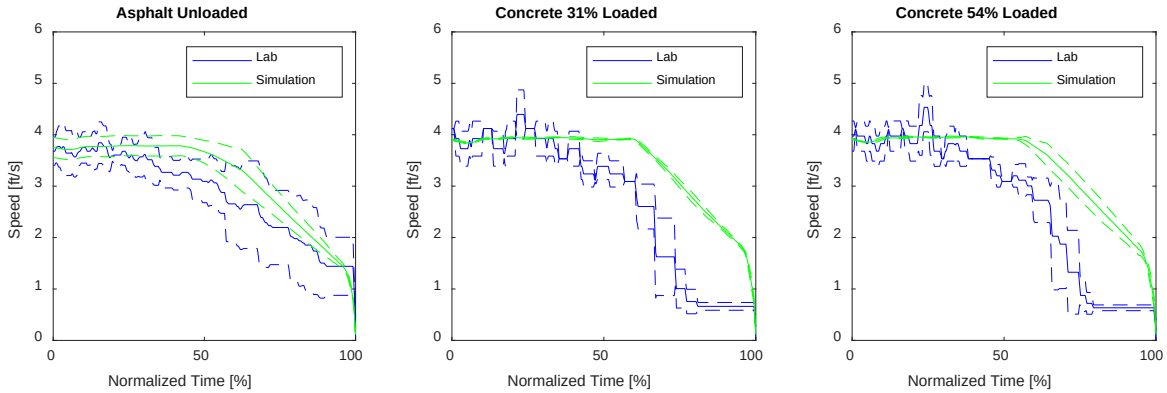

Figure 3. Graphs depicting averaged validation lab (blue) and simulation (green) speed profiles from the entry into the red zone until the vehicle stopped. The dashed lines represent one standard deviation.

Table 4 demonstrates that the simulation is on average within the reported accuracy of the PDS system (6 in) when the calculated initial conditions are used, again indicating good agreement. Interestingly, despite efforts to recreate the exact same initial conditions the values varied. Specifically, the observed deceleration rates varied considerably. On asphalt, decelerations ranged from 3.1 ft/s^2 to 6.8 ft/s^2. On the concrete, the light load trials ranged from 3.8 ft/s^2 to 4.0 ft/s^2, and the heavy trials ranged from 3.7 ft/s^2 to 5.1 ft/s^2.

Table 4. Validation Comparison

Test Condition	N	Avg. Initial Conditions			Avg. Stopping Distance		
		Initial Speed [ft/s]	PDS Delay [s]	Decel. rate [ft/s^2]	Val. [in]	Sim. [in]	Diff. [in]
Asphalt	8	3.8 (0.20)	0.56 (0.09)	4.9 (1.5)	46.4 (4.2)	41.9 (4.9)	4.4 (1.9)
Concrete (31% load)	3	3.9 (0.00)	0.74 (0.09)	3.9 (0.2)	55.4 (1.7)	53.7 (5.1)	1.6 (3.7)
Concrete (54% load)	4	3.9 (0.01)	0.77 (0.05)	4.4 (0.6)	53.4 (3.4)	52.5 (3.7)	0.9 (1.0)

* Standard deviations are shown in parenthesis

Sensitivity Analysis

Under the tested ranges of the independent variables, many of the trials failed, resulting in a collision. Table 5 shows the failure rates for the trials in the simulation by vehicle and PDS configuration. Higher failure rates were observed for both the Joy 10SC32B and the Joy BH20 as well as for the Extra Small PDS configuration, though almost all categories resulted in some failures.

A summary of the effects of the independent variables are also demonstrated in Figure 5, where the effects of each continuous variable (except the asymptote and extremum force and slip coefficients) with each PDS configuration are displayed for the Joy BH20 with Yellow and Red braking as well as all the vehicles with the Small PDS configuration and Yellow and Red braking. Figure 5 shows that the relationships not only change by variable, but also by vehicle. Changing initial speed appears to exhibit a piecewise linear behavior where the first part is flat and drops into a linear decline in performance between 4 and 6 ft/s depending on the PDS configuration. Slope appears to have an inverse exponential relationship to performance, where distance to MWC approaches a stable value after the slope starts to incline. Load level appears to have a linear effect that can change the distance to MWC by as much as 4 ft from empty to 25% overloaded, but the magnitude of this affect depends on the vehicle. The effect of changing friction is fairly small, except for the sharp decrease in performance below a multiplier of 0.2. Braking torque appears to exhibit an inverse exponential improvement in performance with an increase in torque, where reduced torque can reduce the distance to MWC by more than 10 ft beyond a collision. Lastly, PDS delay also demonstrates a negative linear relationship that can result in a decrease in performance of over 5 ft with a 1 s increase in delay. Changing the friction coefficients independently resulted in almost no change in the slip coefficients and only a sharp drop in performance for force coefficients at 0.05 (not pictured).

Table 5. Simulation Trial Failure Rate

	Vehicle				PDS Configuration		
Variable	**Joy 10SC32B**	**Joy BH20**	**Bucyrus CH816C**	**CAI 4880**	**Large**	**Small**	**Extra Small**
Initial Speed	58.8%	55.6%	37.6%	38.9%	34.1%	43.9%	65.2%
Slope	59.2%	54.2%	44.1%	44.8%	41.2%	45.6%	65.0%
Loaded Weight	44.4%	39.2%	16.7%	16.0%	0.0%	13.0%	74.3%
Friction	49.0%	49.7%	18.3%	17.3%	1.2%	25.2%	74.3%
Braking Torque	53.9%	47.1%	22.9%	24.8%	14.9%	26.7%	69.8%
Delay	59.5%	49.0%	26.5%	27.1%	5.1%	29.2%	87.2%

*Darker red denotes higher failure rates

As a comparison between the braking models, Figure 4 depicts how the Red Only trials lack the inflection point found in the Yellow and Red braking trials, following a roughly negative linear relationship. However, no other variables exhibited different behaviors between braking models.

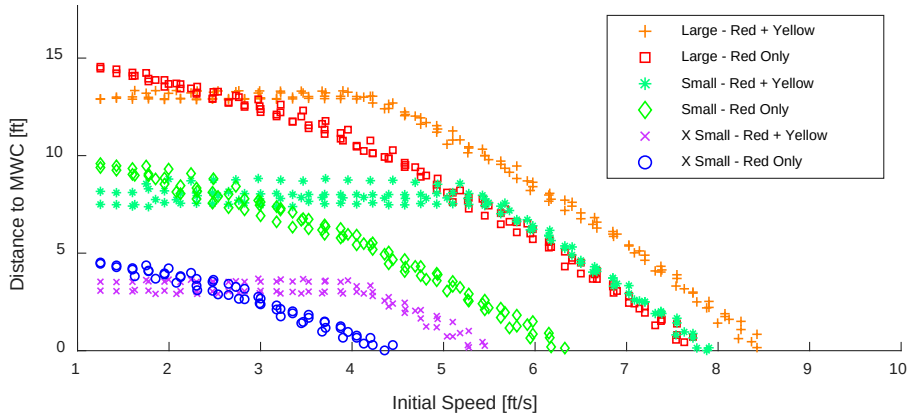

Figure 4. Graph depicting changes in initial speed grouped by PDS configuration and braking model.

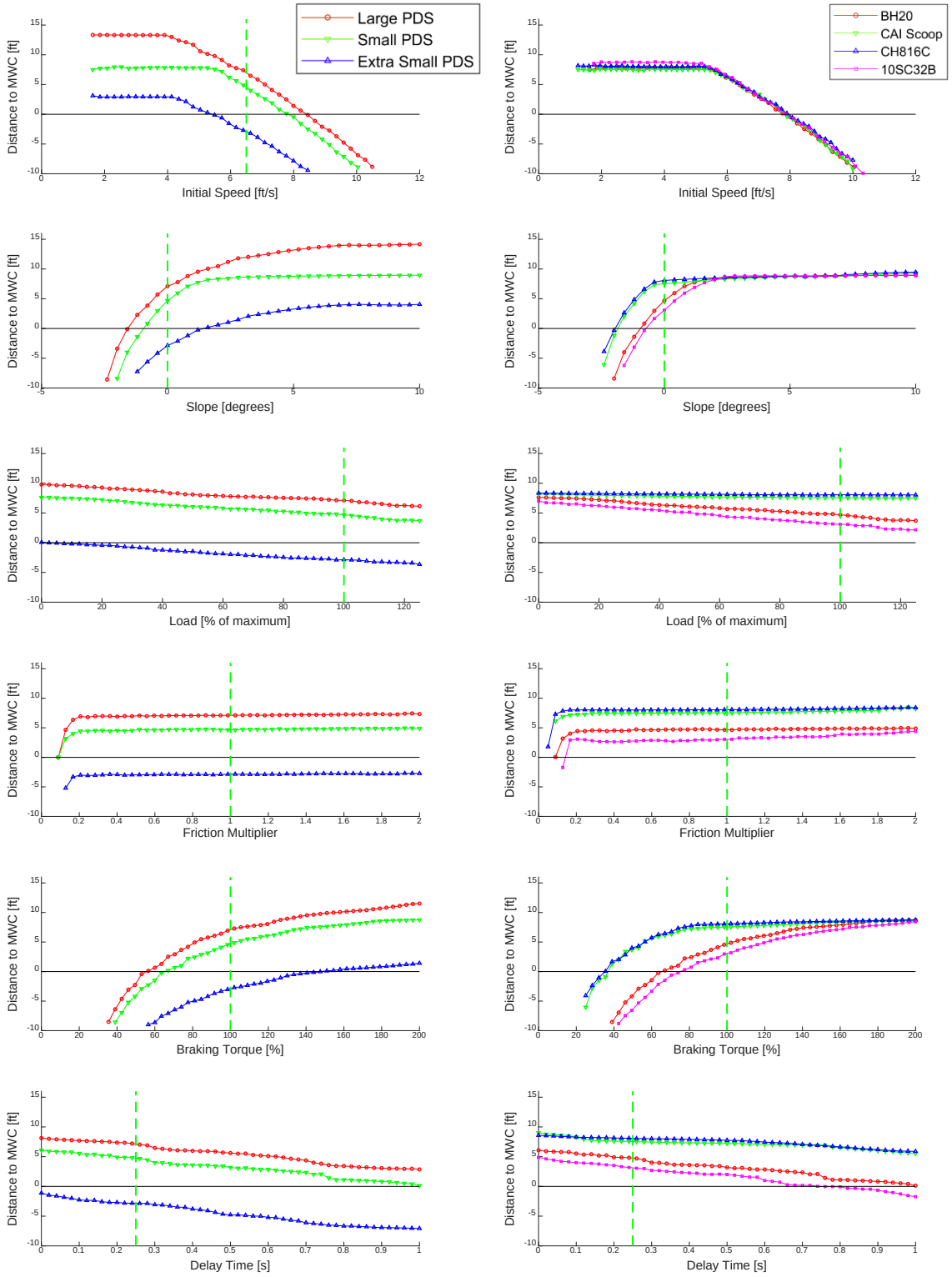

Figure 5. Graphs depicting distance to MWC across six of the continuous independent variables, where the graphs in the left column display results for the Joy BH20 across the three PDS configurations and the right column displays results for all four vehicles with the Small PDS configuration. Only results for the Yellow and Red braking model are included. The vertical dashed green lines indicate the nominal values.

The sensitivity results indicate that slope, initial speed, and braking torque have the most potential to affect the distance to MWC (Table 6). Table 6 also shows that the sensitivity varies across vehicle, PDS configuration, and braking model. Specifically, smaller PDS configurations generally resulted in higher sensitivities, except for the lower speed vehicles (Bucyrus CH816 and CAI 4880) for initial speed, loaded weight, and braking torque. The Red Only braking model was also more sensitive than the Yellow and Red. Lastly, on the whole, the faster vehicles (Joy 10SC32 and Joy BH20) were more sensitive to variable changes.

Table 6. Maximum Sensitivities across Variables

Variable	Vehicle	Red and Yellow			Red Only		
		Large	Small	Extra Small	Large	Small	Extra Small
Initial Speed	Joy 10SC32B	1.56	1.91	3.24	1.69	2.55	10.98
	Joy BH20	0.73	0.74	1.23	0.75	1.08	1.68
	Bucyrus CH816C	1.54	1.85	7.71	2.43	4.04	21.10
	CAI 4880	0.70	0.81	1.59	1.38	1.14	1.83
Slope	Joy 10SC32B	4.32	5.15	7.09	3.97	5.48	11.54
	Joy BH20	2.56	3.09	3.84	2.54	2.49	3.75
	Bucyrus CH816C	4.46	5.23	10.12	4.40	5.78	33.45
	CAI 4880	3.23	3.65	4.14	2.43	3.61	5.32
Loaded Weight	Joy 10SC32B	0.38	0.45	0.74	0.66	0.63	2.21
	Joy BH20	0.09	0.05	0.32	0.11	0.21	0.25
	Bucyrus CH816C	0.35	0.47	3.90	0.92	2.08	7.89
	CAI 4880	0.10	0.16	0.31	0.33	0.16	0.23
Friction	Joy 10SC32B	0.49	0.38	0.50	0.71	0.49	1.48
	Joy BH20	0.50	0.39	0.93	0.77	0.95	0.85
	Bucyrus CH816C	0.51	0.47	1.39	0.77	1.32	3.59
	CAI 4880	0.20	0.09	0.60	0.29	0.47	0.77
Braking Torque	Joy 10SC32B	1.20	1.28	2.10	1.30	1.68	5.13
	Joy BH20	0.68	0.75	1.02	0.78	0.96	1.31
	Bucyrus CH816C	1.30	1.40	3.35	1.39	1.92	10.83
	CAI 4880	0.73	0.87	1.16	0.89	0.99	1.53
Delay	Joy 10SC32B	0.21	0.28	0.38	0.34	0.29	3.05
	Joy BH20	0.10	0.05	0.19	0.09	0.21	0.38
	Bucyrus CH816C	0.20	0.23	1.30	0.32	0.48	3.45
	CAI 4880	0.07	0.09	0.14	0.48	0.13	0.31

*Darker red denotes higher sensitivity

DISCUSSION

NIOSH researchers created a medium-fidelity model and simulation in order to create an intuitive picture of how PDSs on underground coal mobile vehicles perform under various conditions. NIOSH researchers performed validation tests using an instrumented representative vehicle in several loaded conditions. NIOSH researchers then individually varied environmental, equipment, and PDS variables to examine their sensitivity and behavior. This section discusses the results and insights for stakeholders.

Overall, the validation results suggest that the model appears to be in good agreement with the lab trials. Specifically, the stopping distance behavior is within the reported error of the PDSs available in the United States. Therefore, the model should give a good approximation of actual vehicle behavior. Nonetheless, the high variability of the initial conditions merit additional investigation. Because the initial speed was controlled by a human operator, some variability was expected. However, the variability in PDS delay and deceleration rates was expected to be minimal. The variability of the PDS and vehicle performance may be due to poor measurement resolution, especially at low speeds because a tachometer was used. Additional testing should be done to improve the validation of the model and expand the validated range specifically for underground surfaces and on a slope. However, this variability is also a

good reason that ranged values should be examined, because it is also possible that the variability is inherent in the PDS and the vehicle control.

As expected, some of the independent variables (i.e., load level, system delay) demonstrated a linear relationship with distance to MWC, and others were more complex. Slope, initial speed, and braking torque exhibited the largest change in distance to MWC over the tested range and the largest sensitivities overall. Surprisingly, load weight and friction had less of an effect outside the extremes, especially for slower vehicles. This suggests that mine design, operator control, maintenance, and PDS configuration may require more focus during the implementation of a PDS.

The simulation results indicated that slope displayed increasingly greater sensitivity as it decreased. Almost 50% of the slope trials failed, starting at downhill trials greater than 1 degree. Given that mines often have some slope, the results suggest that the initial conditions with the PDS configurations tested here are largely inadequate for general use. This result matches with the recommendation from the Australian Coal Industry's Research Program (ACARP) that the standard 5 m (16.4 ft) red zone configuration typically used in Australia is not sufficient in sloped conditions (De Kock and Bennett, 2018). Because of concerns about nuisance alarms (Bellanca et al., 2019a), mine operators should be aware that changing slopes may require different PDS configurations to maintain mineworkers safety. If it is not possible to increase the size of the PDS configuration, operators may consider improving the vehicle performance (e.g., braking) and being mindful of vehicle maintenance. Worn brakes can similarly affect PDS performance as suggested from the braking torque variable examined here. Regardless, mine operators and mineworkers should be aware of the limitations of PDSs and have appropriate expectations.

In the simulation, the relationship between performance and initial speed changed based on the PDS configuration and braking model. The change in the relationship appears to be a result of the inclusion of yellow zone braking. Because, in the Yellow and Red braking model, entry into the yellow zone reduces and limits the speed of a vehicle, PDS performance is relatively stable for all initial speeds that are low enough to allow the vehicle to reach its yellow zone slow speed. The extent of the stability varies based on the size of the yellow zone. Thus, this is likely the reason that the Small PDS configuration is less sensitive for the slower vehicles (i.e., Bucyrus CH816, CAI 4880). However, at higher initial speeds and with the Red Only braking model, the distance to MWC linearly decreased as speed increased. This result would indicate that the use of yellow and red zone braking could help mine operators mitigate increased risk due to operator speed control.

While this simulation is useful for exploring the general trends, there are some limitations that should be considered when interpreting the results. First, the model sacrifices some numerical accuracy by simulating at a lower frequency (120 Hz) which does not capture some transient tire effects (> 1KHz) (NVIDIA, 2018), but the simulation gains flexibility in testing and visualizing the results. For example, this simulation is currently being used in a VR head-mounted display (i.e., HTC Vive Pro (New Taipei City, Taiwan)) to help stakeholders gain a more intuitive understanding of stopping distances. The simplified model also allows rapid iteration and testing of wide ranges of input variables. Second, the assumed values of this simulation are approximate. The braking torque used was taken as an average of those observed in the field from several different vehicles. It is likely that the higher speed vehicles employ higher braking torques/deceleration rates as observed with the Joy BH20 (Table 3). Changing the vehicle initial conditions could dramatically improve performance. Lastly, this simulation only manipulated variables one at a time. It is likely that the magnitude and behavior of the vehicles would change if more than one variable was changed together. Additional investigation should be done to more fully characterize the systems.

CONCLUSION

The results of the simulation discussed in this paper illustrate the importance of carefully considering all environmental, equipment, and PDS factors when implementing a proximity detection system (PDS). Slope, speed, and braking torque have a greater effect than other variables, and these effects can be further amplified if smaller zones and Red Only braking configurations are used. Beyond the specifics of PDSs in mining, the general relationships highlighted here are relevant to other vehicle control systems, such as autopilot or general collision avoidance technologies. It is critical that designers, managers, and users all have appropriate expectations in order to successfully implement and use these types of systems. Furthermore, this application demonstrates the feasibility of dual-use development for numerical simulation and stakeholder communication. NIOSH researchers are actively using this simulation tool, and the materials, media, and VR experiences created with it will help to raise awareness of and build a more intuitive understanding of PDS behavior and stopping distances.

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