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DEVELOPMENT OF PARAMETERS FOR DYNAMIC MODELING OF UNDERGROUND HAULAGE VEHICLES

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ABSTRACT

To address concerns of how mobile proximity detection systems will adapt to underground mobile haulage vehicles, researchers have collected and categorized data on the parameters of 145 mine haulage vehicles in 5 categories including load-haul-dump, shuttle car, roof bolter, haul truck, and mobile coal haulage (face drill, production drill, and others.) Statistical methods were used to determine the appropriate representative vehicle for each category. These representative vehicles' parameters and characteristics could then be used to develop a dynamic model that predicts their dynamic behavior on an underground haulageway surface. These models can be used in conjunction with worker escapability data and/or interaction with other vehicles to provide insight as to whether or not the proximity detection systems will be adequate for the underground mining workplace.

INTRODUCTION

Injuries and fatalities occur every year when mine workers are struck or pinned by mobile haulage equipment in underground coal mines. During the period from 2009 to 2013, there were 104 underground fatalities of which 22.1% (23) were due to powered haulage [1]. To prevent these accidents, the mining industry is adapting proximity detection systems to this class of equipment. These systems use various technologies, such as RFID, RADAR, infrared, and others. A developing concern about this adaptation is that systems are being designed without sufficient scientific investigation to determine the parameters governing the dynamics of underground mobile haulage vehicles. To address this concern, a database was created detailing the specifications and important parameters of the

many different types, makes, and models of mobile haulage equipment used underground. This information was then categorized and analyzed to determine the appropriate representative vehicle for each category of similar kinematic types (e.g. skid steer, articulated steering, Ackerman steering and all wheel steering.) This information can be used for the development of a dynamic model that is representative of the machines that are used in underground mining. These models can be used in conjunction with worker escapability data and/or interaction with other vehicles to provide insight as to whether or not the proximity detection systems will be adequate for the underground mining workplace.

MARKET ANALYSIS OF MINING VEHICLES

To begin the process of defining characteristics, the vehicle dynamics for the majority of mobile haulage equipment were studied [2-10]. Characteristics such as acceleration, tractive effort, braking, steering, and other parameters were gathered.

The first task was to create a database of all the available mining vehicles in the market. The database detailed specifications and important parameters that could be used directly with a dynamic model. The specifications were found from manuals for each vehicle model. From the literature review, the important characteristics were categorized. These categorized characteristics could then be used to determine the corresponding dynamic model for each group.

Researchers collected data and categorized the parameters for 145 mine haulage vehicles into 5 categories including load-

haul-dump, shuttle car, roof bolter, haul truck, and mobile coal equipment (face drill, production drill, and other).

Load-Haul-Dumps

A load-haul-dump (LHD) is a machine that combines the operations of loading and hauling useful minerals or rock to an unloading point. LHDs are used in underground mines during excavation and haulage of ore from the working face. LHDs usually have large capacities, so their tire models could be classified by different sizes and stiffnesses. A tire/road friction model is essential to the accuracy of the model. Also, the rolling resistance and tractive effort need to be considered carefully when modeling the grade ability of the vehicle. Load-haul-dumps are made up of front and rear components that articulate and, unlike with other industrial vehicles, have no steering wheels. The headings of these vehicles change when the orientation of the two components change [7].

Thirty-seven different LHD models were identified, and data were collected on the identified parameters of interest. These parameters included gross power, nominal payload capacity, gross machine operating weight, axle load distribution, maximum speed in each transmission gear, forward and reverse; outside clearance radius; inner clearance radius; axle oscillation; articulation angle; tire used; dimensions (overall length, wheelbase, front axle to hitch, rear axle to bumper, width, height); and recommended clearance width and height.

Shuttle Cars

In room-and-pillar systems, electric-powered, rubber-tired vehicles called shuttle cars are frequently used to haul coal from the face to the intermediate haulage system. These shuttle cars are usually used at a slow speed with a high load. Shuttle cars have different types of suspensions and operating speeds. At low speed, air drag effects can be ignored, and the transmission model can be simplified to reflect only one set of gears.

Twenty-three different shuttle car models were identified, and data were collected on gross power; nominal payload capacity; gross machine operating weight; tire used; outside clearance radius; inner clearance radius; tram speed; dimensions (overall length, wheelbase, width, height, ground clearance); and recommended clearance width and height.

Roof Bolters

A roof bolter is a hydraulically driven bolting rig used to install rock bolts in mines. It frequently features a bar- or beam-type automated temporary roof support (ATRS) system and multiple booms that allow multiple roof bolts to be installed from one machine. Roof bolters can be classified by their frame type. Fixed frame and articulated frame roof bolters would be modeled differently because they steer and slip differently. Some of the roof bolter machines use hydraulic motors instead of engines to drive the wheels, which would result in a different drive train model.

Fourteen different roof bolter models were identified, and data were collected on gross power; frame type; weight; outside clearance radius; inner clearance radius; axle oscillation; articulation angle; tire used; tram speed; dimensions (overall length, wheelbase, front axle to hitch, rear axle to bumper, width, height); and recommended clearance width and height.

Haul Trucks

Haul trucks provide an intermediate method for removing material from a production section. They are typically rubber-tired, articulated vehicles. They have a wide variety of payloads and sizes in that they are frequently designs adapted for specific mines.

Nineteen different haul truck models were identified, and data were collected on the identified parameters of interest. These parameters included: gross power, nominal payload capacity, gross machine operating weight, axle load distribution, maximum speed in each transmission gear, forward and reverse; outside clearance radius; inner clearance radius; axle oscillation; articulation angle; tire used; dimensions (overall length, wheelbase, front axle to hitch, rear axle to tail, width, height); and recommended clearance width and height.

Mobile Coal Equipment

Some other types of mobile mining equipment that may be of interest include, but are not limited to, face drills and production drills. Only tire-mounted vehicles were considered for the purposes of dynamic modeling. Data were collected for some additional mobile equipment (roof support carriers, transporters, multi-task, and sprayers) to provide information for additional models should they be determined necessary.

Seventeen face drill and nineteen production drill models were identified, and data were collected on the identified parameters of interest. These parameters included gross power; gross machine operating weight; outside clearance radius; inner clearance radius; axle oscillation; articulation angle; tire used; dimensions (overall length, wheelbase, front axle to hitch, rear axle to bumper, width, height); and recommended clearance width and height.

SELECTED REPRESENTATIVES OF CATEGORIZED MINING VEHICLES

To use the gathered information systematically for developing vehicle models, the important characteristics were listed in groups. The categorized characteristics can be used to determine the corresponding dynamic model for each group. From the physical data collected, the representatives were assigned by studying important parameters such as gross weights, weight distributions, dimensions, gross power, etc. The selected representatives were similar to all the models in each category for future modeling use of that machine type. In this task, two methods were used to find the proper representatives for each category. The first method used the average values for each parameter to represent the machine type. The second method used a statistical analysis to choose a specific model type

for each machine type. The chosen model types are intended to be the most similar to all available types in all categories.

The selected parameters for data analysis were operating weight, gross power, inner and outer turning radius, and length, width, and height of the vehicle. These parameters were chosen because: 1) most of the models in the database have the information about those parameters; 2) they can be used as the inputs to simulate the dynamic models; and 3) these parameters are frequently the main criterion when purchasing the machines. Capacity is the first thing that customers usually consider. The turning radius, however, can become the limiting factor based upon working conditions.

Dynamic Analysis: Mean value for each category

The average values for each important parameter were calculated and given to construct the representative value for each category of the mining vehicles (Table 1).

Table 1. Mean values given to the representatives of each categories.

Parameter Categories	Operating Weight (lb)	Gross Power (hp)	Inner Turning Radius (in)	Outer Turning Radius (in)	Length (in)	Width (in)	Height (in)
Load-Haul-Dumps	81,755	234	127	256	357	95	87
Roof Bolters	39,512	148	144	283	355	111	75
Shuttle Cars	59,250	156	-	-	363	142	62
Haul Trucks	248,773	692	211	396	426	143	133
Face Drillers	61,229	166	182	328	554	95	122
Production Drillers	30,021	108	132	224	320	80	107

Dynamic Analysis: Statistical analysis to select model representative for each category

For statistical analysis, the models that have all the selected parameters mentioned above were considered to find the candidates of the representatives. The limit of the ranges was set to 10% percent from the average for normalized weight, and to 30% for others. If one of the chosen parameters was out of the range, the model was removed from the candidates group. After applying an algorithm to all the parameters, two or three models survived, and they were the selected representatives for their machine types.

The normalized weight was considered after analyzing the gross weights for each category since it was found that gross weight was widely distributed (Figure 1). However, the weight of the vehicles is significantly related to their dimensions. In order to further evaluate these parameters and select the best representative model type, the normalized parameters were considered. Normalized parameters can better explain weight distribution/size relation and capacity of the vehicles and their usage. For example, the smaller size capacity may be widely used in narrow haulageways, since the smaller size facilitates easier turns and safer, more efficient mining.

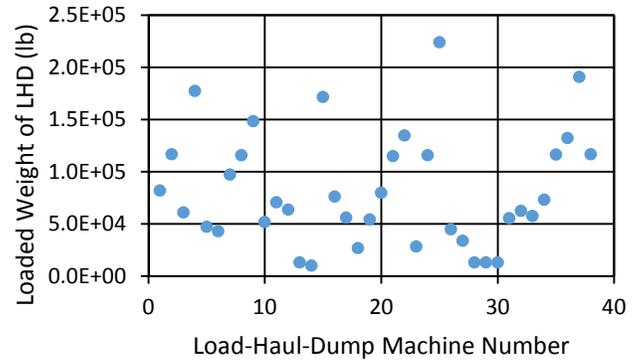


Figure 1. Load-haul-dump loaded weight shows a large nonconcentrated range.

Tables 2-7 show the results of the selection process show the selected representatives for all categories of vehicles including load-haul-dumps, roof bolters, shuttle cars, haul trucks, face drillers, and production drillers. The tables show the mean values for the physical data which could be used in the implementation of dynamic models developed for the selected representatives to validate a simulation. A more detailed analysis with different criteria for each type of machine could be performed and discussed in light of specific goals and different usages in the future.

Table 2. Selected representatives for LHDs.

Parameter Categories	Operating Weight (lb)	Gross Power (hp)	Inner Turning Radius (in)	Outer Turning Radius (in)	Length (in)	Width (in)	Height (in)
CAT CL215	63,940	230	130	252	323	100	75
Sandvik LH208L	56,209	188	117	241	338	109	62
Sandvik LS170L	57,717	230	115	236	349	92	67

Table 3. Selected representatives for roof bolters.

Parameter Categories	Operating Weight (lb)	Gross Power (hp)	Inner Turning Radius (in)	Outer Turning Radius (in)	Length (in)	Width (in)	Height (in)
Sandvik LH208L	55,116	150	150	291	471	108	132
Sandvik LS170L	62,832	209	209	327	494	98	154

Table 4. Selective representatives for shuttle cars.

Parameter Categories	Operating Weight (lb)	Gross Power (hp)	Length (in)	Width (in)	Height (in)
Sandvik LH208L	60,000	230	371	138	57
Sandvik LS170L	63,500	200	379	156	59

Table 5. Selected representatives for haul trucks.

Parameter Categories	Operating Weight (lb)	Gross Power (hp)	Inner Turning Radius (in)	Outer Turning Radius (in)	Length (in)	Width (in)	Height (in)
Atlas Copco MT42	168,650	520	183	350	432	120	106
CAT AD30	132,300	408	198	337	398	104	116
Sandvik TH551	224,900	691	200	370	455	126	124

Table 6. Selected representatives for face drillers.

Parameter Categories	Operating Weight (lb)	Gross Power (hp)	Inner Turning Radius (in)	Outer Turning Radius (in)	Length (in)	Width (in)	Height (in)
Atlas Copco Boomer 282	40,345	78	110	224	466	78	120
Atlas Copco Boomer E1 C	74,957	154	189	339	569	100	125

Table 7. Selected representatives for production drillers.

Parameter Categories	Operating Weight (lb)	Gross Power (hp)	Inner Turning Radius (in)	Outer Turning Radius (in)	Length (in)	Width (in)	Height (in)
Atlas Copco Simba 260	24,912	70	106	201	257	94	111
Sandvik DL331	37,479	99	128	235	386	78	122

DYNAMIC MODELING OF UNDERGROUND VEHICLES

To develop a model that explains dynamic behavior of various types of vehicles, mainly underground vehicles on the road surface, the types of motion to model must be determined. The vehicle motions to model include, but are not limited to, ride, cornering, braking, and accelerating. The model describes how the vehicle’s components will respond to excitation under particular conditions. The following governing equations apply generally to most vehicle models, but some are vehicle specific.

The kinematic and potential energy are derived with respect to global coordinates X_n, Y_n, Z_n , as shown in Figure 2. Translational and rotational velocity equations need to be developed in order to use Lagrange equations. The load on the front and rear axles, W_f & W_r , can be determined based on translational and rotational equilibrium, as shown in Figure 3.

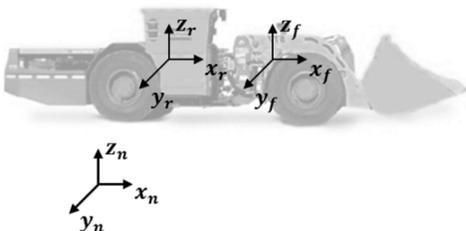


Figure 2. Coordinate systems of vehicle.

CG is the center of gravity. Other variables define the motion of the vehicle as:

- x_n : CG x-axis position
- \dot{x}_n : CG x-axis velocity
- y_n : CG y-axis position
- \dot{y}_n : CG y-axis velocity
- z_n : CG z-axis position
- \dot{z}_n : CG z-axis velocity
- \dot{p} : roll velocity about x-axis
- \dot{q} : pitch velocity about y-axis
- \dot{r} : yaw velocity about z-axis

W is the weight of the vehicle, L is the wheelbase, D_A is the aerodynamic force acting on the vehicle, and h_{cg} is the height of CG. Newton’s second law about the rear tire point of contact yields

$$\frac{W}{g} a_x h_{cg} - W_f \cos \theta L - D_A h - W \sin \theta h_{cg} + W \cos \theta d_r = 0$$

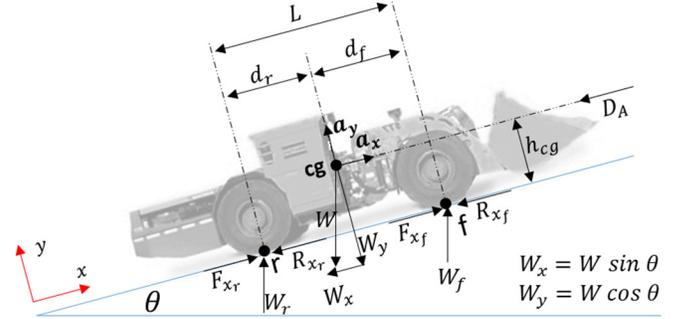


Figure 3. Forces acting on vehicle.

Static loads

Assuming that $\theta = 0$, for the wheelbase, L , reaction forces are related to the forces acting on the tires:

$$F_f = \frac{d_r mg}{L}$$

$$F_r = \frac{d_f mg}{L}$$

where F_f and F_r are the forces acting on the front and rear tires respectively, d_f and d_r are the distance between CG to the center of the front tire and rear tire, m is the mass of the vehicle, and g is the earth’s gravitational constant. Distances d_f and d_r can change depending on load, but will always satisfy $d_f + d_r = L$.

Low-speed acceleration

Extra torques are distributed to the front and rear tires when the vehicle is accelerating or decelerating. Thus:

$$F_f = \frac{d_r mg}{L} - h_{cg} ma$$

$$F_r = \frac{d_f mg}{L} + h_{cg} ma$$

Tire size, air pressure, and the stiffness of the suspension can affect these parameters.

Acceleration Performance

Power train

Horsepower (HP) can be defined by considering the power train torque (T) and angular speed (ω_e) as follows:

$$Power = Torque * RPM = F_x \dot{x}_n$$

$$HP = T \omega_e$$

The relationship between engine torque and power transmission is shown in Figure 4.

The tractive force can be expressed based on the torque supplied from the engine to the transmission, the transmission to the drive shaft, and the drive shaft to the axles:

$$F_x = \frac{T_e N_t f}{r} - \{(I_e + I_t) N_t f^2 + I_d N_f^2 + I_w\} \frac{a_x}{r^2}$$

The term $\frac{T_e N_t f}{r}$ represents the static-state tractive force, and $N_t f$ is the efficiency factor. The second term $(I_e + I_t) N_t f^2 + I_d N_f^2 + I_w$ can be denoted as $m_r a_x$. Thus Newton's second law becomes

$$(m + m_r) a_x = \frac{T_e N_t f \eta_t f}{r} - R_x - D_A - R_{hx} - W \sin \theta$$

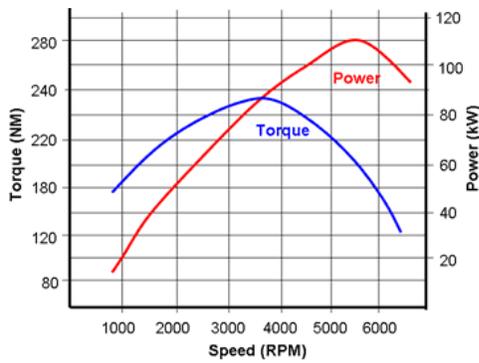


Figure 4. Engine power and torque curves [14]

Rotational dynamic

The following parameters describe the rotational dynamics of the system:

Rotational Inertia	Rotational Acceleration
I_e : Engine	α_e : Engine
I_t : Transmission	α_w : Wheels
I_w : Wheels and shafts	α_d : Drive Shaft
I_d : Drive shaft	

From Figure 5, the rotational velocity and acceleration of the wheel can be found:

$$T_a - T_b - F_x r_n = I_w \alpha_w$$

where T_a is the torque transmitted at the axels, T_b is the braking torque, F_x is the force tangent to the wheel along the axis of motion, and r_{nom} is the nominal radius of the wheel. The radius can be affected by a number of factors include tire stiffness, load, and inflation pressure.

Braking system

Braking force

Assuming pure rolling when braking:

$$m a_x = \frac{W}{g} D_x = -F_{bf} - F_{br} - D_A - W \sin \theta$$

F_{bf} and F_{br} are braking forces on the front and rear wheels. Assuming that the brake force is uniformly applied on the vehicle, and that the stopping distance is $x = \frac{(V_0^2 + V_f^2)}{2(F_{br} + F_{bf})m}$, the stopping time can be expressed as

$$t_s = (V_0 - V_f) \frac{m}{F_{xt}}$$

where V_0 is the original velocity, V_f is the final velocity, and F_{xt} is the total longitudinal force on the wheels.

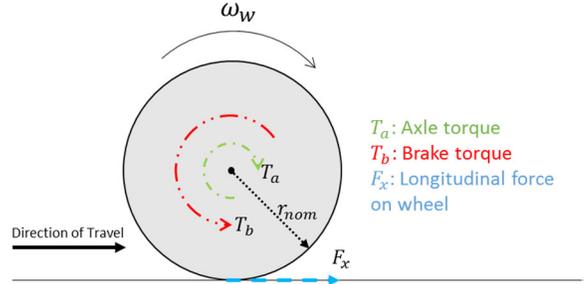


Figure 5. Forces and torques on tire.

Brake Structures

There are two common types of brakes: drum and disc. When brakes are applied, the torque will closely match the actuation effort, p_a , as illustrated in Figure 6. Velocity, V , and generated temperature, $Temp$, also affect the torque during braking:

$$T_b = f(p_a, V, Temp)$$

Thus the braking force is

$$F_b = \frac{T_b - I_w \alpha_w}{r_{nom}}$$

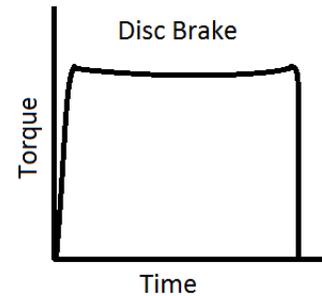


Figure 6: Torque of a typical disc brake measured by dynamometer.

Brake distribution

The maximum brake forces for each axle can be shown as

$$F_{bf} = \mu_p W_f$$

$$F_{br} = \mu_p W_r$$

where μ_p is the peak coefficient of friction. The maximum brake forces vary with the deceleration.

Tire model

Rolling resistance

Rolling resistance is the major resistance force for speeds under 80-90 km/h.

$$R_x = R_{xf} + R_{xr} = \mu_x W$$

where μ_x is the rolling resistance coefficient, R_x is the reaction force on the front and rear wheels, and W is the weight of the vehicle. The effect of velocity acting on rolling resistance coefficient is very small at low speed. However, considering the high load of underground vehicles, this is an important factor in the model.

Slip

The longitude wheel slip is defined as follows [12]:

When braking:

$$s_x = 1 - \frac{R\omega}{v_x}$$

When driving:

$$s_x = \frac{R\omega}{v_x} - 1$$

The relationship between friction and slip can be found in Figure 7.

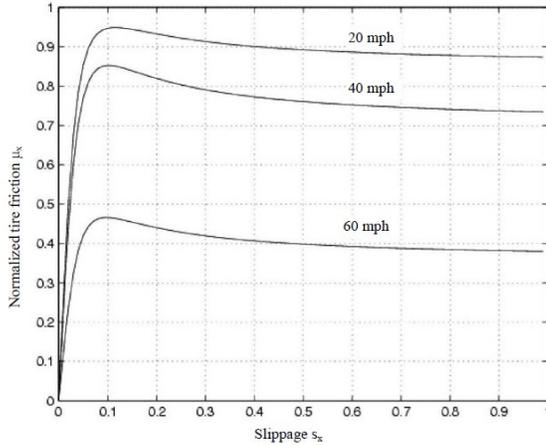


Figure 7: The relationship between friction and slip under different speeds [3].

There are many types of models to curve-fit the μ_x and s_x curve, which has both a linear part and nonlinear part. The brush model is one of the most suitable models [8]. Since the nonlinear part of the model is not very important, the piecewise linear model can be used [9], which is simple and empirical due to its consideration that the relationship between s_x and μ_x is linear.

There are more models proposed both as semi-empirical and analytical to increase the accuracy of the model [9]. The longitude force can be calculated as

$$F_x = C_l s_x$$

where C_l is the longitudinal stiffness. The lateral dynamics of the tire is caused by slip. The lateral force can be expressed as

$$F_y = C_\gamma \gamma$$

where γ is the slip angle and C_γ is the proportional constant.

Suspension model

The suspension system will maintain the tires on the road surface for control. The suspension system also controls the tire kinematics, and the roll and pitch of the vehicle. It will contain springs, dampers and Coulomb friction [10]. The perturbation in vertical direction can be expressed as:

$$F_p = F_c \sin \dot{e}_i + K e_i + D \dot{e}_i$$

where e_i is the deflection of the spring from the equilibrium position, F_c is the Coulomb friction, K is the spring stiffness and D is the damping ratio.

Dynamic model

One component vehicle dynamic

The kinetic energy of the system is needed in the longitudinal and lateral direction to utilize the Euler-Lagrange equation. Using unit vector (i_n, j_n, k_n) , the velocity can be represented in global coordinates:

$$V = (\dot{x}_n \cos r + \dot{y}_n \sin r)i + (-\dot{x}_n \sin r + \dot{y}_n \cos r)j$$

where r is the angle about the yaw angle about the z axis. Thus the Lagrangian is:

$$\begin{aligned} L = T &= \frac{1}{2} \frac{W}{g} V^2 + \frac{1}{2} I \omega^2 \\ &= \frac{1}{2} \frac{W}{g} (\dot{x}_n \cos r + \dot{y}_n \sin r)^2 \\ &\quad + \frac{1}{2} \frac{W}{g} (-\dot{x}_n \sin r + \dot{y}_n \cos r)^2 + \frac{1}{2} I r^2 \end{aligned}$$

The generalized forces acting on the tires can be obtained by

$$\begin{aligned} \frac{\partial}{\partial t} \frac{\partial L}{\partial \dot{x}_n} - \frac{\partial L}{\partial x_n} &= F_{gxn} \\ \frac{\partial}{\partial t} \frac{\partial L}{\partial \dot{y}_n} - \frac{\partial L}{\partial y_n} &= F_{gyn} \\ \frac{\partial}{\partial t} \frac{\partial L}{\partial \dot{r}} - \frac{\partial L}{\partial r} &= F_{gr} \end{aligned}$$

The state-space equation can be expressed as

$$M \ddot{q} = -h(q, \dot{q}) + F_g$$

where $q = \begin{Bmatrix} x \\ y \\ r \end{Bmatrix}$, M is matrix of inertia, and F_g is the generalized force.

Two components vehicle dynamic

For the articulated vehicles like load-haul-dumps, there are two components to analyze [13]. The velocity of the second component can be expressed as

$$V_2 = V - D_1 r_{jf} - D_2 (\dot{r} + \dot{r}_f) j_r$$

Where D_1 and D_2 are the distance from articulation joint to CG of front and rear components respectively. The Lagrangian becomes

$$L = T_1 + T_2$$

Where T_1 and T_2 are the kinetic energy of the front and rear components respectively, and

$$T_2 = \frac{1}{2} \frac{W}{g} V_2^2 + \frac{1}{2} I_2 \omega_2^2$$

Kinematic Model

Cornering

For vehicles turning into a crosscut or at a bend, cornering is necessary. The cornering equation describes the lateral force acting on the tires during a turning motion, as shown in Figure 8. The equation for a turnabout radius R can be shown as:

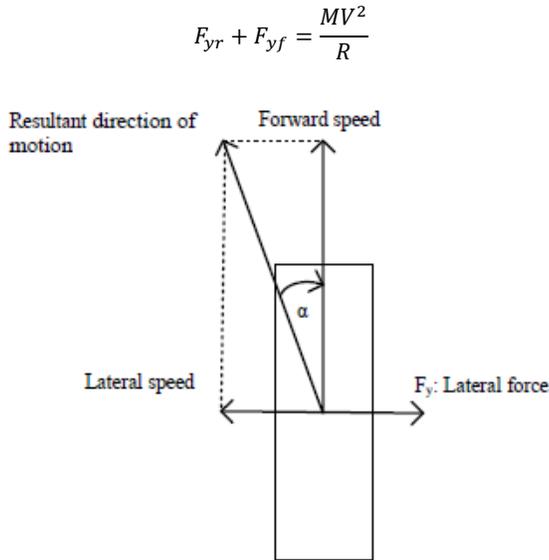


Figure 8: Illustration of tire force [11].

The slip angles for the front and rear tires can be written as:

$$\alpha_f = \frac{W_f V^2}{C_{\alpha f} g R}$$

$$\alpha_r = \frac{W_r V^2}{C_{\alpha r} g R}$$

The steer angle is thus:

$$\gamma = 57.3 \frac{L}{R} + \alpha_f - \alpha_r$$

$$\gamma = 57.3 \frac{L}{R} + K \alpha_y$$

where K is the understeer gradient (deg/g) and α_y is the lateral acceleration. These equations can describe the turning response of the vehicle. There are three possible situations for the cornering:

1) Neutral steer: $W_f/C_{\alpha f} = W_r/C_{\alpha r}$, where $K = 0$. No need to change the steer angle to make a constant radius turn under a different speed.

2) Understeer: $W_f/C_{\alpha f} > W_r/C_{\alpha r}$, where $K > 0$. The increasing steer angle with the increasing speed is needed to make a constant radius turn. The slip caused by lateral acceleration is greater for the front wheels.

3) Oversteer: $W_f/C_{\alpha f} < W_r/C_{\alpha r}$, where $K < 0$. The decreasing steer angle with the increasing speed is needed to make a constant radius turn. The slip caused by lateral acceleration is greater for the rear wheels.

The effect of suspension on cornering is ignored due to the stiffness of suspension in large load vehicles. The roll moment distribution can be expressed as:

$$F_{zi} - F_{zo} = \frac{2F_y h_r}{t} + \frac{2K_{\Phi} \Phi}{t} = 2\Delta F_z$$

where F_{zi} is the load on the inside wheel;

F_{zo} : load on the outside wheel, and $F_y = F_{zi} - F_{zo}$;

h_r : roll center height;

K_{Φ} : roll stiffness of the suspension;

Φ : roll angle of the body; and

t : width of the track.

Steering

Off tracking is a concern for vehicles with a long wheelbase traveling underground. The off track distance for the rear wheels is

$$\Delta = R \left[1 - \cos\left(\frac{L}{R}\right) \right] \cong \frac{L^2}{2R}$$

where L is the wheelbase and R is the distance between the turn center and the center of mass of the vehicle. Thus the distance from the rear axle to the center is

$$r = V \frac{D_2 + D_1 \cos \gamma}{V \sin \gamma + D_2 \dot{\gamma}}$$

DISCUSSION

The representative vehicles' parameters and characteristics collected during this research can be used to develop a dynamic model that predicts their dynamic behavior on an underground haulage surface. These models can be used in conjunction with worker escapability data and/or interaction with other vehicles to provide insight as to whether or not existing proximity detection systems will be adequate for the

underground mining workplace. The resulting models can also be validated through observation of vehicle performance in various underground environments. Through the use of these models, it is hoped that any potential functional incompatibilities can be avoided between the haulage vehicles in use and the proximity detection systems intended to provide additional protection to personnel in the mining environment.

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