Quantitative Framework for construction Safety Evaluation in Designing Temporary Haul Road Layout on Site Grading Projects

Chaojue Yi[a] and Ming Lu[b]

[a] Hole School of Construction Engineering, Department of Civil & Environmental Engineering, University of Alberta, Edmonton, Alberta, Canada
[b] Hole School of Construction Engineering, Department of Civil & Environmental Engineering, University of Alberta, Edmonton, Alberta, Canada
E-mail: chaojue@ualberta.ca, mlu6@ualberta.ca

Abstract –

Temporary haul road layout design is a main factor influencing the cost and safety of haulage in heavy civil construction, especially on large site grading projects which entail mass earthworks. The ideal design of temporary haul road layout is to deliver the project in the lowest construction budget while guaranteeing haulage safety. Previous research endeavours have focused on achieving the lowest earthmoving cost in designing temporary haul road layout but failed to incorporate the equally important safety factors, thus rendering the optimized design to be possibly associated with high safety risks. This paper proposes a framework that aims to quantify haul road design related safety factors in a large site grading project. The feasibility and effectiveness of the proposed methodology is further evaluated by a real world case study. A comparative table with information on safety performance index values and safety indicator values of four alternative layout designs is given to visualize the quantification outcome. In conclusion, the proposed methodology enables construction planners to quantitatively evaluate haul road related safety impact, leading to significant improvements in the safety performance of temporary haul road layout.

Keywords –

Site Grading; Temporary Haul Road; Layout Design; Safety; Evaluation

1 Introduction

Haul roads are most commonly built in mining projects to improve hauling efficiency and ensure hauling safety on mine haul jobs. In the Guidelines for Mine Haul Road Design [1], haul roads are categorized into temporary, semi-permanent and permanent haul road. Unlike the mining project, for site grading and earthmoving operations over a large area, it is not realistic to link a loading area (cut) and a dumpsite area (fill) by permanent or semi-permanent haul roads since the project generally lasts several months. For improving hauling efficiency and safety in large site grading projects, the common practice is to build a limited length of temporary haul roads (e.g. gravel surfaced) along critical truck hauling paths on site. Due to its temporary nature, temporary haul roads are typically built with pit run, limestone or gravel with minimum thickness or even directly laid on rough ground. Generally, the temporary haul road can be simply classified as high grade vs. low grade where high grade haul road can be gravel surfaced while low grade haul road remains rough ground requiring frequent maintenance (by grader) [2].

While haul road design guidelines are available to regulate on various aspects of the haul road on mining projects (e.g. alignment, curvature, surface, and etc.) [1][3], there lacks insightful design specifications for temporary haul roads for heavy civil projects. In trying to establish the guideline, several research endeavors were made recently. Liu [4] proposed a multi-generation compete genetic algorithm (MCGA) to search for the least-cost temporary haul road layout design. Based on Liu's work, Yi and Lu [2] further proposed a more sophisticated mixed-integer linear programming (MILP) method to analytically identify the least-cost design by considering accessibility and connectivity constraints. Though cost-efficiency has been satisfied in the resulting design, the previously proposed methods failed to consider safety factors, thus making the optimized design possibly exposed to potential safety hazards.

As operations safety is highly dependent on well-designed, well-constructed and well-maintained haul roads, insufficient haul road design will have an immediate negative impact on operations safety. Due to the size and weight of earthmoving equipment, when accidents occur, consequences are often severe. According to electronic educational material published by Occupational Safety and Health Administration (OSHA), approximately 75% of struck-by fatalities involve heavy equipment. Also, in the same source it mentioned that one in four "struck-by vehicle" accidents resulting in a fatality involves construction workers, more than any other occupation [5]. The most common causes of heavy construction equipment accidents resulting in fatalities and injuries are categorized by OSHA (2003) [6], namely: (1) being caught in/between; (2) being struck-by equipment/falling objects; (3) falling from vehicle; and (4) equipment rollover. In a typical earthmoving site where large amounts of heavy equipment exist, a well-designed and maintained haul road network will considerably reduce the possibility of encountering safety hazards.

In order to incorporate safety as a design factor in designing temporary haul road layout, the quantification for the underlying safety hazards in a unified measurement is required. Given that there are no safety quantification methods for the earthmoving operations in existing literatures, the objective of this paper is to propose a conceptual framework that can support the quantification of safety by (1) introducing a grid model to represent the earthmoving site and temporary haul road layout design; (2) identifying haul road related safety impact factors in earthmoving operations; and (3) proposing formulating schema for each identified safety impact factor in a consistent unit of measure based on the presented model. The following sections provide a detailed description of how to fulfil the objective step by step with a practical case study.

2 Grid Model, Graph, And Traffic Flows

The grid model of a possible haul road layout design on a rough-grading site was proposed by Liu and Lu, (2015) [4], as demonstrated in Figure 1. For each cell, the centroid is simplified to be the cell's geometric centre; thus, the potential road layout design can be denoted by road links, each connecting the centroids of two adjacent cells with straight-line sections. The road type of each link can be distinguished by a dot line for "rough ground" by default and by a solid line for "gravel surfaced". It should be noted that the "road links" are segments between the centroids of any two adjacent cells, instead of between any two cell centroids; two cells are deemed adjacent only if they are 'immediately adjacent' or 'diagonally adjacent'.

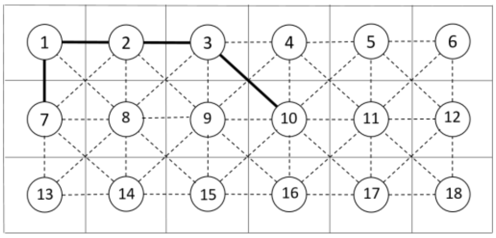
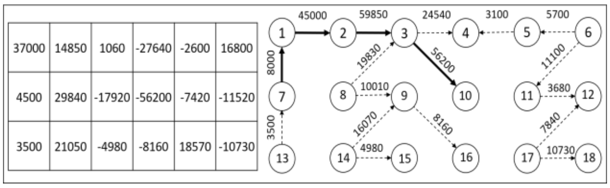


Figure 1. Site partitioning strategy and road links to represent haul road design

Based Graph Theory, an undirected graph is written as $\mathrm{G} = (\mathrm{V}, \mathrm{E})$, meaning that G consists of node-set V and edge-set E. We use v to represent a node (centroid of a cell) and (i,j) to represent an edge (road link) in the haul road network. Note $\forall$ v $\in$ V, and all $\forall$ (i,j) $\in$ E where i and j are end nodes of edge (i,j). The type of haul road is denoted by a Boolean parameter $\mathrm{x}_{(\mathrm{i,j})}$, which equals to "0" given "rough ground" haul road; equals to "1" given "gravel surfaced" haul road (e.g. in Figure 1. $\mathrm{x}_{(1,2)} = 0$; $\mathrm{x}_{(6,7)} = 1$).

Validated by previous research [4][7], when cut and fill volume data of each cell is given, the optimally allocated traffic volumes on each road link (i.e. traffic flows, in m^3) can be determined by applying linear programming techniques, as shown in Figure 2. The previous research achievements for determining traffic flows on each road link lay a firm foundation for proposing safety index formulating schema described in the subsequent chapter.



37000	14850	1060	-27640	-2600	16800
4500	29840	-17920	-56200	-7420	-11520
3500	21050	-4980	-8160	18570	-10730

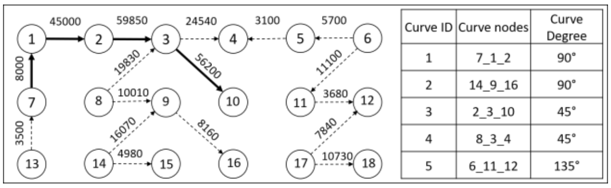
Figure 2. Cell based cut and fill design and optimal earthwork flows

3 Safety Quantification Framework

In trying to quantify hauling safety in earthmoving based on the presented model, a comprehensive literature review [1][3][8] and several field studies were conducted in order to define practical measures that can be taken during the temporary haul road layout design process in evaluation of construction safety. This investigation led to the identification of three major safety measures: (1) proper design of temporary haul road (both geometrically and structurally) to improve the safety at curves and minimize the hazards (e.g. collision, out of control) caused by blocking line of sight; (2) reducing surface hazards such as potholes, rutting, settlement, wash-boarding, and heaving caused by heavy traffic volume; and (3) control of hazardous equipment near labour-intensive onsite facilities.

3.1 Curve Safety Index (CSI)

In current model, a curve is denoted by (i,j,k), which stands for truck hauling from node i to node k, passing node j; i is curve starting node, j is curve centre node; k is curve ending node; note i and k are interchangeable since trucks haul in round trip. In this study, three curve angles are considered, as 45°, 90° and 135° in alignment with the grid model, as illustrated in Figure 3. The dot circles indicate curve centre nodes. Different curves could share the same curve centre node, forming an intersection (e.g. node 3). All the curves are identified based on earthwork flows and cut and fill design, as summarized in Figure 3.



Curve ID	Curve nodes	Curve Degree
1	7_1_2	90°
2	14_9_16	90°
3	2_3_10	45°
4	8_3_4	45°
5	6_11_12	135°

Figure 3. Horizontal curves

From a safety standpoint, haul road must be designed to accommodate the braking capabilities of those vehicles having the least braking potential which will most likely to transverse or directly hit on obstacles (such as wild animals, breakdown trucks, and falling rocks) due to inability to stop in time. This situation is especially severe at horizontal curves. At curves, driver's line of sight is blocked by a hill crest, trees, or an obstacle on the inside of the curve. Insufficient stopping distance can adversely affect the truck hauling safety at a curved section. According to published design regulations [1][3], truck's stopping distance is related to road grades, friction coefficients, rolling resistance, climate condition, and truck sizes. In order to guarantee the safety of truck hauling at curves, contractors are responsible to properly design the temporary haul road layout. To this end, a minimum stopping distance is required to guarantee the hauling safety at curves.

In this paper, the degree of safety at curves is quantified by a performance metric named Curve Safety Index (CSI), scaled from 0% to 100%. This index is formulated in Equation (1):

$$\text{CSI (\%)} = \text{Function}\ (\text{R}, \text{SD}, \text{L}, SD^{z}_{ijk}) \qquad (1)$$

R is the minimum allowable radius of a horizontal curve which can be found in AASHTO Green Book, (2001) [9]. In this study, it is assumed that the minimum allowable radius criteria are used by the contractors to design the curve's geometry at the preliminary design phase in that a lot of detailed information on site conditions and crew selections are generally unavailable. With R known, the minimum stopping distance (SD) can be derived from equation in [10]. According to the equation in Department of Labor (1999)[8], the actual stopping distance (L) can be estimated.

With L and SD known at each horizontal curve, a percentile-based measurement indicating the degree of risk in accordance with the SD-L relationship is proposed, namely stopping distance safety indicator (SD_{ijk}). This indicator (SD_{ijk}) classifies the SD-L relationship into four different categories, as (1) L ≥ SD, which represents the occurrence of accidents with SD_{ijk} valued at 100%; (2) 3/4 SD ≤ L < SD, which represents the high risk due to high probability of haulage-related accidents - any minor misbehaviour would cause accidents, SD_{ijk} is valued at 75%; (3) 1/2 SD ≤ L ≤ 3/4 SD, which represents an intermediate level of risk due to low probability of haulage accidents such as driver's absent mindedness and brake failure, $SD_{ijk}$is valued at 50%; and (4) L ≤ 1/2 SD, and therefore haulage safety is unaffected with SD_{ijk}valued at 0%.

3.2 Surface Hazard Safety Index (SHSI)

According to Thompson and Visser [11], haul road surface condition is related to traffic volume, wearing courses, maintenance management and weather. Failure to establish a good haul road surface will result in increased possibility of encountering surface hazard. Poor haulage surfaces (e.g. potholes rutting, settlement, wash-boarding, frost heaving, and etc.) caused by poor compaction, precipitation/runoff, heavy traffic volume, and inadequate maintenance will severely compromise the ability of a vehicle to safely negotiate the route; or in many instances, drivers may attempt to avoid a certain situation, which could cause serious accidents [12]. According to Mine Safety and Health Administration (MSHA) [8], the surface haulage accidents include: (1) haulage trucks going out-of-control; (2) vehicles/persons being run over by large trucks; and (3) trucks going over dump points. These hazardous situations need to be properly addressed so as to minimize the risk of haulage accidents.

In order to improve safety on construction sites, planners need to comply with MSHA standards and design proper haul road surface condition onsite. The haul road grades should be selected according to truck type, traffic volumes, and maintenance frequency. In the present model, a newly developed performance metric named Surface Hazard Safety Index (SHSI) is proposed to accommodate the quantification of haul road surface hazard. As shown in Equation (2):

$$\text{SHSC(\%)} = \text{Function}\ (f^{1}_{ij}, f^{2}_{ij}, QM_1, QM_2, \text{N}) \qquad (2)$$

f_{ij}^1 is the allocated traffic flows on rough ground haul road while f_{ij}^2 is the allocated traffic flows on gravel-surfaced haul road; N is the total quantity of haul road segments onsite; QM_1 and QM_2 are the "need maintenance" threshold volume of earth being transported on rough ground haul road and on gravel-surfaced haul road, respectively; which means once QM_1 m3 of earth have been transported on rough ground and QM_2 m3 of earth transported on gravel-surfaced haul road, the haul road surface deteriorates to the need - maintenance level. The maintenance frequency, denoted as $f_{ij}^1/\,QM_1$ and $f_{ij}^2/\,QM_2$, will help classify the degree of risk in the present methodology. The higher maintenance frequency, the more likely trucks will encounter surface hazard. The degree of risk can be expressed as 10%*(f_{ij}/QM), subject to $f_{ij}/QM \leq 10$.

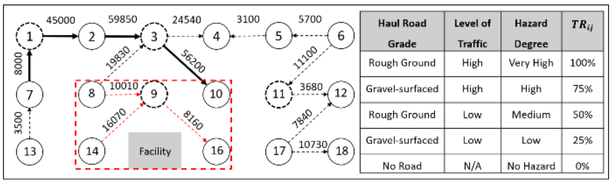
3.3 Travel Routes Safety Index (TRSI)

On site construction facilities such as parking lot and temporary office, where the density of workers peaks among the entire site, is the most sensitive area to safety issues. Frequent truck hauls near the facilities will not only expose the workers to high safety risks (e.g. hit by out-of-control trucks), other harmful effects such as noise, air pollution by dust, and etc., will be produced, potentially influencing workers' health. Therefore, the haul roads need to be properly designed to minimize the safety impact near these facilities. OSHA recommends possible hazards (e.g. fire, explosions, pollution, heavy traffic) shall be located far away from onsite facilities [6].

The present model incorporates a newly developed performance metric named Travel Routes Safety Index (TRSI), as shown in Equation (3). In calculating TRSI, the model allows the user to specify whether a haul road segment within safety impact area (1) has a high level of traffic and close distance to facility, giving rise to high safety risks; or (2) has a low level of traffic and far distance to facility, therefore does not create a significant risk.

$$TRSI(\%) = Function\ (d_{ij-f}, TR_{ij}) \qquad (3)$$

Where d_{ij-f} is the shortest distance between the geometric centre of the facility and the haul road segment; TR_{ij} is a percentile-based measurement indicating the degree of risk in accordance with traffic volume and haul road grade (as shown in Figure 4). In the present model, a safety impact area is defined as a rectangular area within site boundaries that contains the facility area, with 100 meters side-to-side distance (assume all facility areas can be represented by a rectangle). A detailed illustration is given in Figure 4. The red dot line encompassing the onsite facility denotes the safety impact area. The red dot haul road links denote the haul road segments presenting significant safety risks to the facility.



Haul Road Grade	Level of Traffic	Hazard Degree	TR_{ij}
Rough Ground	High	Very High	100%
Gravel-surfaced	High	High	75%
Rough Ground	Low	Medium	50%
Gravel-surfaced	Low	Low	25%
No Road	N/A	No Hazard	0%

Figure 4. Measuring the near-facility hazard on site

3.4 Haul Road Safety Indicator (HRSI)

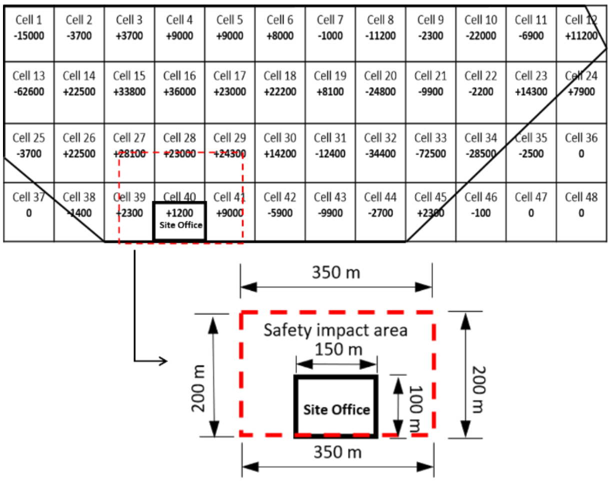
Therefore, the temporary haul road layout safety is quantified by introducing a safety indicator named Haul Road Safety Indicator (HRSI), which aggregates the three indexes by relative weights, as shown in Equation (4):

$$\mathrm{HRSI} = \mathrm{w1} * \mathrm{CSI} + \mathrm{w2} * \mathrm{TRSI} + \mathrm{w3} * \mathrm{SHCI} \qquad (4)$$

In this formula, the relative weights (w1 to w3) of the three safety indexes can be best obtained from historical safety records of previous projects that classify fatalities and/or injuries into these three major categories. In the absence of such company data, the planner can provide his/her best judgment on their relative weighting by referencing national average figures such as the occupational injuries statistical report published by Bureau of Labor Statistics [13].

4 Case Study

A practical rough grading project is utilized for evaluating the proposed method. The rough grading project was the preliminary work package of a camp site construction in Fort McMurray, AB. The field is divided into 48 cells each being 150 m by 150 m. The project had a total amount of 335,600 m3 of banked earth to be handled from cut and fill. The material considered has no appreciable swell. The cut (-) or fill (+) volume of each cell along with the cell identification number is shown in Figure 5.



Cell 1 -15000	Cell 2 -3700	Cell 3 +3700	Cell 4 +9000	Cell 5 +9000	Cell 6 +8000	Cell 7 -1000	Cell 8 -11200	Cell 9 -2300	Cell 10 -22000	Cell 11 -6900	Cell 12 +11200
Cell 13 -62600	Cell 14 +22500	Cell 15 +33800	Cell 16 +36000	Cell 17 +23000	Cell 18 +22200	Cell 19 +8100	Cell 20 -24800	Cell 21 -9900	Cell 22 -2200	Cell 23 +14300	Cell 24 +7900
Cell 25 -3700	Cell 26 +22500	Cell 27 +28100	Cell 28 +23000	Cell 29 +24300	Cell 30 +14200	Cell 31 -12400	Cell 32 -34400	Cell 33 -72500	Cell 34 -28500	Cell 35 -2500	Cell 36 0
Cell 37 0	Cell 38 -1400	Cell 39 +2300	Cell 40 +1200 Site Office	Cell 41 +9000	Cell 42 -5900	Cell 43 -9900	Cell 44 -2700	Cell 45 +2300	Cell 46 -100	Cell 47 0	Cell 48 0

Figure 5. Haul road within safety impact area of onsite facility

The relative weights denoting the three safety indexes were chosen as w1: w2: w3 = 0.4:0.4:0.2. The four layout design options in [4] are selected for evaluation purposes, as shown in Figure 6-9. The proposed approach is coded in Python Version 3.5 [14]. The safety evaluation results of the four layout options are summarized in Table 1.

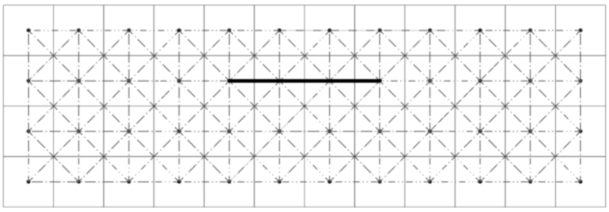


Figure 6. Haul road layout option 1

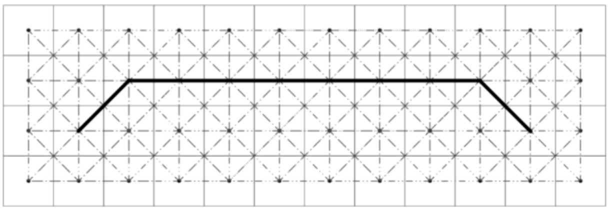


Figure 7. Haul road layout option 2

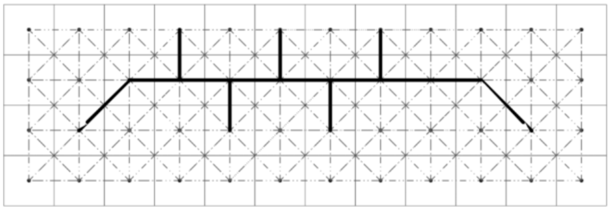


Figure 8. Haul road layout option 3

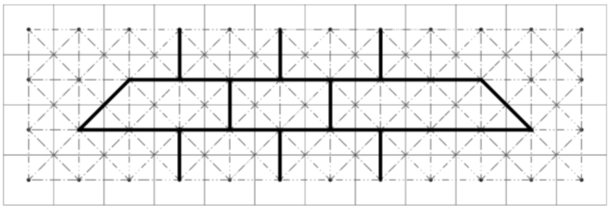


Figure 9. Haul road layout option 4

Table1. Safety evaluations and comparison between the layouts

Layout Option	Road Length (m)	CSI (%)	SHSI (%)	TRSI (%)	HRSI (%)
1	450	65.8	75.3	50.0	66.44
2	1,474	58.5	64.5	57.1	60.62
3	2,224	46.0	55.3	57.1	51.94
4	4,024	34.6	25.7	71.4	38.40

Layout 1 is the riskiest design alternative (HRSI = 66.44) while layout 4 has the least safety risk (HRSI = 38.40). The proposed methodology can lend effective assistance for designers or project manager to evaluate hauling safety, providing insight in designing safer temporary haul road layout.

5 Conclusion

This paper proposes a framework for the quantification of temporary haul road related safety to aid in designing a safer temporary haul road layout in large site grading projects. The quantification approach is developed in four major steps that focus on (1) modelling the earthmoving site and temporary haul road network; (2) identifying potential safety hazards in earthmoving operations in connection with haul road designs; (3) proposing formulating schema for each identified safety hazard in unit measure (0%-100%); and (4) integrating them into a unified safety indicator. A case study with four alternative temporary haul road layout designs is given as a test-bed to evaluate and validate the proposed methodology. The safety evaluating results for respective design alternatives are summarized in a comparative table to intuitively visualize the quantification outcome. In summary, the proposed methodology can be readily implemented in the real world in order to materialize safety impact on temporary haul road layout design. In addition to safety evaluation, the research deliverables could lay a solid basis for immediate future research in developing a robust model that supports multi-objective optimization of temporary haul road layout design in order to realize maximization of safety and minimization of total earthmoving cost simultaneously.

References

[1] Dwayne, D.T. and Regensburg, B. Guidelines for mine haul road design. School of Mining and Petroleum Engineering, Department of Civil and Environmental Engineering, University of Alberta. 2001.

[2] Yi, C. and Lu, M. A mixed-integer linear programming approach for temporary haul road design in rough-grading projects. *Automation in Construction*, 71, pp.314-324. 2016.

[3] Holman, P. and Charles, I.L. Caterpillar® haul road design and management. St. Charles, IL: Big Iron University. 2006.

[4] Liu, C. and Lu, M. Optimizing Earthmoving Job Planning Based on Evaluation of Temporary Haul Road Networks Design for Mass Earthworks Projects. *J. Constr. Eng. Manage*., 141(January), pp. 51–60. 2014.

[5] Occupational Safety and Health Administration (OSHA), 2010. Construction e-tool. Online: https://www.osha.gov/SLTC/etools/construction/struckby/mainpage.html

[6] Occupational Safety and Health Administration (OSHA). Safety and health regulations for construction. 29 Code of federal regulation, Washington, D.C. 2003.

[7] Li, D., Liu, C. and Lu, M. Optimizing earthwork hauling plan with minimum cost flow network. *International Construction Specialty Conference.* University of British Columbia, Vancouver, Canada. June 7-10, 2015, pp. 1–9, 2015.

[8] Department of Labor. Haul Road Inspection Handbook. pp. 7–8. Handbook Number, MSHA, PH99-I-4.1999.

[9] AASHTO. A Policy on Geometric Design of Highways and Streets, American Association of State Highway and Transportation Officials. Washington DC, USA. 2001.

[10] Wood, J. and Donnell, E.. Stopping sight distance and horizontal sight line offsets at horizontal curves. *Transportation Research Record: Journal of the Transportation Research Board*, (2436), pp.43-50.2014

[11] Thompson, R.J. and Visser, A.T. Selection and maintenance of mine haul road wearing course materials. *Mining Technology.* 115(4). 2013.

[12] Kaufman, W.W. and Ault, J.C. Design of Surface Mine Haulage Roads: A Manual (No. BuMines-IC-8758). Department of the Interior, Bureau of Mines.2011.

[13] Department of Labor. Bureau of Labor Statistic. Industry Injury and Illness Data. 2015. Online: http://www.bls.gov/iif/oshsum.htm#15Summary_News_Release

[14] PYTHON. [Computer Software]. PYTHON, Version 3.5, Python Software Foundation, 9450 SW Gemini Dr., ECM# 90772, Beaverton, OR 97008, USA.