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Identifying and Prioritizing Factors Affecting Bursting of Dump Truck Tires in Mines using Fuzzy Best-Worst Method

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Abstract

Due to the high number and severity of tire burst accidents of dump trucks, the present work is conducted to identify and prioritize the effective causes of dump truck tire bursts using the fuzzy best-worst method (FBMW). The present work is conducted using content analysis and FBMW. First, by using focus groups and exploring the texts and events, and then these factors are weighted and then prioritized using FBMW. The results of the first phase show that the factors affecting the bursting of dump truck tires can be classified into 5 main categories of road conditions (six sub-categories), maintenance (six sub-categories), monitoring, and inspection (10 sub-categories), unsafe behavior (seven sub-categories), and tire conditions (five sub-categories). The results of the second phase also show that the tire conditions and unsafe behavior are the most important factors with a mean weight of 0.2252 and 0.1681, respectively. The results of the present work show that the most important cause is the monitoring of temperature, pressure, and tire conditions. Therefore, it can be concluded that in order to reduce these accidents, in addition to choosing the right tire, the conditions such as temperature and pressure inspection should be given a high attention.

1. Introduction

Extraction of solid, liquid, and gas minerals from the mines is a complex process with high technology that is done using various technical tools [1]. One of the most important mining processes is the transportation of extracted equipment and materials, which is currently done in two main ways: rail and road. Road transport has a wide range of applications compared to other types of mineral transport. The advantages of this type of transport are high maneuverability, overcoming huge and very heavy loads, and higher mobility [2]. Machines used for road transport in various mines include graders, bulldozers, dump trucks, and loaders. Dump trucks are off-road trucks that are specifically designed for use in high-production mining and heavy construction environments, and have a capacity of 40 to 400 tons [3].

Dump trucks are widely used in harsh environments, mainly due to their high weight, nominal load capacity, shorter axle expansion, strong power, massive body, complex structures, and slope and bending. Functional features such as high power and capacity of these vehicles in mines cause a lot of losses and damages in case of accident or overturning, and have several risks and possible economic losses [4]. According to accident statistics, each year, a mean of all fatal accidents in mines, 12% of these accidents were caused by dump trucks, and there are countless accidents without casualties and with damage to equipment and financial losses [5].

Most accidents are due to structural features due to mining dump trucks and the work environment but 12% of all liability is due to non-responsibility or improper operation of operators; therefore, it is necessary to discover the causes of the accident to

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prevent injury. lureA review of studies of dump truck accidents shows that from 1988 to 1997, with 370 accidents, casualties and lost time were very high, of which 26 were deaths and these accidents were responsible for a mean of 50 working day lost compared to the 33 working days lost that were related to other mobile mining equipment [6]. Statistics from the National Institute for Occupational Health and Safety (NIOSH) from 1992 to 2007 also show that 6 deaths of dump truck operator due to overturning, colliding with overhead power lines, rollover the dump truck on driver, getting the driver stuck in or between the bed and the dump truck box. Finally, the statistics of this organization in 2017 show that 50% of the casualties (14 cases out of 28 cases) and 57% (4 cases out of 7 cases) in the first few months of 2018 are related to dump truck transportation [7].

In fact, the most dump trucks accidents are due to their huge volume and more slope and bending, unevenness and muddy road surface, which can cause problems in braking, excessive turning angle and very fast turning [8]. Other problems with dump trucks include limited driver visibility, full body vibration, excessive noise, and flat tires [9]. One of the most important components of dump trucks, which is involved in all problems from dump truck overturning to vibration of the entire driver's body, are the tires of these vehicles. Tires are also a vital component of dump trucks because they protect them against harsh terrain, providing stability and maneuverability [10]. Increasing the size of the dump truck leads to a corresponding increase in the size of the tires. For example, dump trucks with a load capacity of more than 270 tons use very large tires with a rim diameter of 1.45 m or 1.6 m [11].

Kecojevic et al. have analyzed the equipment-related fatal accidents in U.S. mining operations in 1995–2005. The results showed that the greatest proportion of fatalities is related to haul trucks (22.3%), belt conveyors (9.3%), front-end loaders (8.5%), and miscellaneous equipment (36.6%). The relationship between the number of equipment-related fatalities and mining experience of the workforce was also examined. Study shows that workers with less than five years of appropriate mining experience constitute 44% of all fatalities that occurred during the period of 1995–2005 [12].

Haq et al. have shown that vehicle speeds greater than 75 mph, summer season, daytime, the presence of rough surface, downgrades, and concrete pavement are all related to higher tire failure occurrences. On the other hand, the incidence of a tire failure in a crash significantly contributed to more severe injuries when combined with any of the following instances: fire or explosion, runoff road, angle, rear-end, clear weather, speeding, downgrades, and curved segments [13]. Zhang et al. have investigated the haul truck-related fatal accidents in surface mining using fault tree analysis. The results showed that inadequate or improper pre-operational check and poor maintenance of trucks were the two most common root causes of these accidents. A total of eight accidents occurred on haul roads, while 10 accidents occurred while the trucks were moving forward [14]. Also Drury et al. have investigated the patterns of mining haul truck accidents. The results showed that the accident causes were divided in two categories including driving causes (loss of control, ground fails, and two-vehicle collision) and non-driving cuases (unexpected movement, falls from vehicle, and hit by other vehicle) [15]. Also there are some studies about tire lifetime estimation. For example, Pascual et al. have shown that tire lifespan depends on proper type selection. Each tire-type implies choosing a combination of rubber compounds and geometric specifications that are suited to road parameters. In general, each route has a specific optimal tire type [16]. Kansake et al. have presented some mathematical models for estimating tire dynamic forces on haul roads. The results show that road roughness significantly affects impact forces on roads, with tire dynamic forces (1638.67 kN) ~1.6 times static forces (~1025 kN) at rated tire payloads [17].

One of the most frequent accidents in dump trucks is the bursting of tires, which due to their large volume and size, causes a very high degree of damage. Damage to dump truck tires is mainly due to operating conditions such as dump truck speed, road obstacles, wind pressure, heavy load, poor road design, and inherent defects in the design and manufacture of tires. The movement of dump trucks at high speeds, especially at the corners, leads to the detachment of the belt in the tires; asymmetric load transfer to the tires may lead to a reduced tire performance [18]. Due to the high frequency of dump truck tire accidents, identifying and prioritizing the factors affecting this accident is of great importance for managing the purchase of the best tires and better control of accidents by monitoring and inspection.

The mining industry is one of the most important economic activities in Iran, and despite a significant progress in other industrial areas in terms of mining safety in Iran, there is not much progress, and studies show that many accidents occur in mines [19]. Considering the high number of active mines in Iran and the high use of dump trucks in these mines, as well as the numerous and high intensity of tire burst accidents in Iranian mines [20, 21], the aim of this work is to first identify the factors affecting this incident by examining the causes of accidents, and then prioritize the identified factors using the fuzzy best-worst method (FBWM) to help better manage the incident.

2. Materials and methods

The present work was conducted using two phases: a) qualitative method of content analysis and b) quantitative method of FBWM. The qualitative method included the study of texts and events, then conducting a focus group, which was conducted to extract the factors affecting the bursting of dump truck tires. FBWM is also one of the multi-criteria decision-making methods that helped to achieve the second goal of studying and prioritizing the effective factors.

2.1. Phase 1: content analysis method

Content analysis is one of the important research methods that has received more attention from the researchers in the recent years. This method means the analysis of relationships in a systematic and objective manner, the data and results of which are obtained by reviewing documents, documents, and interviews with experts [22]. In content analysis, the researcher analyzes the messages produced and seeks answers to his/her research questions.

In the present work, in order to extract the factors affecting the bursting of dump truck tires, all accidents in this field were analyzed using focus group meetings consisting of 10 people who were health and safety experts and technicians. Of these, 5 were industrial safety and health expert and 5 technicians. All of them were men, and the mean (standard deviation) age and work experience of them were 37.47 years (6.23) and 14.18 (5.40) years with a minimum of 5 years of work experience. Also the most educational level were Bachelor's degree (8 people) and two of them were Master's degree. These sessions were audio-recorded, transcribed, and reviewed by three researchers. The two main steps in this section were open and pivotal coding.

A) Open coding: is an analytical process through which known concepts and their characteristics and dimensions are discovered in the data. At this stage, the researchers form the initial categories of the phenomenon by segmenting the information [23]. The process of shredding, testing, comparing, conceptualizing, and classifying data is called coding. This coding ultimately groups the concepts into categories, and is called open because the categories are named without any restrictions.

B) Axial coding: The process of linking categories to sub-categories and linking at the level of features and dimensions. This coding is called axial because it is described around the category axis. Categories that were extracted from raw data in the form of causal conditions (causes of the main phenomenon), strategy (interactions are created to control and deal with the main phenomenon), context (conditions of creating the strategy), intervenor conditions (general conditions affecting strategies), and consequences (results of strategies) are categorized.

All the written interview sessions were read, and in the first stage, the coding was open coding to the initial and linear review of the data in which the qualitative data was coded into units of meanings (concepts) that are completely similar to the words used by the participants and the second stage was axial coding.

After studies related to dump truck burst accidents, they were extracted from national and international databases and studied by researchers, adding all the factors that were not mentioned in the focus group meetings. Finally, in order to ensure the accuracy of the work and also to ensure the finalization of the obtained results, the results were reviewed by the research team and some experts, and the qualitative study was completed with the unanimity of all people.

2.2. Phase 2: fuzzy best-worst method (FBWM)

The second phase was designed and implemented in order to prioritize the factors extracted from the first phase (based on two separate contractors). In this phase, the factors affecting tire bursting were compared and weighted by experts using FBWM. The experts who participated in this stage were the same 10 people in first phase. FBWM is one of the very new methods in multi-criteria decision-making models, which Gu et al. introduced for the first time in 2017 and used to solve complex problems. In this method, instead of comparing two-by-two variables, comparison and conclusions are made in the following three steps according to previous studies [24, 25].

In this method, instead of comparing two-by-two variables, comparison and conclusions are made in the following three steps:

A) Selection of the best and worst criteria: In this step, in each comparison, experts choose the best and worst criteria.

B) Comparison of the degree and intensity of the importance of the criteria relative to each other with verbal values: In this step, the experts determined the degree of importance of the best criteria compared to other criteria and the degree of importance of the other criteria compared to the worst one of the words in Table 1.

Table 1. Linguistic variables in fuzzy best-worst method.

Linguistic variables	Membership function
Equal importance	(1, 1, 1)
A little more important	(0.67, 1, 1.5)
More important	(1.5, 2, 2.5)
Much more important	(2.5, 3, 3.5)
Absolutely more important	(3.5, 4, 4.5)

C) Calculating the final weight of the criteria: In this step, after collecting the data, equations 1 to 4 were used to weight the criteria.

Equation 1: Comparison function of the best criterion compared to other criteria

$$\tilde{A}_B = (a_{B1}, a_{B2}, a_{B3}, \dots, a_{Bn}) \tag{1}$$

where $\widetilde{A}_B$ is the comparison function of the best criterion compared to other criteria, a_{Bj} represents the linguistic variable of the degree of importance of the best criterion compared to criterion j, and this comparison is repeated for the number of criteria.

Equation 2: Comparison function of other criteria compared to the worst criterion

$$\tilde{A}_W = (a_{1W}, a_{2W}, a_{3W}, \dots, a_{nW}) \tag{2}$$

where $\widetilde{A}_W$, the comparison function of other criteria compared to the worst criterion, a_{iW} indicates the linguistic variable of the degree of importance of the other criterion "i" compared to the worst criterion, and this comparison is repeated for the number of criteria.

In order to determine the fuzzy weight of criteria, the fuzzy comparison of the best criteria to other criteria $\widetilde{W}_B/\widetilde{W}_j$ and the fuzzy comparison of other criteria to the worst $\widetilde{W}_j/\widetilde{W}_W$ should be done.

Equation 3: The final relationship of weighting criteria in the fuzzy best-worst method.

$$\min \quad k\left\{\left|\frac{\widetilde{W}_B}{\widetilde{W}_j} - \tilde{a}_{Bj}\right|, \left|\frac{\widetilde{W}_j}{\widetilde{W}_W} - \tilde{a}_{jW}\right|\right\}$$

$$s.t. \begin{cases} \left|\dfrac{(l_B^w, m_B^w, u_B^w)}{(l_j^w, m_j^w, u_j^w)} - (l_{Bj}, m_{Bj}, u_{Bj})\right| \le k \\ \left|\dfrac{(l_j^w, m_j^w, u_j^w)}{(l_W^w, m_W^w, u_W^w)} - (l_{jW}, m_{jW}, u_{jW})\right| \le k \\ \sum_{j=1}^{n} R(\widetilde{W}_j) = 1 \\ l_j^w \le m_j^w \le u_j^w \\ l_j^w \ge 0 \\ j = 1, 2, \dots, n \end{cases} \tag{3}$$

Defuzzification of the obtained number and Equation 4, the final weight of each criterion is obtained.

$$R(a_i) = \frac{l_i + 4m_i + u_i}{6} \tag{4}$$

where $R(a_i)$ is the defuzzified number and the final weight of each factor. Also the final weight of each factor was calculated by calculating the arithmetic mean of all experts' opinions. Finally, the data of the first step was analyzed manually. The software used in the second step included the FBWM Excel software.

This method works with a choosing checklist that each expert should completed. An example of this checklist is as follows:

Comparison of the main factors affecting tire bursting

Targeted criteria: road conditions, maintenance, monitoring and inspection, tire condition, and unsafe behavior

Degree of importance: equal importance, A little more important, more important, much more important, absolutely more important

Best criteria	Road conditions	Maintenance	Monitoring and inspection	Tire condition	Unsafe behavior
*	**	**	**	**	**
* Put the best criteria					
** Put the degree of importance of the best criteria compared to other criteria					

Worst criteria	*
Road conditions	**
Maintenance	**
Monitoring and inspection	**
Tire condition	**
Unsafe behavior	**
* Put the best criteria	
** Put the degree of importance of the other criteria compared to the worst criteria	

3. Results

The results of the first step showed that the factors affecting dump truck tire bursting could be categorized into the 5 main categories of road conditions, maintenance, monitoring and inspection, unsafe behavior, and tire conditions (Table 2).

Table 2. Weighting results of the factors affecting the bursting of dump truck tires according to the experts of first contractor.

Categories (weight)	Sub-categories (weight)	Categories (weight)	Sub-categories (weight)
Road conditions (0.2038)	Road roughness (0.2835)	Maintenance (0.1946)	Inappropriate storage of tires (0.2481)
	Road width or slope (0.1380)		Puncturing and non-standard tire maintenance (0.0955)
	Turning radius and its transverse slope (0.1930)		Failure to take care of the road (0.2136)
	Road used materials (0.1105)		Inappropriate installation of the rim (0.1723)
	Cleaning the road surface (0.1042)		Welding the rim on the tire (0.2044)
	Deep bumps (0.176)		Use of anti-puncture gel (0.0660)
Monitoring and inspection (0.2629)	The condition of the rim and its screws (0.1172)	Tire condition (0.0955)	The quality of tire components (0.1319)
	Temperature, pressure and tire inflation (0.2470)		Tire brand (0.2341)
	Depth and percentage of tire tread (0.1170)		Tire resistance (0.1267)
	Brokenness, cracks, corrosion and inappropriate shape of the rim and screw (0.1201)		Tire size (0.1313)
	Inappropriate shape of the tread (0.1420)		Tire symmetry (0.1459)
	Asymmetric tire wear (0.1506)	Unsafe behavior (0.2432)	Non-observance of the permissible loading weight (0.1982)
	Peeling and tearing on the wall and tread of the tire (0.1040)		Non-observance of symmetrical load distribution (0.1991)
	Presence of external objects inside the tire (0.1420)		Non-observance of the pair tires rule (0.1474)
	Stuck stone between the tire tread (0.1420)		Fast driving (0.0662)
	Valve leakage (0.1430)		Using tires in long distances (0.1343)
			Use of tires with tread less than 40% (0.1361)
			Use of worn-out rims (0.1369)

3.1. Road conditions

This category means the condition of the road used in mines for the passage of dump trucks, which due to the presence of damage or other inappropriate conditions leads to a decrease in the lifespan of the dump truck tire or a sudden burst. This category was divided into six sub-categories: road roughness, road width or slope, turning radius and its transverse slope, road used materials, clearing the road surface, and deep bumps.

Road roughness: Accident investigation experts stated that if the road surface had roughness, it caused tire tread and mud to be torn off, and excessive tire fatigue due to roughness leads to tire bursting. This category can damage the tire in the long run.

The road width or slope: The adjustment and symmetry of the load on the tires is very important in terms of applying pressure on them; therefore, experts say that if the width or slope of the road is not suitable, due to the movement of the dump truck, the load will spread asymmetrically on the tires and lead to the fatigue of one or more tires.

Turning radius and its transverse slope: This category, like the road width or slope, refers to the symmetry of the load on the tires. At the head of an inappropriate turn with a high lateral slope, one or more tires will bear more pressure than the others, and this will lead to tire fatigue.

Road used materials: The experts stated that the used materials are among the important factors of increasing tire fatigue. The rougher the road or the finer the particles, the fatigue between the tire and the road causes the tire tread to disappear, and this contributes to tire fatigue.

Cleaning the road surface: The experts stated that the presence of sharp objects, wood and garbage, and anything that gets stuck between the tire tread and leads to tire tearing, can accelerate the tire fatigue process and also cause the tire to burst suddenly. Therefore, by cleaning the road surface, it is possible to ensure the absence of such cases.

Deep bumps: The presence of deep bumps, like the unevenness of the road surface, by causing sudden shocks and vibrations to the tire, especially the tires that have been used for a long distance, leads to a sudden increase in the pressure inside the tire, and this increase Pressure will cause it to burst.

3.2. Maintenance

This category means keeping the tire in a suitable place and repairing the rim and tire accessories in time so that the life of this equipment is increased and the damage does not cause the tire to burst suddenly. Some of the sub-categories of this section such as welding on the rim, and use of anti-puncture gel are part of the rules and regulations for the maintenance and repair of dump truck tires.

Inappropriate storage of tires: The experts stated that due to the importance of the tread and the plastic used in tires, the appropriate storage of tires should be in a place away from sunlight, rain, and cold weather, and this place should be clean and well-ventilated. Therefore, with inappropriate storage, the quality of the tire decreases in the long term, and there is a possibility of it bursting due to high pressure and load.

Puncturing and non-standard tire maintenance: Puncturing and their maintenance of dump truck tires have specific and safe procedures. Therefore, if this process is done in a non-standard way, the repaired tire may not have the right conditions to carry huge loads and may have an accident during work.

Failure to take care of the road: The experts stated that there is no supervision of the road improvement and the required repairs are not done. Also the road is not cleaned well and sharp objects, wood and garbage can be found on all its surfaces. These can get stuck between the tire tread and leads to tire tearing, can accelerate the tire fatigue process and also cause the tire to burst suddenly. Therefore, by cleaning the road surface, it is possible to ensure the absence of such cases.

Inappropriate installation of the rim: The correct connection of the rim on the tire causes the correct distribution of pressure on the entire surface of the tire, and also prevents the tire from breaking. The experts of this study stated that sometimes due to the difficulty of the weight and high size of the rims, the installation of the rim is not done correctly and causes the tire to burst.

Welding the rim on the tire: As it was said that some cases are part of the rules of dump truck maintenance, welding on the tire is prohibited due to heat generation and increase in tire pressure. The heat of welding increases the heat and pressure inside the tire and this leads to its bursting.

Use of anti-puncture gel: The experts of this study stated that the puncture gel cannot withstand the pressure of the tire during operation, and the tire punctured with gel is more likely to burst.

3.3. Monitoring and inspection

This category means inspecting all the factors affecting tire bursting including the maintenance process, road conditions, installation, and maintenance of tires, etc. Correct monitoring and inspection can always identify existing risks before they become accidents, and is a very important step to prevent accidents. This category is divided into 10 sub-categories, condition of the rim and its screws, inspection of temperature, tire pressure and inflation, tire tread depth and percentage, fracture, crack, corrosion and inappropriate shape of the rim and screw, inappropriate shape of the tread, asymmetric fatigue of the tire, tearing, and tears on the tire wall and tread, the presence of wood chips, cleaning cloth, etc. inside the tire, stone stuck between the tire tread and valve leakage are categorized.

The condition of the rim and its screws: Monitoring and inspecting the condition of the rim and screws helps to distribute the tire pressure and the weight of the dump truck correctly on the entire surface of the tire during the connection of the rim to the tire, and more accurate monitoring makes it possible to identify the main problems before rim damage and tire burst.

Temperature, pressure, and tire inflation: One of the most important causes of tire bursting is not adjusting the temperature, pressure and tire inflation. The experts stated that with the increase of inflation or temperature of the tire (due to movement or inappropriate adjustment), the pressure of the tire increases, and this will cause the sudden burst of the tire if it exceeds its limit.

Depth and percentage of tire tread: Tire treads contribute to the friction between the tire and the road, the distribution of force on the tire, and the tire's pressure tolerance. If the depth and percentage of tread decrease, it means that the tire has lost its resistance and the increase in pressure and weight can lead to the tire bursting.

Brokenness, cracks, corrosion and inappropriate shape of the rim and screw: As mentioned, monitoring and inspecting the condition of the rim and screws is very important, and the presence of any brokenness, crack, corrosion, and inappropriate shape can cause inappropriate distribution of pressure and weight, as well as reducing resistance. Careful monitoring of these factors makes it possible to detect major problems before rim damage and tire burst.

Inappropriate shape of the tread: The tread of the tire is designed so that no stone or external object gets inside the tire tread. Now, if this part of the tire loses its shape and inappropriate monitoring and inspection cannot detect it, the external object can easily damage the tire.

Asymmetric tire wear: The presence of wear in the tire causes some points to bear more pressure, and this causes damage from that point; therefore, with an appropriate inspection, tires that are worn asymmetrically can be removed from the working category.

Peeling and tearing on the wall and tread of the tire: This factor also acts like tire wear, and the peeling off of a part of the tread or wall of the tire reduces the pressure bearing of that part, and this will cause the tire to burst; therefore, an appropriate inspection will identify the tear of the wall or the tread, and unsuitable tires can be removed from the working category.

The presence of external objects inside the tire: The presence of external objects inside the tire can cause accidental impact and tearing of the tire. With an appropriate inspection, these objects can be removed before using the tire and work with the tire safely.

Stuck stone between the tire tread: The presence of external objects such as stones in the tire can cause unwanted impact and tearing of the tire.

Valve leakage: The presence of oil and oily fluids on the tire causes the tire to slip and destroy its components; therefore, the presence of these fluids on the tire should be known through appropriate inspection. One of the most important parts to be inspected should be valve leakage to avoid such risks.

3.4. Unsafe behavior

This category means the actions and behavior of dump truck drivers and operators, which can cause the tire to burst. This category is divided into seven sub-categories, non-observance of the permissible loading weight, non-observance of symmetrical load distribution, non-observance of the tire pair rule, fast driving, use of tires in long distances, use of tires with less than 40% tread, and use of worn-out rims.

Non-observance of the permissible loading weight: The permissible weight of the load regulates the tire pressure, and an excessive increase in the load increases the tire pressure and increases the possibility of bursting. Respecting the weight of the load is one of the safe behaviors of the driver and loading operator.

Non-observance of symmetrical load distribution: Symmetrical weight also causes a proper and equal distribution of pressure on the tires, and in case of improper symmetry, one or more tires suffer excessive pressure and lead to damage to them. Addressing and complying with this requirement is also considered a safety behavior by the driver and the loading operator.

Non-observance of the pair tires rule: Pair tires means the use of equal number of tires at the same time. If the driver does not comply with this requirement, the weight of the dump truck, and the load will be placed on one or more other tires and lead to an increase in their pressure.

Fast driving: In addition to certain risks such as accidents and overturning of dump trucks, this unsafe practice can increase the pressure on the tires and this increase will lead to tire burst.

Using tires in long distances: In addition to tire fatigue, long distances also lead to an increase in pressure and temperature, and if the driver or the operator of the tire does not follow the allowed distance for using tires, it causes the tire to be destroyed and this leads to its destruction. Gradual or sudden tire burst.

Use of tires with tread less than 40%: The amount of tire tread actually indicates the strength and pressure tolerance of the tire. The use of tires with a tread below 40% indicates insufficient tire tolerance and loss of suitable conditions.

Use of worn-out rims: This act is actually the unsafe behavior of the driver and the maintenance operator, which was explained in the maintenance section.

3.5. Tire condition

This category means the structure and type of tire; in fact, this part depends on the type, brand, maintenance, and conditions of the tire. This category was divided into five sub-categories: quality of tire components, tire brand, tire resistance, tire size, and tire symmetry.

The quality of tire components: Each tire company uses different types of materials used in tire according to the available raw materials, production cost and cost for the consumer, and this causes the quality of each tire to be different.

Tire brand: Dump truck tires used in Iran are purchased from several specific foreign companies, each of which designs tires with specific resistance according to their own facilities. Therefore, some brands can be better and some inappropriate.

Tire resistance: Experts stated that important factors reduce the resistance of tire, so the resistance factor can also be one of the effective factors.

Tire size: The larger tire will bear the more pressure and temperature, and the size of the rim and tire must be chosen according to the dump truck, so if the tire size is not suitable for the weight of the load, the size of the dump truck, and other variables, the probability of bursting increases.

Tire symmetry: Tire symmetry balances force and pressure. If a tire with low symmetry is used, the probability of bursting increases.

3.6. Results of second phase

The results showed that tire condition with a mean weight of 0.2252 and unsafe behavior with a mean weight of 0.1681 were the most and least important factors, respectively. Also among the factors of road conditions, the most important factor was road roughness with a mean weight of 0.2379, and the least important factor was the materials used on the road with a mean weight of 0.1232. This weighting in the monitoring and inspection factors was the most important and the least important factor, respectively, including temperature, pressure and tire inflation with a mean weight of 0.2162, and the presence of external objects inside the tire with a mean weight of 0.1127. This weighting in the maintenance factors was the most important and the least important factors, respectively, including failure to take care of the road with a mean weight of 0.2184 and use of anti-puncture gel with a mean weight of 0.0773. In addition, the weighting of tire condition factors was the most important and the least important factor, respectively, including tire brand with a mean weight of 0.1850 and tire size with a mean weight of 0.1084. Finally, the weighting of unsafe behavior factors was the most important and the least important factor, respectively, including non-observance of symmetrical load distribution with a mean weight of 0.1654 and fast driving with a mean weight of 0.1014.

Table 2 shows the results of weighting the effective factors by the first contractor (5 experts). As it can be seen, according to the contractor, the most important factor is monitoring and inspection with a weight of 0.2629 and the least important factor is the tire condition with a weight of 0.0955. Table 3 also shows the weighting results of the effective factors by the second contractors (5 experts); the most important factor is tire conditions with a weight of 0.3548, and the least important factor is unsafe behavior with a weight of 0.0929.

4. Discussion

The present work aimed to investigate the factors affecting dump truck tire bursting in one of the Iran's mines. The first phase was the content analyzing of all incidents and past studies, then all factors were extracted and classified into 5 categories: road conditions, maintenance, monitoring and inspection, tire conditions, and unsafe behavior. Also in the next phase, these factors were prioritized by examining the opinions of experts in two different contractors. The results showed that in total, the main factors responsible for tire conditions with a mean weight of 0.2252 and unsafe behavior with a mean weight of 0.1681 were the most important and least important factors in tire bursting, respectively.

Previous studies showed that tire failure is one the most causes in the bursting of dump truck tires. Zhou et al. and Anzabi et al. showed that the factors that affect tire life can be presented in different categories: tire-truck interaction (such as truck load, truck size, truck speed, wheel position), tire-road interaction (curves, grades, super-elevation, tire friction, road surface profile), tire-maintenance interaction (tire alignment, tire rotation, tire air pressure, preventive maintenance), and tire-environment interaction (weather, temperature, snow or rain). As summarized in Table 1, there are various reasons why tires are removed from service [26, 27]. Frimpong et al. showed that the road conditions increase the tread wear, cuts and complete failures. The load-bearing capacities of these tires are sometimes exceeded, with truck overloading, overstressing, heating and subsequent failures [28]. Also Rahimdel et al. showed that the ambient temperature has a significant effect on the reliability performance [29]. This shows that the results of previous studies are consistent with the present study.

Table 3. Weighting results of the factors affecting the bursting of dump truck tires according to the experts of second contractor.

Categories (weight)	Sub-categories (weight)	Categories (weight)	Sub-categories (weight)
Road conditions (0.2120)	Road roughness (0.1958)	Maintenance (0.1716)	Inappropriate storage of tires (0.1653)
	The road width or slope (0.1357)		Puncturing and non-standard tire maintenance (0.2100)
	Turning radius and its transverse slope (0.1414)		Failure to take care of the road (0.2232)
	Road used materials (0.1358)		Inappropriate installation of the rim (0.1730)
	Cleaning the road surface (0.2007)		Welding the rim on the tire (0.1399)
	Deep bumps (0.1406)		Use of anti-puncture gel (0.0885)
Monitoring and inspection (0.1687)	Condition of the rim and its screws (0.1230)	Tire condition (0.3548)	The quality of tire components (0.1889)
	Temperature, pressure, and tire inflation (0.1854)		Tire brand (0.1358)
	Depth and percentage of tire tread (0.1391)		Tire resistance (0.1829)
	Brokenness, cracks, corrosion, and inappropriate shape of the rim and screw (0.1520)		Tire size (0.0855)
	Inappropriate shape of the tread (0.1419)		Tire symmetry (0.1150)
	Asymmetric tire wear (0.1937)	Unsafe behavior (0.0929)	Non-observance of the permissible loading weight (0.1080)
	Peeling and tearing on the wall and tread of the tire (0.1601)		Non-observance of symmetrical load distribution (0.1317)
	The presence of external objects inside the tire (0.0834)		Non-observance of the pair tires rule (0.1472)
	Stuck stone between the tire tread (0.1180)		Fast driving (0.1366)
	Valve leakage (0.1292)		Using tires in long distances (0.1618)
			Use of tires with tread less than 40% (0.1220)
			Use of worn-out rims (0.1927)

Studies have shown that the failure of dump truck tires, especially the rear tire, is mainly caused by operating conditions such as speed, road obstacles, wind pressure, heavy weight, poor design of the transportation road, and inherent flaws in the design and manufacture of tires [11]. Asymmetric load transfer to poorly designed tires in cornering sections of the road may lead to overloading, and thus a reduced tire performance. Although it is the air pressure that carries the load, truck tires are often loaded beyond their pressure capacity, leading to tread and ply separation and sidewall cracking. On the other hand, adjusting the inflation pressure to compensate for excessive loads may lead to rapid fatigue of the tread, reduced strength in the reinforcements, and fracture and impact cracking [18]. The results of the present study in the first phase are consistent with the previous studies.

The results showed that the most important factor in monitoring and inspection is the factor of checking temperature, pressure and tire inflation. Dynamic properties of materials are responsible for their heat production. The temperature of any material increases when the heat produced in that material exceeds the rate of its loss. Direct measurement of the rate of heat generation and overall temperature rise in tires is very difficult and expensive, and the results of such measurements do not provide the complete temperature distribution in the tire. The tire deformation problem is actually a coupled thermal viscoelastic problem with a strong interdependence between nonlinear viscoelastic material properties and temperature. Trivisonno noted that lower tire operating temperatures could lead to an increased tire durability, and thus the need to achieve full temperature distribution in a tire to ensure that operating temperatures are kept below critical values [30].

One of the most important factors investigated in this work is the tire brand. Dump truck tires are all imported and usually sourced from a few specific companies. Each company designs tire with special conditions according to the cost, raw materials and technology at its disposal, and therefore, choosing the best brand is very important. The rising cost of dump truck tires is largely due to the limited supply of natural and synthetic tire, the raw materials used in tires. Natural tire is one of the main driving forces in the continuous increase in tire prices from manufacturers. Tire production in Thailand and Indonesia, which accounts for 60% of global supply, has declined as a result of excessive rainfall in Thailand and leaf blight disease in Indonesia [31]. Global demand for natural tire increased by 3.5% to 11.58 million tons in 2012, and may remain stable in the long term, analysis has shown. Tire shortages have been repeated after every major commodity market downturn. This makes tire-ground interaction studies one of the most important research topics for engineers and the researchers in the mining and construction industries.

Choosing a tire for a material handling job is based on its rating in ton miles per hour. When a tire is operating at a temperature higher than it can handle, serious problems can occur. It is not uncommon for mining truck tires to run above the ton-mph rating, especially in hot weather and overload situations. Super class truck tires support a total of about 635 tons (700 short tons) of car and cargo weight. Heat is generated due to hysteretic losses in the tire as it undergoes cyclic bending at the ground contact area. Tire heat is generated faster than it is dissipated and therefore accumulates inside the tire over time. Heat generation from heavy vehicle loads and high speeds is detrimental to the structural integrity of the tire material. Operating a tire above its critical MPH rating over time may cause the vulcanized tire to return to the gum state. Despite its success, the use of metric ton-miles per hour has not yet solved the problem of tire heat-related failures in the industry. A sustainable solution appears to be possible through basic and applied research initiatives.

Also the inelastic deformation of the tire leads to partial absorption of the energy transferred from the car engine to the wheels. The absorbed energy is due to the hysteretic processes that occur in the ropes and tire material and is directly converted to heat over time. The heat generated may increase the temperature of the tire. Service conditions, construction, and material (viscoelastic) properties of the tire help to increase the overall heat in it. Kainradl P, Kaufmann [32] in a review study stated that for a certain tire construction, the operating temperature of the tire can be reduced only by changing its tire viscoelastic properties. Their investigation led to the idea that the viscoelastic properties of the elastomers in the tire determine the amount of heat generated in it. Over the years, the viscoelastic properties of tire elastomers have been measured in both the frequency and time domains. This section covers previous studies related to viscoelastic property measurement and prediction of heat generation and temperature rise in tires.

5. Conclusions

The results of the present work showed that several causes were important in the bursting of dump truck tires, the most important of which was the monitoring of temperature, pressure, and tire conditions. Direct measurement of the rate of heat generation and overall temperature rise in tires is very difficult and expensive, and the results of such measurements do not provide the complete temperature distribution in the tire. The tire deformation problem is actually a coupled thermal viscoelastic problem with a strong interdependence between nonlinear viscoelastic material properties and temperature. Heat is generated due to hysteretic losses in the tire as it undergoes cyclic bending at the ground contact area. Tire heat is generated faster than it is dissipated, and therefore, accumulates inside the tire over time. Therefore, it can be concluded that in order to reduce these accidents, in addition to choosing the right tire, it is necessary to consider conditions such as temperature and pressure inspection, not exceeding the permissible load limit, taking into account the conditions of the tire such as the resistance and components of the tire, and even unsafe behaviors such as non-compliance symmetrical distribution of load and non-observance of the law of the pair of tires should be taken into consideration.

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Statements and Declarations

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The datasets used and/or analyzed during the current study are available from the corresponding author on a reasonable request.

Conflict of interest:

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Ethics approval:

Ethics approval was obtained by ethics committee of Golgohar Mining and Idustrial Company.

Author contributions:

H.R. was the leader of study, and edited the final manuscript. M.M, H.N., and M.A. gathered field data, and were a major contributor in writing the manuscript. E.H., V.K.G, and H.M. completed and analyzed data and was a major contributor in writing the manuscript. All authors read and approved the final manuscript. All authors contributed to the article, and approved the submitted version.

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شناسایی و اولویت‌بندی عوامل مؤثر بر ترکیدن لاستیک‌های دامپ تراک معادن با استفاده از روش بهترین–بدترین فازی

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چکیده:

با توجه به تعداد و شدت بالای حوادث ترکیدن لاستیک این کامیون‌ها، مطالعه حاضر با هدف شناسایی و اولویت‌بندی عوامل مؤثر ترکیدن لاستیک دامپ تراک با ا ستفاده از روش بهترین - بدترین فازی انجام شد. با توجه به تعداد و شدت بالای حوادث ترکیدگی لا ستیک دامپ تراک‌ها، مطالعه حا ضر به منظور عوامل مؤثر ترکیدن لاستیک دامپ تراک با استفاده از روش بهترین-بدترین فازی (FBMW) انجام شده است. مطالعه حاضر با استفاده از تحلیل محتوا و FBMW انجام شده ا ست. ابتدا با ا ستفاده از گروه‌های کانونی و برر سی متون و رویدادها عوام موثر استخراج شده و سپس وزن دهی و اولویت بندی این عوامل با استفاده از FBMW انجام شد. نتایج مرحله اول نشان می‌دهد که عوامل مؤثر بر ترکیدگی لاستیک‌ها را می‌توان در ۵ دسته اصلی شرایط جاده (شش زیر مجموعه)، تعمیر و نگهداری (شش زیر مجموعه)، پایش و بازر سی (۱۰ زیر مجموعه)، رفتار ناایمن (هفت زیر مجموعه) و شرایط لاستیک (پنج زیر مجموعه) طبقه‌بندی کرد. نتایج فاز دوم نیز نشان می‌دهد که شرایط لاستیک و رفتار ناایمن به ترتیب با میانگین وزنی ۰/۲۲۵۲ و ۰/۱۶۸۱ مهم‌ترین عامل هستند. نتایج کار حاضر نشان می‌دهد که مهم‌ترین علت نظارت بر دما، ف شار و شرایط لا ستیک ا ست. بنابراین می‌توان نتیجه گرفت که برای کاهش این حوادث علاوه بر انتخاب لا ستیک منا سب باید به شرایطی مانند بازرسی دما و فشار نیز توجه بالایی داشت.

کلمات کلیدی: دامپ تراک، معدن، بهترین–بدترین فازی، تحلیل محتوا، حوادث.