CAUSAL LOOP DIAGRAM FOR A TIRE-ROAD CONTACT SYSTEM

Bachelor Thesis in Civil Engineering

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Summary

Tire-road contact system is of immense importance for the tire and road industries as well as for its users. Lately, the contact system has received considerable attention due to its potential effects on the environment and the vehicle performance. In this thesis, a preliminary study of this system is performed by means of "Causal Loop Diagrams" (CLD). Firstly, a list is made of all the possible phenomena involved in this contact system along with their respective causes and effects. In addition, a set of potential factors/variables that influence each phenomenon is compiled. The identified factors act as the building materials for the CLD. The resulting CLD shows the causal relationship between the factors and the influenced phenomenon. The major effects of each phenomenon are also highlighted in the CLD. The report concludes with a discussion on how each phenomenon can be improved followed by some future research directions for both the tire and the road industries.

Contents

List of Figures

List of Tables

1.Introduction

The interaction between a vehicle and a road infrastructure takes place on a pavement. A pavement is mainly defined as a structure constructed using various durable materials with an intend to sustain road traffic. This contact system is of immense importance as it influence the vehicle dynamics and the durability of both the vehicle and the road pavement. In addition to it, it also safeguards the road users and potentially promotes a better quality of life of the communities located around the road. When the elements of the system are in contact with each other several forces act in the contact area between the tire and the road which results in the production of different type of energies such as heat and noise.

Furthermore, the interaction between the tire and the road involves various types of phenomena which have a direct and an indirect effect on the environment. Thus, it is quite important to know how the different phenomena are interrelated and what role they play in the tire-road contact system. Nevertheless, the causes, effects and the interaction between the phenomena involved in this contact system are not yet fully known. This study focuses on improving the understanding of the possible causes and its effects (social, economic, or environmental) that might be related to the tire- road interaction.

2.Problem Context

2.1 Problem Description

Recently, the tire-road contact system has been on the spotlight due to its behaviour and potential effects in the environment and the vehicle performance. Previously the focus of both tire and road construction industries was on developing a cheap but reliable product for its consumers irrespective of its multiple impacts. Gradually the trend is shifting, and more research is being done to improve the quality and sustainability of the tires and road pavements. In addition, all the phenomena involved in this contact system are being individually studied to gain more knowledge about the system. The main phenomena involved in this contact system are rolling resistance (Barrand & Bokar , 2008) , skid resistance (Asi, 2005) noise/sound emissions (Koners & Lehmann, 2014)and tire and road wear (Baensch-Baltruschat & Kocher, 2020). These phenomena have been in debate for several years now. Although most of the phenomena in the contact system are already known- there is yet a lack of understanding about the causal chains that exists in this contact system. That is because the multiple inter-relationship of different phenomena and variables/factors related to this contact system is not completely obvious. Hence, this research will contribute to improve the understanding of each phenomenon in relation to the encompassing the tire-road contact system with the help of a causal loop diagram.

2.2 Research Motivation

The potential negative impact of the tire-road contact system on the environment is becoming a huge concern nowadays. In order to mitigate the effects of this contact system on the environment various steps has been taken, such as the improvement of the quality of the tires and road infrastructure. However, a holistic and far-reaching improvement of the system can only be achieved if the possible causes-effect related to this contact system are understood. This is the need that anchor the relevance of the research work performed in this bachelor assignment.

There are several phenomena involved in tire-road contact system namely rolling and skid resistance, noise emission and tire/road wear which will act as a basis for this research work. It is highly important to understand these main phenomena due to their potential effects on the environment (e.g., GHG emissions) and the vehicle performance (e.g., the fuel consumption), among others. Apart from the knowledge of phenomena themselves it is equally important to understand how the different the factors/ variables influence the tire-road contact system. Factors like temperature, precipitation, humidity, vehicle load, air pressure and tire design are likely to play a vital role in this contact system and potentially has a significant effect on the phenomena's involved this contact system. Moreover, the holistic understanding of this contact system is important due the existing trade-offs. For instance, the reduction of the macro structure of the pavement surface will help in reducing the rolling resistance but at the same time it will also reduce the skid resistance hence potentially compromising the road safety.

Finally, a clear understanding of the causal chains in the tire-road contact system is important along with their inter-relations to avoid any undesirable consequences when actions are taken to improve a given component of the system. So, this research work will provide an encompassing overview of the main possible causal chains that may exist in this contact system, which will further help in establishing clear relationships between each variable-phenomenon relevant for this contact system. Lastly, it will also help to identify areas relevant for future research as a response to the pressing challenges faced by tire and road construction industries.

3.Research Objective and Research Question

This chapter will outline the research objective and its corresponding research questions and sub-questions, which should lead to the realization of the research objective.

3.1 Research Objective

The objective of this research is as following:

"To develop a causal loop diagram (CLD) that maps the relation between various factors and variables that contribute to the main phenomena in the tire-road contact system".

3.2 Research Question and Sub questions

Following from the research objective a research questions has been developed which is as following:

"How the various factors relevant for the tire-road contact system relate to each other and influences the main phenomena existing in this system"?

To answer the main research question, the following three sub-questions are formulated:

1. What are the main phenomena related to the tire-road contact system?
    a. Which phenomena are present in the contact system?
    b. What is the main cause of each phenomenon?
    c. What are the consequences of each phenomena for the environment, road users and communities around the road?
2. What are the main factors/variables and parameters relevant for each phenomenon involved in the tire-road contact system?
    a. Which factors (both internal and external) effects each phenomenon?
    b. How is each phenomenon effected by the different variables and factors?
3. What are the conditions, causal chains, and effects, existing in the CLD representing the tire-road contact system?
    a. What are the building blocks of the CLD?
    b. How does each cause relate to the effect?
    c. How does different conditions effect the causal relationship?
    d. What are the feedback loops existing in the CLD?

4.Main Phenomena with their Causes and Effects

In this section of the report, the main phenomena involved in the tire-road interaction system are discussed. First of all, a literature research is carried out in order to identify these phenomena. Five main phenomena are identified which are the following: Rolling Resistance, Skid Resistance, Noise Emission, Tire and Road Wear. The main causes and effects of these phenomena towards the environment and road users are discussed below.

4.1 Rolling Resistance

Rolling resistance is one of the major resistive force acting on a moving road vehicle. It accounts for approximately one third of the energy consumed by a vehicle engine. (Mie`ge & Popov, 2005).

Rolling resistance, sometimes called rolling friction or rolling drag, is mainly defined as the energy loss that takes place in the tire-road contact area due to the nonelastic deformations of the tires and losses in the wheel suspension system (Andersen & Larsen, 2015). Or in other, is the force resisting the motion when a body (such as a ball, tire, or wheel) rolls on a surface (Mukherjee, 2014). Figure 1 shows a general diagram of a rolling tire on a road surface with the resistive force, rolling resistance acting against the direction of travel. This figure also depicts some of the important parameters that influence this resistive force, but these parameters will be discussed in the next section.

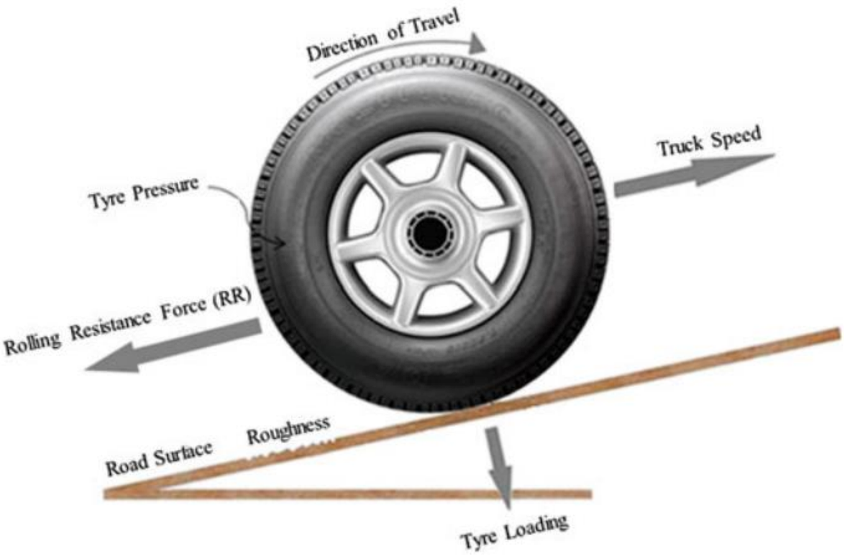

Figure 1: Rolling resistance acting on a tire (Soofastaei & Karimpour, 2008)

Since, one can assert that rolling resistance is an important phenomenon in the tire-road contact system, it is hence important to know its causes.

Causes

The primary and major cause of rolling resistance is known as “Hysteresis”. Hysteresis is mainly a characteristic of a deformable material which means that the energy of deformation is greater than the energy of recovery. The energy lost in this process is in the form of heat (Staff, 2014). Hysteresis can also be explained as follows, when a tire is allowed to roll on a road surface it will undergo deflection due to the combination of the vertical load and the forward rolling effect of the car. The vertical load tends to flatten the circular profile of the tire on the ground whereas the forward rolling effect spreads the contact edges of the tire on the ground. This means that the energy is being used in rolling the tire over the ground and not all of the energy is being returned as the strain energy when the tire takes up its original shape (Heisler, 2002). Hence, energy is lost during this whole process thereby significantly effecting the rolling motion of the vehicle. This mechanism can be responsible for 80-90% of the total tires rolling resistance.

Moreover, the rolling resistance can also be caused by the ''aerodynamic drag'' due to the tire cutting through the surrounding air as it rotates, which eventually oppose the tire movement and promotes heat transfer between the air and the tire. Such mechanism can cause 0–15% of the total tire rolling-resistance depending on the tire speed (Aldhufairi & Olatunbosun, 2017).

Furthermore, the ''frictional slip'' that takes place when the tire comes into contact with the wheel rim and with the road surface during its rotation leads to heat build-up. This is the least important causal factor of the rolling-resistance accounting for about only 5% of the total tire rolling-resistance (Aldhufairi & Olatunbosun, 2017).

Effects

First of all, since hysteresis is a major cause for the rolling resistance. It also directly influences the performance of the vehicle. The hysteresis energy is lost in the form of heat, as the vehicle works extra in order to overcome that energy loss. As a result, the vehicle consumes more fuel and eventually the fuel consumption rate of the vehicle increases. This is one of the major impacts of the rolling resistance on a vehicle. Existing literature has documented that for tires with a rolling resistance coefficient of 0.012, the fuel consumption due to tire rolling resistance can amount to 20-30% of the total fuel consumption depending on the drive cycle (Redrouthu & Das, 2014).

Consequently, the increase in the fuel consumption means that the vehicle will emit more carbon dioxide which is a primary greenhouse gas (GHGs) responsible for about three quarters of the emission which can stay in the atmosphere for thousand years (Redrouthu & Das, 2014) . Moreover, the effects of GHGs on the environment are in turn quite adverse. It directly impacts the ozone depletion which further results in the global warming and the climate change (Nunez, 2019).

4.2 Skid Resistance

Another important phenomenon that is often discussed in the tire-road contact system is the skid resistance. It is defined as the force developed when a tire is prevented from rotating slips along the pavement surface. It shows the relationship between the vertical force and the horizontal force developed as a tire slides along the pavement surface and eventually measures the resistance of the pavement surface to the skidding of the vehicle. Therefore, the texture of the pavement surface and its ability to resist the polishing effect of traffic is of prime importance in providing skidding resistance (Asi, 2005)**.**

Causes

The pavement friction can be divided into two components (Mayora & Pina, 2009): i) the longitudinal friction coefficient measuring the friction in the direction in which the vehicle is moving which directly impacts the distance required for a vehicle to decelerate hence determining the safety margin of the driver and ii) the transverse friction coefficient measuring the skid resistance in a perpendicular direction of the vehicle's movement. It allows a driver to steer the vehicle in curves and in other situations where changes of direction are required.

The pavement friction is mainly affected by two basic components namely: adhesion and hysteresis. Adhesion results from the formation of molecular bonds between the tire tread and the pavement surface (Canada, 2011). Adhesion represents the shear force that is created when a rolling tire, tread changes its shape in order to adapt with the asperities present on the surface aggregates (Wilson, 2006). This shear force is proportional to the strength of these bonds. The micro texture of the aggregates (which represents the deviation of the pavement surface from the true planar surface by less than 0.5mm) has a significant influence on the adhesion component (Plati & Pomoni, 2019).

Moreover, the mechanism of hysteresis also contributes to this phenomenon. As discussed in the section above, hysteresis is developed due to the continuous compression and decompression that a tire-tread faces when it comes in contact with the aggregates present on the pavement. The continuous compression and the decompression cause loss of energy in the form of heat (Hall & Smith , 2009). Hence, these are the two primary causes of skid resistance, but these causes are further effected by several factors which will be discussed in the next section of the report.

Effects

Worldwide, more than 1 million people are killed yearly due to traffic accidents (Organisation, 2021). Although high percentage of these accidents is due to drivers' errors, the road pavement may a significant effect on this percentage of traffic accidents. The most important factor related to the road pavements affecting traffic accident rates is the skid resistance (Asi, 2005). This is especially true during a wet season when the friction between the tire and the road is relatively low when compared to a dry season.

Moreover, skid resistance also directly influences the safety of the residents/ communities that might be living next to a road network. Because it can act as a major threat for them especially during the rainy season due to the lower friction which increase the chances of skidding.

Lastly, it can be asserted that the skid resistance is an important phenomenon in the tire-road contact system because of the following reason (Asi, 2005) i) inadequate skid resistance will lead to higher incidences of skid related accidents; and ii) most roadway agencies have an obligation to provide users with a roadway that is ''reasonably'' safe.

4.3 Tire/ Road Wear

An additional phenomenon existing in the tire-road contact system is the tire and road wear. Both aspects are interlinked as the behaviour in one can significantly affect the other.

First of all, tire wear is basically a mechanical tearing process of the tire when the energy is dissipated in the contact area between tire and road which eventually leads to a hight temperature at the points of highest stress concentration i.e., the points at which a mechanical separation of abraded particles is most likely (Grosch, 2008).

Similarly, road wear refers to the disruption that might be caused on the road surface due to high friction between the road and the vehicle tires which eventually makes the road surface worn out (Gon, Broeke, & Hulskotte, 2008).

Causes

The causes of the road wear are relatively straight forward. First of all, heavy traffic on the road can act as major threat to the surface along with the velocity of each vehicle Heavy traffic imposes constant stress on the road surface which eventually results in the formation of different types of cracks and lead to the formation of potholes (Grading, 2017). In addition to it, a process called oxidation can also force the road particles to become worn out. When asphalt oxidizes, it breaks down and becomes less flexible and more rigid. A lack of flexibility makes asphalt more susceptible to cracks, particularly when paired with heavy traffic. Oxidation mainly refers to the process that the asphalt surface experiences when exposed to the sun. It triggers the molecular bonds between the asphalt which creates new polar sites or the bonding sites (Services, 2019). Moreover, the presence of water on the road surface can also adversely affect the road properties. Water settling on the top of roads can wear on the asphalt and cause initial cracks. If water sinks into already formed cracks, it can cause further damage in the base layer (Grading, 2017). Lastly, the presence of friction between the tire and the road forces the tire particles to get torn off in the contact area eventually causing both the road wear along with the tire wear.

On the other hand, the major cause of tires being worn can be the irregularities present on the road surface or in simple words when the road wear occurs. Any type of potholes and depressions present on the surface will directly affect the tread pattern which will influence the tire properties. Other causes of the tire wear include the improper inflation pressure. When the tire pressure is too low, or even too high, the contact patch of the tire tread will not be optimized to handle the wide variety of jobs it is asked to do (Stone, 2017). Moreover, car alignment can also be a major cause of the tire wear. Tire alignment, also known as wheel alignment, refers to the adjustment of the vehicle's steering and suspension components – the system that connects and controls the motion of the wheels. Improper tire alignment can cause the tires to wear unevenly and prematurely (Stone, 2017).

Effects

The effects of the tire and road can be very adverse. It negatively impacts the vehicles performance thus minimizing its efficiency and decreasing the life span of the vehicle engine. In addition to it, several particles are generated during this tire and road wear known as the Tire and Road Wear Particles (TRWP). TWRP are generated on roads during driving processes (when the frictional energy is produced due to the rolling shear of tire tread and the road surface) and contribute to airborne non-exhaust emissions and are discussed in connection with the microplastic pollution (Baensch-Baltruschat & Kocher, 2020). Micro plastic pollution can act as a major threat to the environment which can drastically effect both the human life as well as the marine/ aquatic life. The major amount of TRWP consists of coarser heterogenous particles released to road surface, soils, and aquatic compartments, and it is believed that high levels of braking and acceleration are among the most influential aspects related to the production of both larger (more than 50 µm) and greater number of tire wear particles. (Knight & Parker-Jurd, 2020).

4.4 Noise/Sound Emission

The last phenomenon considered in the tire-road contact system is the "noise/ sound emission". Now-a-days, traffic noise is becoming a huge concern for many cities, especially for the communities residing along any road network, since the increase in noise level effects the quality of life of many people. Tire-road noise is identified as a dominant source of traffic noise (Ho, Hung, & Ng, 2013).

In addition to it, research efforts have been pursued with the objective of lowering the interior noise levels in combination with a comfortable sound for the passenger's cars (P & Sazali Yaacob, 2010). Due to the reduction of many noise sources over the last decades, nowadays tire-road noise has become one of the dominant sources for the interior noise. Especially for manufactures of luxury cars, the reduction of tire-road noise is a big challenge (Koners & Lehmann, R, 2014).

There are different sources in a vehicle that create noise, both internally and externally. Overall, the components that contribute most to vehicle noise include the tires, engine, powertrain, exhaust, intake system, in addition to the aerodynamics of the vehicle. But tires are the largest contributor to total noise, followed by the exhaust and intake systems (Niknam, 2021).

The tire-road noise generation mechanisms can be divided into two groups: i) vibrational mechanisms, which might include tire design and the pavement conditions and ii) aerodynamical mechanisms, which can include air turbulence and air pumping etc (Blom, 2004). Since, this research is mainly about the tire-road contact system, only the first group will be discussed in this particular section.

Causes

The major sources of this noise are the characteristics of the tires, especially the tread design. The grooves in a tire tread plays a vital role in the formation of this sound. The concept for this revolves around the fact that when a tire is rolling the air is continuously trapped or compressed inside the grooves of the tire, in the contact area between the tire and road. Once the tire leaves the contact area that particular section results in a production of the noise (Clinic, 2018). Moreover, due to rubber viscoelastic properties, the air compressed cannot propagate all through the tire and the vibrations are only observed near the contact patch where they are originated. These waves in the tread band are very effective in radiating noise (Azizi, 2020). Figure 2 shows a design of a tire tread and identifies the main component of a tire.

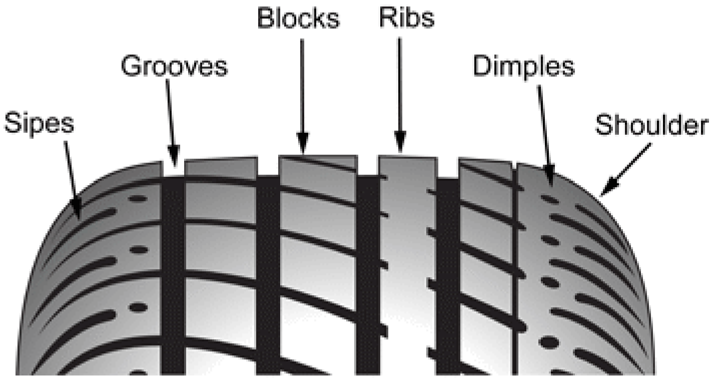

Figure 2: Tire tread design with its main components (Companies, 2015)

Another possible cause of noise effect is the concept of "Structure-borne noise". Structural borne noise is a result of the vibrations. As the tire rolls on the road, at the tire–pavement interface, the tire encounters different imperfections on the road. In some cases, the tire can also encounter some internal mechanisms such as tire nonuniformity. These external and internal excitations, in addition to local tread band deformations, can cause local strains that propagate in the tire carcass (Azizi, 2020).

Furthermore, another possible cause of the noise emission is due to the impact of tire tread protrusions, air pumping, and air turbulence vibration noise. Uniformly distributed tire tread protrusions periodically collide with the road surface as the wheels rotate, then the tire pattern compresses and bounces strongly, which generates the tire vibration noise (Chen & Mulian Zheng, 2021).

Effects

As mentioned previously, the noise produced by the tires is the highest contributor to the overall noise pollution by the vehicle. The noise pollution can have many adverse effects on the human life, along with the connection to the cardiovascular diseases. In addition to it, the communities are also greatly affected by the noise produced in this contact system depending upon its frequency, hence disrupting their daily life.

5.Factors/Variables Effecting Each Phenomenon

This section of the report discusses the possible factors/ variables that have direct and indirect impact on each of the phenomenon mentioned in the section above. Before enlisting and explain each factor it is quite important to differentiate between the internal and the external factors.

Internal factors are the factors that are directly related to the properties and/or attributes of the main elements (i.e., pavement, tire, and vehicle) belonging to the tyre-road contact system.

On the other hand, the external factors are the factors that are not directly related to the properties and/or attributes of the elements belonging to the tyre-road contact system, but that have yet an impact on the phenomenon involved in that system, such as, for instance environmental conditions, driver's aggressiveness, etc.

Once the internal and the external factors are differentiated a list of the main factors/variables causing each phenomenon was compiled based on the literature review and presented in table 1. This is followed by an explanation of how they are related to each phenomenon.

Table 1: Main factors/variables affecting the tire-road contact system

Elements	**Factors/ Variables**
Road	Micro-texture, Macro-texture, Mega-texture, Unevenness, Stiffness, Porosity, Horizontal curvature, Surface temperature, Surface colour, Bitumen penetration value, Bitumen stiffness, Asphalt content, Uniformity of aggregate gradation, Asphalt mixture density,
Tire	Tire inflation pressure, Tread thickness, Wheel diameter, Tire Size, Rim diameter, Tread Depth, Tire temperature (both internal/ external), Slip angle, Rubber strength/ hardness, Tire alignment, Tire load, Rubber in the side walls
Vehicle	Vehicle load/ Mass, Vehicle velocity, Wheel alignment
Environmental/ external	Temperature, Snow on road, Ice on road, Wetness, Driver's aggressiveness, Water depth if precipitation, Hard braking

5.1 Factors effecting rolling resistance

1. Pavement stiffness

Pavement stiffness is mainly defined as the amount of deformation that a pavement undergoes when a load is applied (Transportation, 2016) . Hence, pavement stiffness impacts the rolling resistance and fuel consumption of the vehicle, mainly due to the fact that a pavement has a dynamic deformation characteristic under a rolling tire. Stiffer, more rigid pavements reduce rolling resistance.

2. Surface roughness

Surface roughness can be referred as the irregularities present on the surface texture. The main reason for these irregularities can be the asphalt mixture density which is further effected by the asphalt compaction temperature. An increase in compaction temperature increases the mixture density hence lowering the irregularities or the surface roughness (Frost, 2020). Roughness can be categorized into four components (Qiu, 2009) :

2.1 Micro-texture refers to the small-scale texture of the pavement aggregate component which controls the contact between the tire rubber and the pavement surface. It is the deviation of a pavement surface from a true planar surface with the characteristic dimensions along the surface of less than 0.5 mm. Thus, it mainly depends upon the properties of the aggregate particles in the pavement.

2.2 Macro-texture refers to the large-scale texture of the pavement as a whole due to the aggregate particle arrangement (which controls the escape of water under the tire and hence the loss of skid resistance at high speeds). Macro-texture is the deviation of a pavement surface from a true planar surface with the characteristic dimensions along the surface of 0.5 mm to 50 mm.

2.3 Mega-texture is the corresponding deviations with the characteristic dimensions along the surface of 50 mm to 500 mm.

2.4 Unevenness is the corresponding deviations with the characteristic dimensions along the surface of 0.5 m to 50 m.

Apart from micro-texture, all components mentioned above have a significant impact on the rolling resistance. First of all, tires that are used on a rough macro-texture will deform more and suffer greater energy loss. Also, mega-texture tends to create vibration inputs in the tire and suspension system hence increasing the rolling resistance of the vehicle. Finally, unevenness also results in a higher rolling resistance as more energy will be lost in the form of vibrations when a tire passes over an uneven road.

3. Tire size

Tire sizing is an important parameter with respect to the rolling resistance, but it also plays a vital role in other vehicular aspects e.g., vehicle handling. A high tire diameter decreases the vertical deformation for the same contact patch length from the pure geometry point of view when the tyre is considered in terms of a perfect circle. Hence, it projects an idea that decreasing the vertical deformation shall practically mean low transition of radius on the leading and trailing edges of the contact patch which eventually results in a low bending of tire tread region (when the diameter is high) and hence decreases the hysteresis losses which is the main cause of rolling resistance (Redrouthu & Das, 2014). Figure 3 summarizes the effect of the tire size on the rolling resistance. In the figure the deflection refers to the vertical deformation as mentioned above.

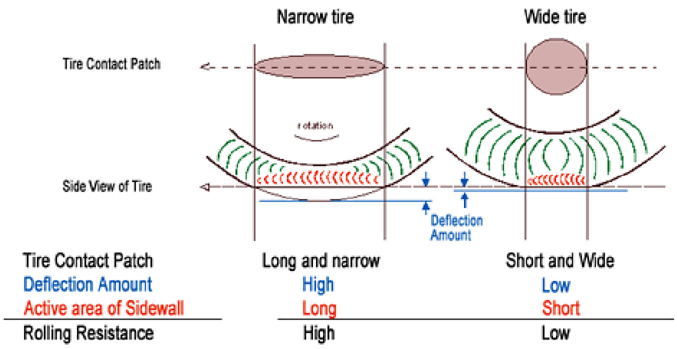

Figure 3: Tire size effect on rolling resistance (Artisanales, 2006)

4. Tire inflation pressure

The tyre inflation pressure is also an important property of the tires that tends to influence the rolling resistance. Generally, the tire rolling resistance decreases with increase in pressure on level road surface as other parameters are kept constant. As the tire pressure increases, the shape of the tire is firmer hence the vertical deflection decreases. Thus, the deformation of rubber is lesser compared to that in a tire with lower pressure which results in the reduction of hysteresis losses thereby decreasing rolling resistance (Redrouthu & Das, 2014).

5. The normal load

The normal load can be referred as the vehicular load or the resultant load on the tire. An increase in the normal load will increase radial deformation of tire elements. Hence, the rolling moment produced due to shift in pressure centre will now increase because of an increase in the vertical component of hysteresis, thus increasing rolling resistance force (Heisler, 2002). In other words, there would be more bending and shearing in the tire when the normal load applied increases. The rolling resistance coefficient, however, is a function of the modelling of the hysteresis.

6. Water depth

Water on the road surface has noticeable effects on the different aspects of the road surface, which includes rolling resistance. When a tire rolls over a wet road, it must displace water before making direct contact with the texture of the road surface. Hence, the water film on the road restricts tire movement not only by mechanical and hydraulic means but also due to the cooling effect on the tire structure which leads to a high rolling resistance. Jerry Ejsmont performed an experiment to identify the relationship between the road wetness and the rolling resistance and concluded that the: wetness of the road surface increases tire rolling resistance considerably. For certain tires and road surfaces in heavy rain, the increase may be as high as 50% (Ejsmont & Leif Sjögren, 2015).

7. Tire internal temperature

The tire internal temperature refers to the temperature of tire at which it is rotating. Generally, the tire temperature increases due to the continuous friction that is present between the tire and road while it is rolling. Hence, the increase in tire temperature increases the mechanism of hysteresis and the tire has to undergo more deformation which eventually has an increasing impact on the rolling resistance. Moreover, tire internal temperature can also be effected by the surface colour. A lighter colour will also lower the surface temperature.

8. Bitumen stiffness

Bitumen is a material that is highly used in the construction sector especially by the road industry for surfacing of the roads. Hence, its stiffness is also defined as the deformation that is undergoes especially when the load is applied. A stiffer bitumen reduces the rolling resistance as deformation will take place which results in less energy loss. An important element of bitumen stiffness is its penetration value which is defined as the vertical distance travelled by a needle into a bituminous material (Chomicz-Kowalska & Krzysztof Maciejewski, 2020). A high penetration value means the less stiff a bitumen mixture is.

5.2 Factors effecting skid resistance

1. Surface roughness

As mentioned in the above section, surface roughness consists of 4 different components. Skid resistance is effected by all the 4 components because the textures result in higher energy losses as the tires will deform more.

2. Aggregate characteristics

The main aggregate properties that have an influence on the skid resistance are, size, gradation, and quality. Similarly, the use of coarse and fine aggregates can greatly influence the skid resistance. The main reason for the reduction of the pavement skid resistance is the smoothness of the surface which is eventually caused by the polishing of aggregate due to high traffic and speed (C.Wang, 2016).

3. Thickness of the water film

Thickness of the water film can be referred as the amount of water assembled on a pavement surface. The skid resistance of a wet pavement varies with the thickness of water film on the pavement surface. Generally, the thicker the water film, the lower is the skid resistance.

4. Tire/Vehicle load

Tire load effects the acceleration, cornering, and braking of a vehicle. When the load on the tire is high, it imposes a vertical downwards force towards the road/ pavement and as the load increases the magnitude of the force also increases. This force holds a strong grip therefore increasing the skid resistance.

5. Tire tread depth

Tire tread mainly refers to the rubber markings present on the circumference of the tire. Each tread has a specific depth. If the tire has very few patterns of treads, accompanied with a less depth the chances of slippage will be high meaning that the skid resistance will be low. Therefore, having tires with a higher tread depth is always recommended.

6. Ice on the road

Having ice on the road can greatly influence the skid resistance of the vehicle. Ice will act as a barrier between the tire and the road; therefore, the tire treads cannot have grip on the road and instead they will be touching the ice surface. Since, the connection between the tire and the road has been disrupted the chances of a vehicle slipping on the ice surface are very high. Therefore, the skid resistance will be decreased.

7. Tire slip angle

A slip angle is the difference between the steering angle and the direction in which the tire footprint is taking. Tire slip angles play a major part in steering systems and have a large effect on steering geometry (Secrets, 2016). Figure 4 shows an overview of what a slip angle is and how it is originated. The higher the slip angle, the higher the chances of a vehicle skidding, which means the skid resistance force decreases.

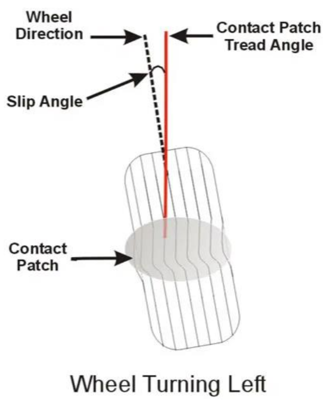

Figure 4: An overview of the tire sip angle (Secrets, 2016)

5.3 Factors effecting noise emission

1. Pavement stiffness

The stiffness of the pavement also contributes to the noise in a tire–road interface, but at a lower extent. Overall, it can be said that the more elastic the coating material, the greater the capacity of reducing the sound pressure level because it can absorb more impact (Woodhead, 2014).

2. Void index

Void Index is mainly defined as the ratio of volume of voids to the volume of a solid. Therefore, with respect to the void index, porous pavements, with voids of 15% or greater, can better absorb sound than traditional coatings with 4% to 8% of voids (Liu & Xiaoming Huang, 2016).

3. Tire tread and grooves depth

A tire tread plays a vital role in this phenomenon. A tire tread has multiple air volumes/cavities and pockets formed by the grooves and the tread slots. As the tire rolls on the road surface, these volumes are compressed or expanded, which forces the air in and out of the pockets at the leading edge, trailing edge, and sides of the tire footprint/contact patch. This results in a process called air pumping which is eventually responsible for the noise (Clinic, 2018). In addition to it, winter tires tend to create more noise than summer tires because of the tread pattern difference. The tread design in the winter tires has deeper blocks.

4. Tire width

A wider tire means that it has more tread block impacts or texture impacts per time unit. Also, a wider tyre means that more air has to be displaced within the tire-road interface. Finally, the horn effect is more effective for wider tyres than for narrow ones. Near the tyre/road contact area, the road surface and the tyre belt form a horn-like geometry, which provides a significant amplification mechanism for sound sources known as the horn effect (GRAF & Chih-Yu Kuo, 2002). Generally, it can be said that an increase of noise with width is around 0.4 dB per 10 mm (Koners & Lehmann, 2014).

5. Rubber hardness

A low rubber hardness is favourable to a low noise tyre design. The impact of soft rubber against the surface leads to less vibrations than the impact of hard rubber.

6. Wetness on road

The more wet a road surface is, the more noise will be produced as a result of friction between the vehicle tire and water present on the surface.

7. Tire inflation pressure

A proper inflation of the tire is highly important due to several reasons mentioned in the section above. A properly inflated tire will have less vertical deflection which means less air will be trapped between the tire treads and eventually less noise will be produced as a result of this action. This happen because the amount of the air compressed by the tire tread will be less and once the tire leaves the road surface less air will be disrupted.

8. Skid resistance

As mentioned in the section above, skid resistance refers to a resistive force produced due to friction between the road surface and the tire. If the resistive force is high, more noise will be produced when the vehicle is forced to stop under the influence of this force.

9. Rubber side walls in a tire

A tire consists of several components as seen in figure 5. The side wall of the tire is made up of a special rubber compound to add flexibility and resistance to noise, vibrations etc.

Therefore, a low-profile tire typically generates more noise because there is less rubber sidewall to absorb it.

Figure 5: Main components of a tire (Bridgestone, 2020)

5.4 Factors effecting tire and road wear

1. Tire inflation

When a tire is improperly inflated, there's a good chance it will start to wear more rapidly. If the tire pressure is too low, or too high, the contact patch of the tire tread is not optimized to handle the wide variety of job it has to do. Thus, different parts of the tread may be abraded away more quickly. Hence, proper inflation pressure helps optimize the distribution of vehicle load, acceleration, braking, and cornering forces in the tread.

2. Tire alignment

It refers to the adjustment of the vehicle's steering and suspension components – the system that connects and controls the motion of the wheels. It is not an adjustment of the tires or wheels themselves. Improper tire alignment can cause the tires to wear unevenly and prematurely and cause unnecessary noise.

3. Temperature

The pavement ages due to the weather and loading. The main reason being the heat from the sun, that vaporizes the components of asphalt bonds. This, in turn, makes the pavement more brittle and, in turn, cracks are formed in the winter when the weather turns cold. This leads to more extensive cracking allowing water into the pavement's sublayers. Once the sublayers are effected, potholes will be formed on the pavement surface.

4. Water depth

Water settling on the top of roads can wear on the asphalt and cause initial cracks. If water sinks into already formed cracks, it can cause further damage in the base layer.

5. Vehicle velocity

The velocity of the vehicles also influences the road wear directly. A high velocity tends to create more pressure on the road surface which may result in the formation of cracks. Along with that a high velocity means the energy losses due to hysteresis will also be high, which leads the tire to be worn out more rapidly.

6. Vehicle mass and load

Vehicle mass and the load mainly represents the overall weight of the vehicle. If the weight of the vehicle is high, the effect of this weight on the suspension system of the vehicle will also be high. Eventually, this will disturb the suspension system and cause it to wear. Along with that, it will also cause the tire to wear because the contact area of the tire and the road will increase, causing more vertical deflection thereby resulting in the road wear.

7. Drivers' aggressiveness

This factor has a direct relation with the speed of the vehicle since an aggressive driver tends to drive the vehicle at a higher speed and a higher speed has an adverse effect on a tires condition. Thus, if the speed of the vehicle is always high the chances of tires getting worn out will also be high as explained in the point 5.

8. Hard braking

Hard braking occurs when a greater force is applied in the braking system of the vehicle by the driver than in a normal situation. Hard braking results in a higher friction which further effects the condition of the tire. A higher friction reduces the tire tread significantly. Moreover, it is will also produce a higher noise.

9. Surface roughness

Micro and Macro texture are the main components of surface roughness that have an adverse impact on the tire wear (Qiu, 2009). Both the textures contribute to the energy losses in the tire due to higher deformation.

6.Causal Loop Diagrams

The answers to the research questions 1 and 2 and respective sub questions will serve as the building blocks for the “Causal loop diagram” (CLD). A CLD shows a relationship between a cause and an effect and how this particular relationship is inter-related. Furthermore, this diagram is also an efficient way of presenting the whole system and the interrelation between each factor and phenomenon in that system.

Since, the tire-road contact system is quite a comprehensive system, several CLD’s are created for the sake of clarity. The global CLD includes all the phenomena identified in section 4 of this report. Moreover, it also includes the parameters that shows existing links with each phenomenon. The other CLD’s illustrate a fewer number of phenomena and should be seen as zoom in versions of the global CLD.

The global CLD is presented in figure 6. It shows the main phenomena in the contact system which are written with capital letters. Moreover, different colours are used, to represent their respective groups e.g., the purple arrows show different properties of the tire effecting each phenomenon and the orange arrows represent the different characteristics of the pavement and its effect on each phenomenon.

A “Legend” has been also included at the bottom of the diagram to allow the readers to differentiate between characteristics. Another important aspect of this CLD is the positive and the negative signs. A positive sign mainly shows that the cause and effect are directly proportional to each other. For example, an increase in surface porosity will also increase the tire wear as the road surface will be a bit rougher. Similarly, a decrease in the surface porosity will also decrease the tire wear since the cause and the effect go in the same direction. This relationship is represented by a positive sign. Conversely, if this is not the case, then the relationship will be shown with a negative sign. This global CLD also highlights the effects of each particular phenomenon on the environment, road users and the communities around, which are represented with blue arrows.

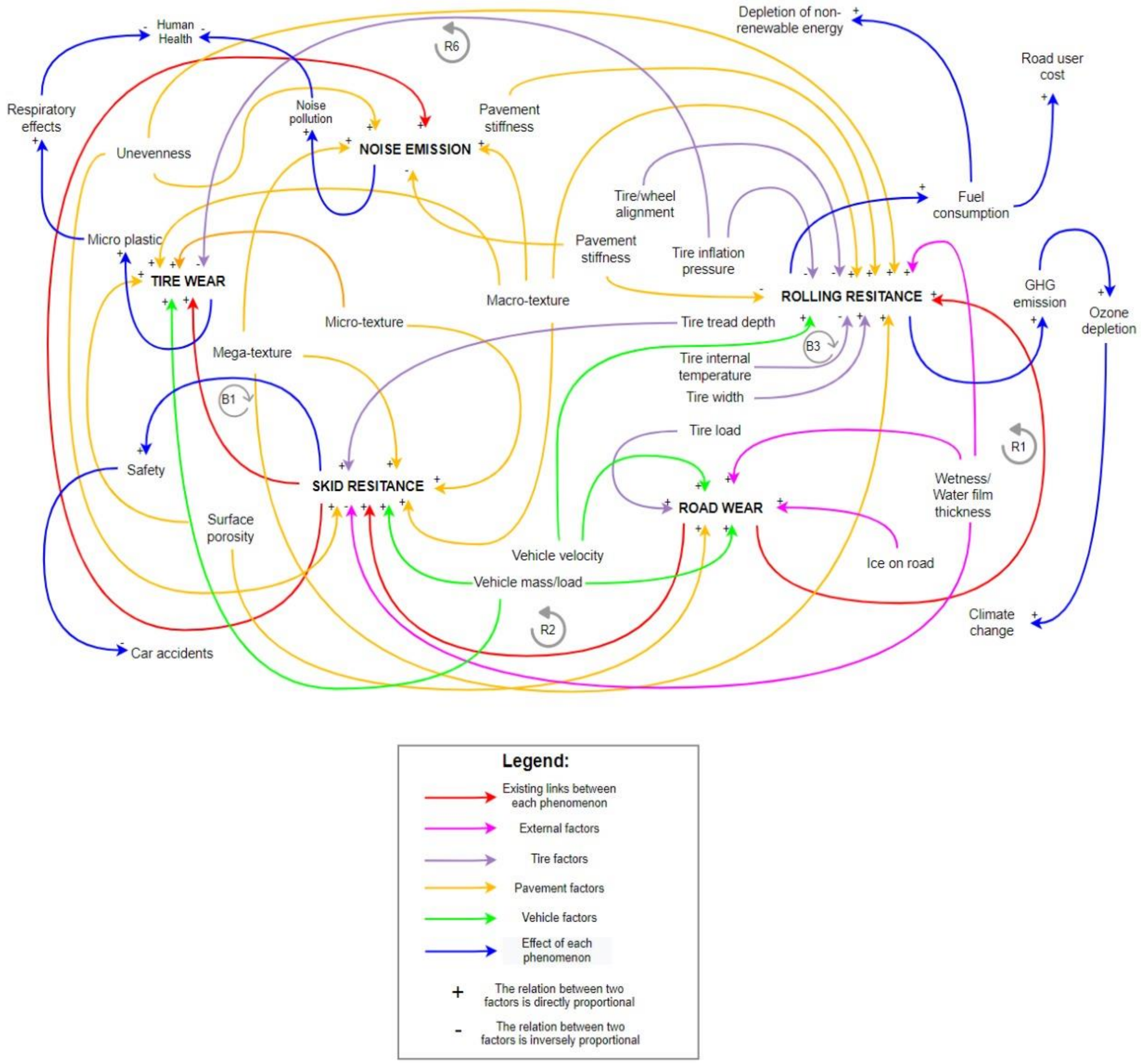

Figure 6: Global CLD of the tire-road contact system

Furthermore, one can also see some small arrows represented by the letter's "B" and "R". These are the feedback loops of a CLD, known as the balancing loop and the reinforcing loop, respectively. The balancing feedback loop is a mechanism that avoids further changes in one direction. It counters change in one direction with a change in the opposite direction. It seeks to stabilize a system (UN, 2016). On the other hand, the reinforcing feedback loop is found whenever behaviours or events inside the loop reinforce one another. These loops amplify the effect of the process (UN, 2016).

Along with the global CLD, two additional CLDs are created to show the relationship of each factor-variable with the phenomenon in a detailed way. Figure 7 presents the first additional CLD consisting of the two main phenomena of the contact system, i.e. the rolling resistance and skid resistance. An aspect worth mentioning from the analysis of this CLD is the identification of the roughness as a major cause of both phenomena. This characteristic further depends on the asphalt mixture density which in turn depends on the asphalt compaction temperature (as discussed in the section 2 of this report).

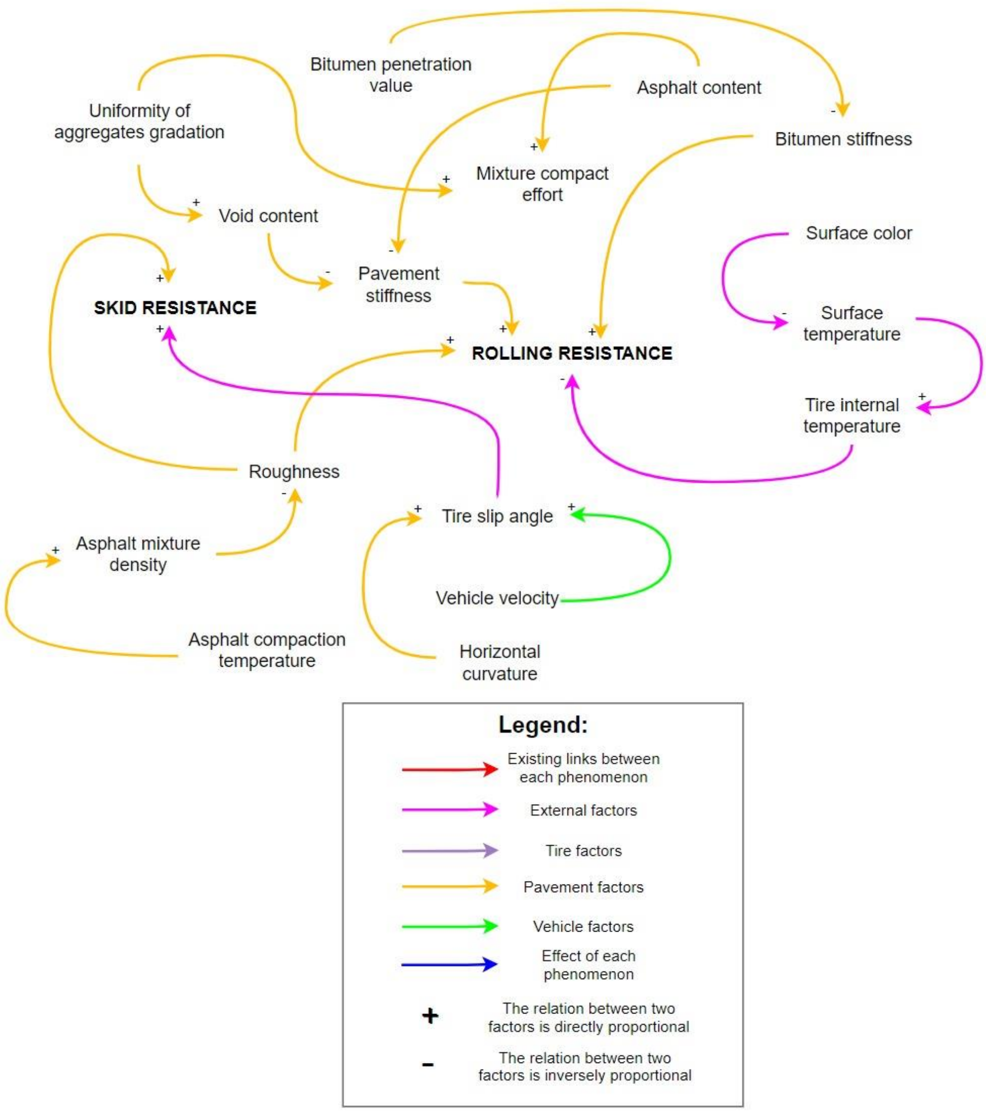

Figure 7: Zoom in view of the global CLD (CLD-1)

The second additional CLD shows the phenomena tire and road wear and the noise emission since these phenomena are particularly intertwined. Noise emission is influenced by several factors. Most of the variables pointing towards the noise emission are depicted with the yellow colour, meaning that this phenomenon is particularly influenced by the tire characteristics. Lastly, it can also be seen in this CLD that it comprises a greater number of feedback loops than the previous CLD. This subject will be further discussed in the next section of the report.

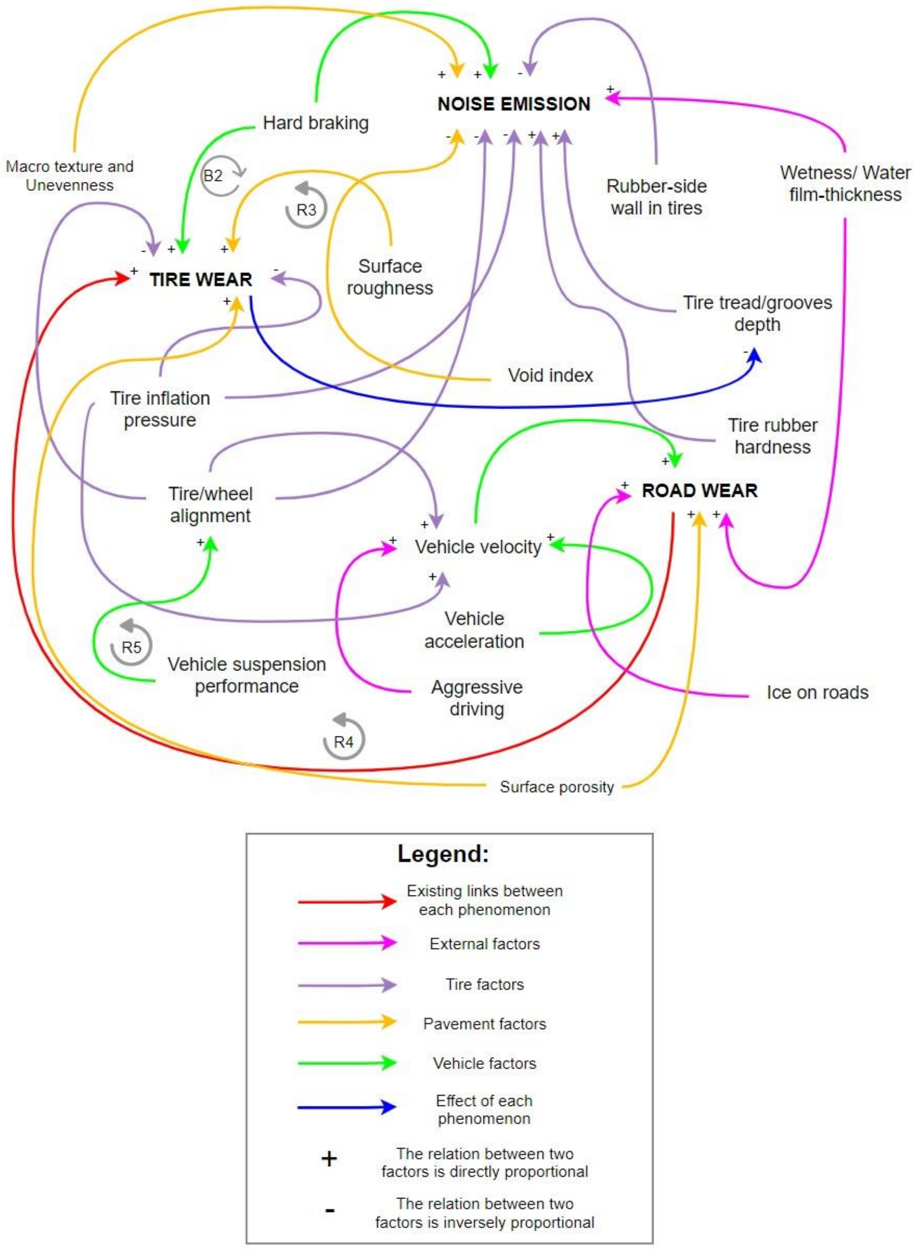

Figure 8: Zoom in view of the global CLD (CLD-2)

6.1 Analysis of the CLD

In total 3 different CLDs are created to illustrate the tire-road contact system, and each CLD has several feedback loops. The global CLD comprises three reinforcing loops and one balancing loop.

- Reinforcing loop R1

R1 shows the relationship between the phenomena road wear and rolling resistance. As mentioned earlier, in reinforcing loops the phenomena reinforce one another. In the case of this loop, the increase in road wear will increase the rolling resistance. Likewise, an increase in rolling resistance will also increase the road wear due to the friction.

- Reinforcing loop R2

R2 concerns the phenomena road wear and skid resistance. Road wear illustrates mainly the condition of the road and how damaged and uneven it is. If the road contains irregularities (e.g. potholes), the chances of a vehicle skidding are very reduced since a lot of friction will be present in the contact area, thereby preventing the vehicle from skidding. On the other hand, skid resistive force can influence greatly the road wear because a higher resistive force will result in more friction which further causes heat losses in the upper surface of the road. Due to the losses some particles of the road will be removed, hence causing a reinforcing loop.

- Reinforcing loop R3

R3 shows the relation between the surface roughness and the tire wear. A rough surface is associated with an irregular surface due to the damage in the pavement caused by pavement distresses, such as cracking or potholes. A rougher surface is one of the main reasons for the tire wear, since the tire has to undergo various deformation cycles when it is in contact with the surface. This reduces its performance and effects its quality. Likewise, a tire in bad condition will affect the quality of the road and make it rougher due to the heat energy that will be dissipated in the contact area. Hence, these variables reinforce each other.

- Reinforcing loop R4

R4 shows the relationship between the phenomena road wear, and the tire wear. Increase in the road wear effects the quality of the tire and eventually increasing the tire wear. Likely, if a relationship is shown from the tire wear to road wear it is also positive making it is reinforcing loop.

- Reinforcing loop R5

R5 shows a relationship between the vehicle suspension performance and the tire wheel alignment. A higher suspension performance means that the wheels of the vehicle are properly aligned. And if the causal effect is made from the wheel's alignment to the performance, the relation is also positive. As the causal effect of both the variables is positive, it is accounted as a reinforcing loop.

- Reinforcing loop R6

R6 depicts the relation between the tire inflation pressure and the tire wear. A higher inflation pressure decreases the chances of tire wear and ensures a smooth contact between the tire and the surface, hence forming a negative relation. Similarly, if the causal effect is made from tire wear to inflation pressure, it is also negative as a higher tire wear means the tire is deformed from its original shape/ size. Therefore, the amount of pressure in the tire will be low.

In addition to the reinforcing loops described above, the CLDs also possess balancing loops. They are as follows:

- Balancing Loop B1

B1 mainly represents the relationship between the skid resistance and the tire wear. The causal effect from skid resistance to the tire wear is positive because a higher resistive force increases the tire wear. However, if a causal effect is made from the tire wear to the skid resistance, it shows a negative relation. This is because the more the tire is worn out, the less the resistive force will be as the tire won't be able to grip the road surface firmly.

- Balancing Loop B2

B2 shows the relation between the hard braking and tire wear. The causal relation from the hard braking towards the tire wear is positive because if the brakes of the vehicle are pressed hard, there will be more resistive force present in the contact area which in turn will remove rubber particles from the tire causing it to be worn out. Conversely, the causal effect from the tire wear and hard braking is negative because if the tire is not in good condition it is not possible to apply hard braking.

- Balancing Loop B3

B3 shows the relation between the phenomena rolling resistance and the tire internal temperature. The causal effect from the internal temperature to the rolling resistance is positive because a higher internal temperature will lead to more heat and energy losses from the concept of hysteresis which is a major cause of rolling resistance. At the same time, the relation from the rolling resistance to the temperature is negative because a higher rolling resistance will imply more dissipation of energy, which will increase the internal temperature thereby causing an opposite effect.

7.Possible Methods to Improve Each Phenomenon

The causal loop diagram gives a detailed overview of how different factors effects each phenomenon. Once the factors and their respective effects are discussed, it is equally important to mention possible ways of reducing the negative consequences associated with each phenomenon. This information will be beneficial for both industries (i.e., tire and road pavement construction and maintenance) as well as for the academic community. Hence, in this section possible strategies are discussed for each phenomenon.

7.1 Rolling Resistance

As mentioned earlier, rolling resistance is a resistive force that opposes the motion of the vehicle. The main variables effecting this phenomenon were explained in section 5.1 of this report, while their relationships have been shown in the CLDs. In this context, it is important to emphasize that the design of a tire plays a vital role in this phenomenon. A tire is generally made of polymers which are a combination of synthetic and natural rubber. Figure 9 provides an overview on how different tire components contribute to each phenomenon.

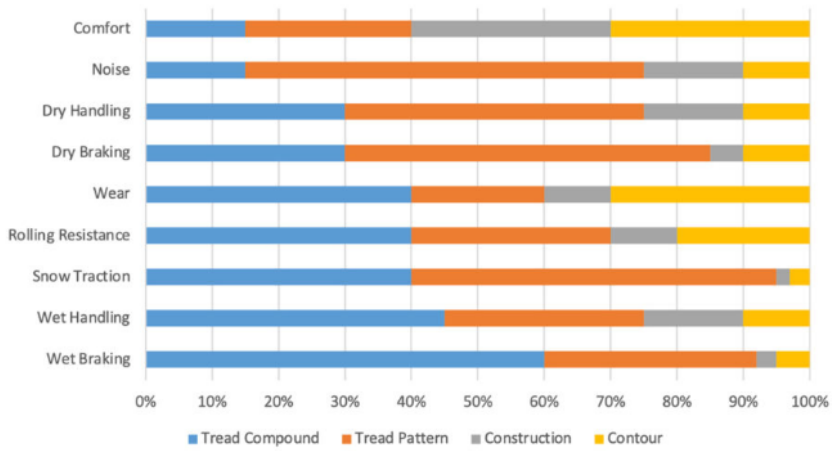

Figure 9: Tire components contribution to each phenomenon in % (Niknam, 2021).

It can be seen from figure 9 that tread compound contribute the highest for rolling resistance followed by tread pattern. The main ingredients of a tread compound involved in a viscoelastic behaviour are rubber, extender oil and filler. The rubber used in the tire shall be of low modulus E'' (which represents the stiffness of a material) and a high storage modulus E' (which represents the ability of a material to store deformation energy) to ensure less energy loss in the tires (Maghami, 2016). Secondly, fillers are designed to fill the tread compound's microscopic holes and improve overall tread compound performance. Two fillers, namely silica and carbon black, can greatly improve the rolling resistance and wear performance of the tire wear by lowering the hysteresis and strengthening the rubber.

Additionally, figure 10 shows the energy loss in different tire elements. It can be seen that the tire tread accounts for most of the energy loss. This is because the weight ratio of the tread rubber is greater than that of other parts. It is therefore reasonable to consider that reducing the energy loss in the tire tread is effective in reducing the rolling resistance. However, major changes in the tread properties can have an adverse impact on the road grip performance which can be quite risky for the users especially in the wet season.

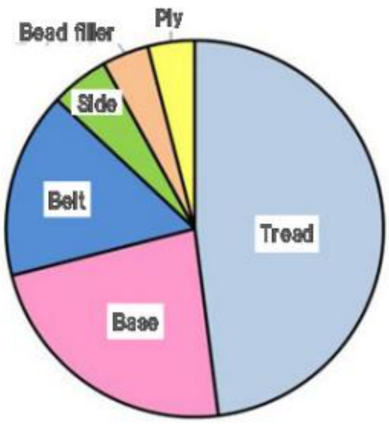

Figure 10: Energy loss in each part of the tire (Akutagawa, 2017)

Another possible way of reducing the rolling resistance consists of considering a tire structure design that discourages the deformation of the tire tread rubber. That can be achieved by increasing the diameter and the internal pressure of the tire. A high tire pressure leads to a rounder shape of the tire, which results in less deformation of the tire when it contacts the road surface. Moreover, narrowing the width of the tire can also help in the reduction of the energy loss. However, a smaller contact patch impacts the tire grip on the road. Therefore, an optimal solution shall be developed.

Finally, the road pavement properties are also equally important along with the tire properties. It was explained previously that a rougher surface leads to a higher rolling resistance. And the roughness of the surface depends on the asphalt compaction temperature and density, among others. So, the road industry should consider to laid down the asphalt at an optimal temperature and density during the construction of the road so that the chances of it becoming rough are minimized. Along with the initial phase, the maintenance phase after the road construction is equally important because the road tends to degrade. One possible way to minimize this degradation is the process of sweeping. Sweeping helps to remove sand and grit of the road surface, which can act as an abrasive. Generally, sweeping is recommended 2 to 6 times a year. Another important step to be taken in the maintenance phase is the crack filling. Cracks can form on a road surface whilst it is use. Hence, crack sealing can be done to prolong the life span of any road network as it won't allow any water to accumulate.

7.2 Skid Resistance

Skid resistance is a resistive force that prevents a vehicle from slipping hence reducing the chances of any unfortunate incident. Both the properties of tire and road play a vital role in causing this phenomenon. Several factors and variables have been mentioned in the sections above. Hence, improving this phenomenon is of utmost importance to provide more safety to the society and its users.

An important way of maintaining the skid resistant of the road surface is by a process called "surface texturing". This method includes the mechanical reworking of the existing surface to improve its frictional characteristics and therefore the resistance to skidding (Mason, 2009). It is a quick and cost-effective method of maintaining the resistant properties of the road surfaces by restoring the micro- and the macro-textures. Moreover, retexturing also helps to remove binders from bituminous surfaces in an environmentally friendly way. There are several ways to re-texture the road surface e.g., bush hammering and high-pressure water jet, etc. So, the road industry can possibly take this mechanism into account. Generally, it is performed after 5 years of road construction since the service life of an asphalt can be 15-18 years depending upon the conditions it is used in (Barr, 2020).

Finally, the tread compound, namely the tire bead, also plays a vital role in this phenomenon as it can be seen in figure 9. Tire bead is the inner circle of the tire and it connects the tire to the rim and hold the entire wheel together and prevents the tire from sliding as the wheel rolls. Therefore, it is quite important for the tire industry to select the right rubber for the tire bead to prevent the bead failure. The tire properties, and in particular the tire tread, are also relevant for this phenomenon. The tire tread provides a grip between the road surface and the tires. If the width of the tire tread is increased, it will eventually provide a stronger grip on the road surface, thereby reducing the chances of the tire skidding. However, the increase in the tread width is associated with the increase of resistance of the tire motion. Similarly, a wider tire will also help to maintain the resistive force but will eventually affect the rolling resistance.

7.3 Noise Emission

The reduction of the noise emission in the tire-road contact system is also equally important. Noise emission is often not appreciated by the road users and more importantly by the communities residing next to a road network. Therefore, ways to reduce the effect of this particular phenomenon are welcomed.

Firstly, a narrow tire design will substantially lower the noise emitted. This is because a narrower tire means that the contact patch between the road surface and the tire is also less and eventually it will result in less noise being emitted. Although it will lower down the noise level, it will adversely affect the road grip properties of the tire and also the skid resistance.

Furthermore, a tire also consists of a rubber side wall which mainly provides a right balance between the road and tire. The rubber side prevents the noise emission by absorbing it. Hence, if the rubber wall is made thicker it can greatly influence the noise emission by absorbing more and eventually less noise will be dissipated to the environment. Given that, the tread pattern accounts the most for the noise emission, it is important to modify its design pattern accordingly. This can be achieved by pattern randomization, which means to vary the tread design, which further helps to reduce tread impact concentrated at specific frequencies (Li, 2020). Secondly, another important element of tread pattern are the grooves. So, modification of the geometry and dimensions of grooves can also lower the noise that is emitted because the increase in the groove depth result in more air cavity hence increasing the air pumping.

As far as the road pavement is concerned, the reduction of the noise emission can be achieved by adding some sound-absorbing additives (i.e., rubber powder) to the asphalt mixture to enhance the elasticity and sound absorption ability. An alternative way consists of adjusting the design of mixture composition to improve the workability of construction, which can improve the texture by reducing the voids/spaces between each other, thereby further reducing he high frequency noise (Chen & Mulian Zheng, 2021).

7.4 Tire/Road Wear

The tire and road wear are the two phenomena that are particularly interrelated in the tire-road contact system, since the road wear can significantly damage the tire, and eventually resulting in the tire wear.

First of all, the road construction industry should pay attention to the drainage system of the road network, even before its construction. This is because water on the roads can affect its entire serviceability. Too much water in the base materials weakens the road pavement. It can also cause soil erosion and breakdown of pavement edges. Hence, a proper surface drainage system prevents the water from infiltrating the pavement surface and promotes its removal. Furthermore, a firm foundation should be built. Although most of the times the road pavements start deteriorating from the top, its deterioration process can also be prompted from the foundation. Thus, an adequate support ensures that the road pavement will not deteriorate rapidly. Also, a well compacted soil is a good practice to ensure a strong base. When the soil is improperly compacted, traffic loads or change in moisture content can cause a failure of the road pavement. So, well-graded soil should be used, as its even distribution of particle sizes are more easily compacted than poorly graded soils that have mostly one particle size (Vermont, 1984).

Moreover, the tread compound contributes to about 40% of the total tire wear. As mentioned earlier, the tread compound consists of several ingredients which are inter-related. Therefore, the tire industry could possibly focus on how the tread compound can be improved by choosing the right material for each particular component and understanding how one compound can affect the others. As far as the tire wear is concerned, a good quality tire will increase its durability. However, the main reasons for avoiding premature tire wear are in "drivers' hands". For example, the tire should be used at the right internal pressure along with the proper alignment. Furthermore, a low level of driving aggressiveness is of paramount importance to prevent premature tire wear.

8.Discussion

The CLDs provide an extensive overview of the tire-road contact system. It includes all the major phenomena and the variables-factors effecting each phenomenon. The respective factors show how their change can result in the change of the phenomena, either in a positive or negative way. Moreover, they also allow the identification of feedback loops, i.e., reinforcing, and balancing loops. These feedback loops provide key information on the actions that can eventually be undertaken by the tire or road industry to mitigate the negative aspects related to the tire-road contact system.

Moreover, all the existing links and the causal relations were not clearly evident. For instance, initially all the major phenomena were being studied separately, but extensive literature research helped in developing unforeseen links between them, e.g., the effect of skid resistance on the noise emission and the tire wear. In addition to it, the detail of several factors was also not known during the initial phase of the research. For example, pavement stiffness is an essential road characteristic, but it is too general to be written in a CLD. Hence, this factor was also studied in depth to know how it is affected by its counterpart variables.

Although a CLD is an efficient and easy way of explaining a system, it has several limitations. First of all, it does not distinguish the non-linear relationships which means there might be some indirect relations that are ignored in the CLD, hence making a CLD incomplete. Moreover, a CLD also does not distinguish between the physical and the information links. Lastly, it might lead to incorrect inferences about the dynamics, and therefore faulty models (Ali Mirchi & Kaveh Madani, 2012).

The CLD's shown in section 6 do provide some viewpoints for both the tire and road industry. First of all, for the road industry it is quite important to focus on the initial or construction phase of a road pavement along with the maintenance phase because the roads tend to degrade after several years. Therefore, it is quite important to perform safety test of the roads. Otherwise, it can have adverse effects on the users, communities and also on the industry itself. For the tire industry, the tire design itself is of immense importance, especially the tire tread and tread compound, as the tread compound contributes the highest for most of the phenomenon involved in the tire-road contact system. Similarly, tire tread is the second highest contributor to each phenomenon. Therefore, an ideal tread design should be made to ensure the negative effect on each phenomenon is decreased.

Lastly, it can be said that although the CLDs shown above already provide a comprehensive overview of the tire-road contact system, its comprehensiveness can be deepened by adding more variables-factors that were left out from the scope of this research due to time constraints.

9.Conclusion

The tire-road contact system is a comprehensive system which consists of several phenomena, which, in turn, are influenced by several factors. Causal Loop Diagrams (CLDs) are a promising solution to address such comprehensiveness and explain to a great extent the complexity of the system being studied. CLDs allow to understand the actual working mechanisms of a system and the outcomes associated with the circular cause and effect relationships. In addition to it, the feedback loops also hold a great influence in this project, because they illustrate how the different phenomena and variables are interrelated with each other and what sort of effect they impose on each other. This information is useful on one hand for helping the multiple industries involved in this system to improve their products, and on the other hand for helping academics to identify areas of research that were initially unseen or out of radar.

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Appendix A: References supporting the relationships depicted in CLD

Table 2: References for the factors effecting rolling resistance

Pavement stiffness	Doi: 10.1201/b17219-39
Tire inflation pressure	Doi: 10.1061/9780784480052.016
Surface roughness	Doi: 10.1061/(ASCE)0733-9399(2009)135:1(20)
Tire width	Doi: 10.1061/9780784480052.016
Tire internal temperature	Doi: 10.1007/s12239-018-0005-4
Tire/wheel alignment	Doi: https://doi.org/10.11351/jsaeronbun.43.1069
Bitumen stiffness and penetration index	Doi: https://doi.org/10.1080/14680629.2016.1159245
Water depth	Doi: 10.13140/RG.2.2.12407.75686
Normal load	Doi: https://doi.org/10.1016/B978-075065131-8/50009-9
Surface porosity	Doi: https://doi.org/10.1061/(ASCE)MT.1943-5533.0000999

Table 3: References for the factors effecting skid resistance

Surface roughness	Doi: 10.1061/(ASCE)0733-9399(2009)135:1(20)
Vehicle's load/mass	Doi: 10.1051/matecconf/201927504002
Tire load	Doi: 10.3141/2005-17
Wetness/Ice (on road)	Doi: https://doi.org/10.1007/s40799-018-0272-z
Tire slip angle	Doi: 10.3390/s18020490
Tire tread depth	Master's thesis: https://core.ac.uk/download/48635908.pdf
Aggregate characteristics	Doi: 10.3141/2104-03
Water film thickness	Doi: 10.13140/RG.2.2.12407.75686

Table 4: References for the factors effecting noise emission

Tire tread/grooves depth	Doi: 10.3390/designs2040038
Surface roughness	Doi: 10.1061/(ASCE)0733-9399(2009)135:1(20)
Tire inflation pressure	Doi: https://doi.org/10.1016/B978-0-12-818409-7.00006-4
Void index	Doi: 10.1016/j.ijsbe.2016.02.001
Tire/ wheel alignment	https://www.lesschwab.com/article/wheel-alignment-faq.html
Rubber side walls in a tire	Doi: https://doi.org/10.2346/tire.18.460412
Rubber hardness	Doi: https://doi.org/10.2346/tire.18.460412
Hard braking	https://cartreatments.com/noise-and-vibration-when-braking/
Tire width	Doi: https://doi.org/10.1016/B978-0-12-818409-7.00006-4

Wetness	https://www.oponeo.co.uk/blog/tyre-labelling-faq

Table 5: References for the factors effecting tire/road

Surface roughness	Doi: 10.1061/(ASCE)0733-9399(2009)135:1(20)
Vehicle velocity	Doi: 10.1177/1687814017700063
Tire alignment	Doi: 10.1515/scjme-2017-0013
Surface porosity/water depth	Doi: 10.1002/jctb.518
Hard braking	Doi: 10.1177/1687814017700063
Tire inflation pressure	Doi: 10.1515/scjme-2017-0013
Surface temperature	Doi: 10.1007/978-3-642-36199-9_312-1
Vehicle load	https://www.bridgestonetire.com/tread-and-trend/drivers-ed/tire-tread-wear-causes