Proceedings of the 2017 International Symposium on Industrial Engineering and Operations Management (IEOM)
Bristol, UK, July 24-25, 2017

Conceptualization of a New Product Development Framework for Eddy Current Braking Systems for Heavy Vehicles in Zimbabwe

Wilson R. Nyemba
Department of Mechanical Engineering Science, Faculty of Engineering and the Built Environment, University of Johannesburg, Auckland Park 2006, Johannesburg, South Africa
nyemba@yahoo.com

Chris Pote, Tauyanashe Chikuku
Department of Mechanical Engineering, University of Zimbabwe, P O Box MP 167, Mount Pleasant, Harare, Zimbabwe
cpote25@yahoo.com, tauyanashec@yahoo.co.uk

Charles Mbohwa
Professor of Sustainability Engineering, Department of Quality and Operations Management & Vice Dean for Research and Innovation, Faculty of Engineering and the Built Environment, University of Johannesburg, Auckland Park 2006, Johannesburg, South Africa
cmbohwa@uj.ac.za

Abstract

One of the most critical requirements for safety in vehicles is the availability of reliable braking systems. Most heavy vehicles in Zimbabwe employ the conventional hydraulic braking system. However changes and improvements in technology have seen the introduction of retarders that make use of magnets and eddy currents. The new technology is friction free but still deemed expensive and thus not yet readily acceptable to vehicle manufacturers for fears of reliability and cost. Hydraulic brakes are equally expensive in the long run owing to maintenance and frequent replacement of brake pads and rotors, particularly in Zimbabwe where the road infrastructure has deteriorated significantly over the years. A case study was carried out at a Zimbabwean company which specializes in the sales, service and backup of Scania heavy vehicles, with a special focus on the braking systems. The aim of the research was to conceptualize and compare various options and concepts of the eddy current retarders. Analysis for the chosen option were made for reliability and efficiency using an industrial engineering approach, with the objective of supplementing hydraulic brakes and recommending the sustainable use of such technology to the company and thereby dispelling any fears of reliability and cost.

Keywords
Brakes, Conceptualization, Eddy current, Heavy Vehicles, Sustainability

1. Introduction

Zimbabwe’s road infrastructure network has been deteriorating over the years owing to a number of reasons such as economic, political or natural disasters, to the extent of serious disrepair. This has been exacerbated by the incessant rains caused by Cyclone Dineo, towards the end of 2016 and most of the early part of 2017 resulting in floods and extensive damage to the road network. The rundown of the road network has become extremely dangerous to road users (Tshuma, 2016). The excessive damage, as shown in the collage on Figure 1, pushed the government to declare the capital, Harare’s roads a state of national disaster in terms of the Civil Protection Act (Ruwende, 2017). The damage to the roads has been a combination of all 3 factors; economic, political and natural disasters and thus cannot be regarded as a seasonal challenge that will be resolved after the rains, as these have continually deteriorated over the years. Apart from the dangers to road users of such a road network, serious challenges are also posed to the vehicles in terms of wear and tear, suspension and braking systems. Most vehicles on Zimbabwe's roads use the hydraulic braking system which relies on friction materials and the more the vehicles brake, as expected in such a road network, the more maintenance is required and the faster the friction materials wear off, requiring replacement. This type of braking system has both technical and economical disadvantages, especially in hybrid vehicles. The disadvantages include fading, complex and slow actuation, significant wear, lack of fail-safe features, increased fuel consumption due to power assistance and requirement for anti-lock controls. In recent years, some of these challenges have been resolved by developing contactless and friction-free magnetic brakes (Karakoc et al, 2016). This technology comprises a novel flux-shunting structure to control the excitation flux generated by permanent magnets. This type of brake is almost wear-free, less sensitive to temperature than friction brakes, fast and simple actuation, and reduced sensitivity to wheel-lock.

Figure 1. State of Zimbabwe's Roads in 2017.

This research was motivated by observations made at the heavy vehicle service company where there were frequent replacements of brake pads and rotors due to wear and tear, hence the need to find ways of reducing this occurrence. However in view of the bad state of the roads, the use of friction brake pads alone, vehicle owners would still face the challenge unless the roads are completely rehabilitated, a target which is unforeseen in the near future. Eddy current braking systems provide a significantly large percentage of the braking force which can lead to a reduced amount of kinetic energy dissipated as heat at the friction pads thereby lowering their wear rate. It is however important to note that eddy current braking systems are contactless, implying that they are almost wear-free and there would be no need for frequent replacements such as witnessed with hydraulic brakes, hence a lot cheaper to maintain (Lee & Park, 1999). These are the main attractions for using electromagnetic retarders, despite their initial cost (Yasa et al, 2016). Additionally, the eddy current braking systems can be incorporated to provide supplement braking force to the friction brakes. The combination of two different braking torque sources will compensate for loss of effectiveness for both of them at extreme temperatures while the friction brake pads are kept cool to increase effectiveness (Karakoc et al, 2012). Although wheel locks are mainly characterized by emergency braking from friction brakes, eddy current brakes are capable of reducing wheel lock sensitivity due to the fact that friction brakes are applied at lower speeds after the eddy current retarder has been applied, for which wheel lock effects are much less at lower speeds than at higher speeds. This is also because eddy current braking systems respond rapidly to control inputs compared to friction brakes, hence the eddy current brake's control system is capable of preventing wheel-lock with much less complications compared to friction brakes.

Eddy current brakes also directly depend on their excitation magnetic field. Mechanical systems response time is much higher than that of electromagnetic braking systems, quite common in pneumatic brakes and power assisted systems (Gay, 2005). Traction control, dynamic stability and Anti-locking Braking Systems (ABS) demand short response times to achieve a safer and precise vehicle control. The characteristic of fast response time associated with eddy current brakes makes them more suitable for interfacing with such electronic driving aids (Gay, 2005). Relying mainly on eddy current brakes lowers the braking force needed from friction braking. As a result, power assistance requirement will be lowered, hence reduced fuel consumption from power assisted actuators. Vacuum assistance and hydraulic actuation are replaced by electric actuation which draws power if actuation is needed (Karakoc, 2012). Even if frictional braking systems are compact, effective and still trusted by many, their advantages can easily be outweighed by those of electromagnetic brakes in the long run after building confidence with the users but more so for badly damaged roads such as the case in Zimbabwe where drivers are required to brake more frequently than on smooth roads where the wear and tear will be much less. The aim of this research was to conceptualize the various options available for electromagnetic braking systems that utilize eddy currents and then using the best option, develop ways to incorporate these to work in conjunction with hydraulic brakes so as to ensure minimal loss of friction materials. The main objective would be to reduce the vehicles' maintenance costs and also prolong their life in view of the extensive damage to the road network in Zimbabwe. However, even in developed countries with smooth road networks, the use of electromagnetic retarders provide a good supplement for friction brakes.

2. Background and Literature Review

The friction braking principle in hydraulic brakes is dissipative in that kinetic energy of the vehicle is dissipated as thermal energy at the surface in contact between the disc and brake pads. The dissipated kinetic energy leads to a very significant temperature rise of the pads and discs. Despite the fact that a large fraction of the thermal energy is dissipated by forced convection with the cooling fins on the disc, the braking phase time involves temperature rise of the pads and disc. The coefficient of friction between the disc and the pads depends on temperature, as shown on Figure 2, which in turn affects the obtainable braking force (Gay, 2005). The reduction in braking force at elevated temperatures leads to "brake fading" usually encountered when trying to control a vehicle descending a long and steep gradient at high speed due to the supplementary force from the vehicle weight and the gradient (Boisvert et al, 2013). In some cases, all the braking capability is lost and the vehicle becomes totally brakeless. Disc warping may also result from very high disc temperatures upon sudden braking. The combined consequences of heat, friction, exposure to dirt and water leads to pads abrasion. Hence, pads need to be constantly changed and sometimes resurfacing of rotors is required. The cost of maintenance personnel and new pads is significantly high in heavy-duty vehicles such as buses and trucks (Fancher et al., 1981) that the case study company specializes in. The dust from the pads is also harmful to the workers during the process of replacing brake linings and the process is time consuming (Gay, 2005).

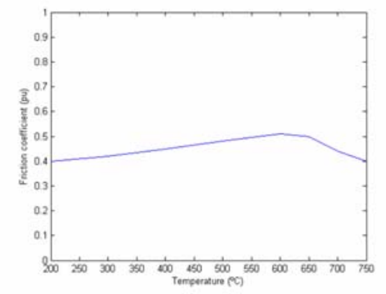

Figure 2. Coefficient of friction and temperature between disc and pad

Fast moving and/or heavy vehicles demand significantly huge braking forces to completely stop the vehicles and sometimes this is beyond operator capability. This has prompted the need for power assistance mechanisms on road, air and rail vehicles (Lu et al, 2014 and Puttewar et al, 2014). This assistance mechanism is usually hydraulic for aircraft and diesel vehicles or pneumatic for trains and gasoline vehicles. The involvement of many parts from the assistant mechanisms significantly increase complexity. There is also increased fuel consumption due to the pumps installed on diesel vehicles. This is because hybrid vehicles require aiding pumps to ensure assistance even if the engine is turned off. Furthermore, there is a propagation time which results from the assistance mechanism, causing a considerable delay to the brake application from the instant the driver commands a stopping force on the pedals. This associated delay is much larger in trucks, trains and buses since the brake fluid tubes are much longer. Brake application delay is associated with an increased braking distance and control complexity. Brake controls are also needed for balancing braking forces available at front and rear axles with such factors as vehicle speed, load and road conditions considered, while wheel-lock is prevented. There is an additional non-linearity in the frictional braking systems as a result of the non-linear contact between the disc and pads and/or delays in fluid linings resulting in an affected brake control delicate (Fancher et al., 1981). In an effort to overcome all these disadvantages of friction brakes, the concept of frictionless brakes was developed based on the eddy current brake that helps the friction brakes with the overall objectives and advantages of; reduction in friction pads wearing and wheel lock and fading sensitivity, improved and faster control dynamics, ease of integration with other electronic driving aids of the vehicle and reduced fuel consumption.

Road, air and rail vehicles largely depend on mechanical friction brakes. Components of these brakes can be classified into two main functional groups; a stator firmly connected to the chassis and a rotor fixed to the wheels of the vehicle. The rotor comprises of a disc or a drum mostly made from carbon fiber in the case of aircrafts and cast iron in the case of rail and road vehicles. The stator can either be the pads for disc brakes or shoes for drum brakes which are made from soft frictional material and mostly a hydraulic piston actuator. Both disc and drum brakes work on the principle of friction, therefore the terminology that will be used will refer to the disc brake. A high coefficient of friction will result from the contact between the rotor surface and brake pad soft material. When a driver commands a braking force, the pads are pressed against the rotor by an actuator, thereby inducing a frictional force which is tangential to the rotor surface. This frictional force opposes vehicle motion as shown in Figure 3. This braking force (F) is directly proportional to the coefficient of friction (μ) and the developed normal force (N) (equation 1) when the pads are pressed against the rotor by an actuator (Gay, 2005).

$$F_{braking} = \mu . N_{actuator} \tag{1}$$

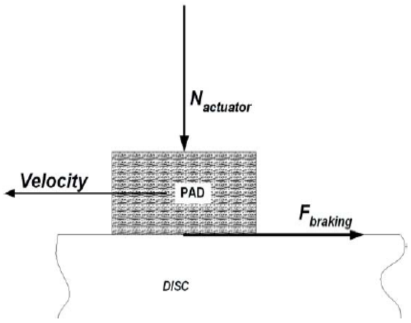

Figure 3. Forces on Friction Braking

Eddy currents are produced due to changes in space and time of magnetic flux cutting across nonferrous conducting metals. This scenario is according to both Faraday's law and Lenz's law of induction (Karakoc et al, 2016). Faraday's law states that when a voltage (emf) is induced in a coil it experiences a time changing magnetic flux. The generated emf tends to produce a current with a magnetic field that opposes this change according to Lenz's law (Hayt & Buck, 2012). Eddy current brake units comprise of a stationary magnetic flux source (electromagnet or permanent magnet) placed in front of a rotating electrical conductor (metal drum or disc). Due to this rotation, a time-changing magnetic flux density is experienced by the conductor, and according to Lenz's law, an electric field is being experienced (equation 2):

$$\nabla \times E = -\frac{\Delta B}{\Delta t} \tag{2}$$

According to Ohm's law, this electric field leads to swirling currents (eddy currents) in the conductor (equation 3):

$$J = \sigma . E \tag{3}$$

The interaction between the generated flux density and these eddy currents results in an induced force which opposes direction of rotation as shown in Figure 4 (Gay, 2005) (equation 4):

$$F = J \times B \tag{4}$$

Where B is flux density, V is tangential velocity of rotation, F is the generated force, σ is the material surface conductivity, and J is the eddy current.

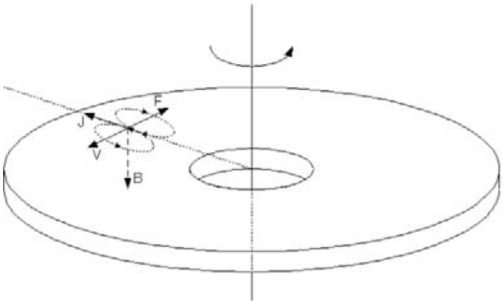

Figure 4. Eddy current brake concept

If permanent magnets are used, the braking torque magnitude, τ_{diss} (Nm) can be derived theoretically as a function of magnetic core diameter, D(m), mean radius, R(m), angular velocity, θ (rad/s), disc thickness, d(m), magnetic field, B(T), material specific conductivity, σ(1/Ω.m), number of magnets, n(#) (Hollowell et al., 2010). In this case torque is expected to vary linearly with the angular velocity but this is not the case in equation (5). It was assumed that the induced magnetic field is significantly smaller relative to the primary magnetic field. From experiments it proved that the braking torque only varies with angular velocity at low speed.

$$\tau_{diss} = n\frac{\pi\sigma}{4}D^2 dB^2 R^2 \dot{\theta} \tag{5}$$

The eddy current braking system in vehicles is usually fitted on the vehicle transmission shaft. Telma induction brakes are some of the earliest electromagnetic retarders that were developed to offer an endurance braking effect by dissipating a large part of the braking energy and in the process assisting conventional hydraulic braking systems (MotorIndia, 2012). The Telma retarder comprises of eight iron core electromagnets with interchanging polarity, arranged in a circular array and having a face of two cast iron rotors on both sides. Braking energy is dissipated through forced convection by the cooling fins on the back of the rotor. The iron ring located on the rotor, the cheek is responsible for the rotor's mechanical rigidity. Rated excitation current lies within the range of 70-90A (Gay, 2005). A novel eddy current braking unit replaced permanent electromagnets with rare earth permanent magnets which provide a compact magnetic flux source compared to electromagnets. Neodymium Iron Boron is the commonly accepted permanent magnet material due to its compactness, affordability, lightness and the ability to produce a powerful flux source (Thompson, 2015). Magnet preservation from hot rotors and controlling flux magnitude have remained the limiting factors when using permanent magnets. Rotated magnetic structure and the shunted magnetic structure have been developed to control flux. A Telma electromagnetic retarder is shown in Figure 5, adapted from Telma, 2015.

Fig. 5: Electromagnetic retarder manufactured by Telma

The rotated magnetic structure consists of a magnet that can be rotated between the position of alignment and quadrature to the magnetic circuit. Permanent magnets offer their total flux through an air gap on alignment position to the magnetic circuit. The magnetic circuit short-circuits the flux and prevents it from reaching the air gap when permanent magnets are in a quadrature position (Gay, 2005). The alignment and quadrature positions of the rotated magnet structure are shown in Figure 6.

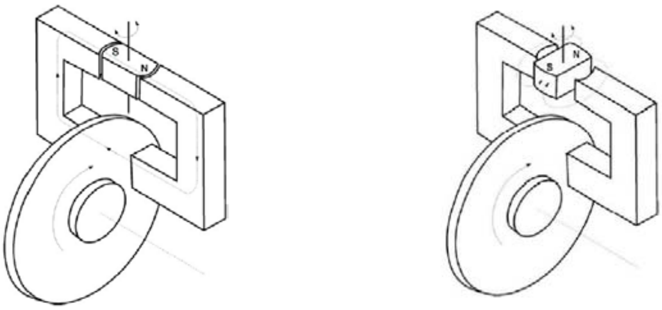

Figure 6. Rotated magnetic structure

In the shunted magnetic structure as shown in Figure 7, a permanent magnetic circuit is short circuited by bypassing the air gap with a ferromagnetic bar (Gay, 2005). Air gap flux density is linearly varied from zero to maximum achievable by moving the ferromagnetic bar between shunting and non-shunting positions (Thompson, 2015).

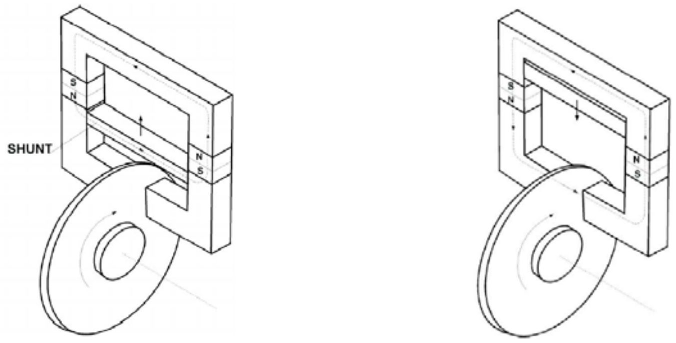

Figure 7 Shunted magnetic structure

Both designs keep the magnets a distance away from the air gap thereby ensuring thermal protection and a room for inserting a thermal insulator. Thus, variable geometry magnetic circuits are cost effective, simple and compact. They are also able to control flux from permanent magnets in a limited amount of time. However, while the Telma induction brakes offer effective means of supplementing friction brakes and thus reduce friction loss materials leading to less maintenance and infrequent replacement of brake pads, there are a number of challenges that need to be resolved. Having looked at the introduction of electromagnetic retarders and the various advantages they bring to the heavy vehicle industry, this research revolves around the conceptualization and analysis of the various options that electromagnetic retarders offer and then answers the research questions on whether this technology can cope with the state of dilapidation in Zimbabwe's road network, focusing on modifications and improvements that can be incorporated in the standard design for such braking systems to enhance their ability to withstand the damaged roads.

3. Research Methodology and Analysis of Concepts

In view of the availability of established electromagnetic braking systems and the challenges associated with conventional hydraulic friction brakes which are the commonly available brakes in most vehicles in Zimbabwe and the state of roads, the research dwelt on analyzing the possible concepts around the electromagnetic braking technology to recommend on improvements to come up with feasible and sustainable systems that can be used on the country's roads to ensure less maintenance and infrequent changes of brake pads. The following concepts were derived to overcome these challenges. The drawings and models in this paper were developed using AutoCAD 2012, Fusion 360 or Solid Works depending on the type and these are annotated in the following sections.

3.1 Concept 1: Use of Electromagnets on the Drive Axle

This concept, as shown in the model on Figure 8, developed in AutoCAD 2012, consists of two main components, the rotor (grey) with cooling fins mounted on the drive axle and the stator (red), which is composed of small magnetic coils, fixed on the vehicle chassis. When the brake is actuated, the coils will produce magnetic field lines (red) as shown on the cross-section in Figure 8. A braking force is induced in the rotating disc which acts in opposite direction to the disc according to Lenz's laws (Jou et al, 2006). This concept provides fast control dynamics and can easily be integrated with other electronic driving aids of the vehicle at maximum rigidity. However, the coils can be exposed to heat generated by the rotor and the force may not be adequate to completely halt the vehicle as the surface area over which the eddy currents act, is limited.

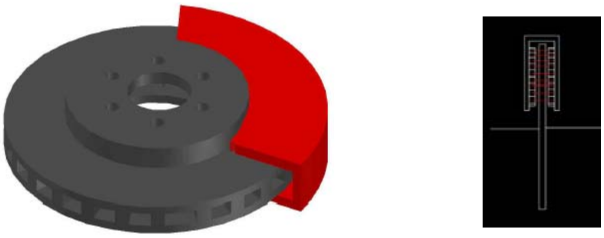

Figure 8. Concept 1: Electromagnets on Drive Axle

3.2 Concept 2: Use of Electromagnets on the Transmission Shaft

In this concept, the eddy current retarder could be fitted to the transmission shaft, drive shaft or drive axle of the vehicle. It consists of eight interchanging iron core electromagnets in a circular arrangement (red) as shown in Figure 9, developed in AutoCAD 2012. Two rotors are located at both ends of the retarder (grey) below and are connected to the transmission shaft rotating with it at the same speed. When the electromagnets are actuated by high direct currents from the battery, they produce magnetic lines as shown in the cross-section on Figure 9. The interaction between the generated flux density and the resulting eddy currents provides an induced braking force which opposes direction of rotation. In this concept, sensitivity to high temperature is reduced and it can easily be controlled by the excitation current providing maximum rigidity. However, the excitation current must be large enough to provide a sufficient braking effect. There is also possible excessive heating of the coils and high conductor ohmic losses and thus limited failure safety (Modi & Bhavsar, 2015).

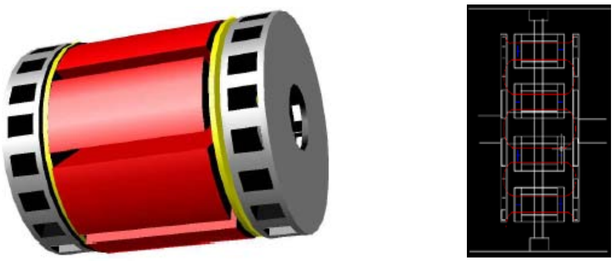

Figure 9. Concept 2: Electromagnets on Transmission Shaft

3.3 Concept 3: Use of Permanent Magnets

This concept incorporates permanent magnets and a rotating disc as shown on the snapshots in Figure 10, developed in AutoCAD 2012. Back iron and permanent magnets ensure a closed circuit. The top ring of the permanent magnets is attached to back iron which is firmly rigid to the stator. The bottom ring of the permanent magnet is attached to the back iron which can be rotated slightly to allow one degree of freedom to the magnetic ring. This rotation presents the same or different polarity of magnets from opposite sides to the rotating disc. Thus the permanent magnetic rings can short circuit each other thereby providing the ability to turn on or off the flux in the air gap. In this concept, the magnetic field is produced by the permanent magnets which are stationary with respect to the rotating disc, hence the opposing force acts on the rotating disc thereby dissipating its associated kinetic energy into thermal energy. The excitation current required in this concept is much less compared to the other two and hence, low eddy current braking, less conductor ohmic losses and average inertia. Although this concept will be simpler to build than the other 2, the close proximity of the magnets to the rotating disc implies that the permanent magnets are less preserved from the heat generated by the rotating disc. Linear variation of flux between the *on* and *off* positions may be difficult to attain. This concept has limited surface area for concentric magnetic rings and thus prone to fatigue failure owing to cyclic loading in the *on* and *off* positions resulting in limited rigidity.

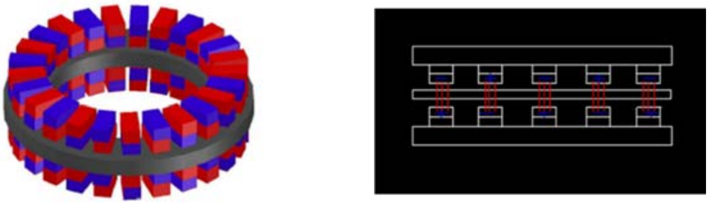

Figure 10. Concept 2: Use of Permanent Magnets

3.4 Concept Development

The objective of using permanent magnets is to eliminate the problem of using a high current in the electromagnetic braking system but achieving the same braking torque and frictionless brakes as the Telma brakes. This can be challenging in that repulsive forces are set whenever the brake is in the *off* position. Therefore the brake gives its maximum braking torque in the *on* position and zero torque in the *off* position without being able to vary braking torque between these two extremes. Stresses are induced in the back iron stator due to repulsion of magnets in the *off* position of which attention is required. The actuating mechanism and cyclic stresses due to repulsive and attraction of magnets in the *on* and *off* positions are prone to fatigue failure hence it must also be taken into design consideration. The other aspects necessary to develop and improve the concept are; paying attention to repulsive forces which are set in the *off* position, linear variation of magnetic flux between maximum and zero torque to be developed, cyclic stresses due to the *off* and *on* positions which may result in fatigue failure must be eliminated in the developed solution and a proper heat dissipation rotor design to be introduced.

4. Results, Development and Analysis of Chosen Concept

Using a weighted objectives criteria, concept 3 which utilizes permanent magnets was chosen and developed further to incorporate some of the positive attributes from the other 2 concepts, while improving on the identified and highlighted shortfalls in the use of permanent magnets. Repulsion and attraction of magnets in the *off* state of the brake is an unfavorable situation in the design since the stator will be subjected to alternating loads which would normally result in fatigue failure of the fixed point of the stator. To minimize this, magnets are arranged with poles perpendicular to the disc surface instead of being parallel as shown in Figure 11(a), developed using Fusion 360. The red and blue parts of the magnets are the north and south poles and with this magnetic orientation, there will be no repulsion of magnets in the *off* state. However there will be considerable repulsion of magnets in the *on* state since the same polarity of magnets will face each other as shown in Figure 11(b), also developed using Fusion 360 and the repulsions cancel each other out because the direction of repulsive forces is opposite around the whole stator. It was also important to note that most of the time, the retarder is in the *off* position, and hence this cancelation of repulsive forces is of little effect compared to the repulsive and attractive forces as initially observed in concept 3. Thus, the repulsive and attractive forces would have been successfully dealt with.

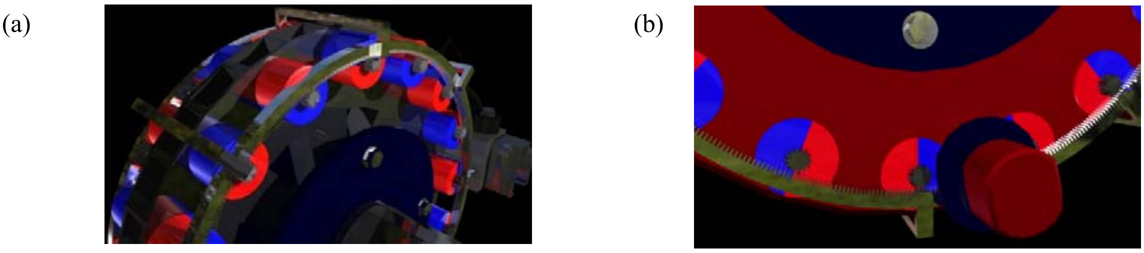

Figure 11 New magnetic orientation of retarder in (a) *off* state and (b) *on* state

One of the shortfalls for concept 3 was the difficulty in attaining linear variation of retarding torque. The magnets only provide their maximum flux in the *on* state of the retarder and zero in the *off* state without being able to vary it linearly. As a result only two torque values will be present, that is maximum and minimum in *on* and *off* positions respectively. With the new magnetic orientation, shape flux will now be able to be varied linearly between the *on* and *off* positions. This is achieved by providing angular displacement of magnets between these positions using an actuating motor. The magnets will therefore be rotated between 0 and 90 degrees. Angular positions of magnets between 0 and 90 degrees correspond to a certain fraction of flux cutting across the disc hence braking torque is varied. Different angular positions of magnets from 0 to 90 degrees and the magnet movements from quadrature to alignment position can thus be attained. Figure 12 shows snapshots of the finite element model of the flux movement in the *on* and *off* positions derived from the analysis using Solid Works.

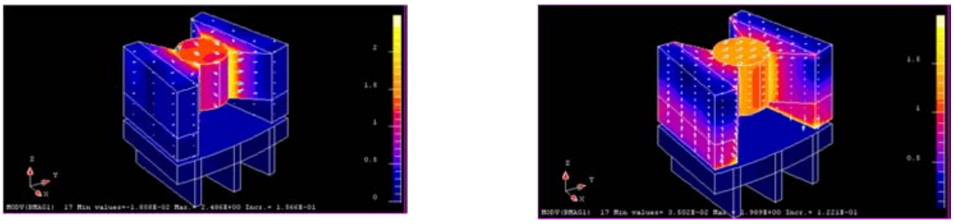

Figure 12. Magnetic flux movement in *on* and *off* positions

For the actuation mechanism, the rotation of magnets is achieved by using a circular rack geared to pinions on each of the magnets. The circular rack will also be connected to an electric motor such that when the motor is powered, it turns the circular rack which will in turn move the magnets connected to it in equal angular displacements. The rotating disc should be capable of dissipating heat properly to avoid overheating which will cause warping of the disc and loss of magnetization power. The disc design will incorporate cooling fins and supporting arms. A flange coupling will be suitable for the connection of the disc to the transmission shaft. The recommended design was therefore a combination of positive attributes from the other 2 concepts while the chosen concept was developed and modelled further using Solid Works. The final design and developed concept is shown in the 2 models in Figure 13, developed using Fusion 360, with the stator and exploded casing while Figure 14 shows the proposed location of the electromagnetic retarder on the transmission shaft of a truck.

Fig. 13: Developed concept with stator and exploded casing

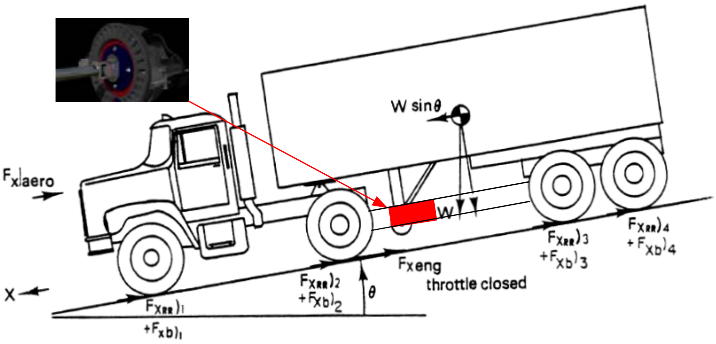

Fig. 14: Location of proposed retarder on the transmission shaft

Table 1. Estimated Bill of Quantities for the Proposed Retarder

Item	**Description**	**Size**	**Material**	**Quantity**	**Unit Cost**	**Total Cost**
1	Motor	316 W	NA	1	USD 135,00	USD 135,00
2	Circular Rack	Φ 346 mm	Bronze	2	USD 50,00	USD 100,00
3	Permanent Magnets	Φ 40 mm	Neodymium Iron boron	32	USD 6,00	USD 192,00
4	Casing		Aluminum 6061	2	USD 35,00	USD 70,00
5	Stator		Silicon Iron	2	USD 35,00	USD 70,00
7	Flange Coupling	Telma yoke part	Steel	2	USD 85,00	USD 170,00
8	Pins	1/8" X 1" dowel	Steel	4	USD 8,00	USD 32,00
9	Motor holder		Steel	1	USD 10,00	USD 10,00
10	Rectangular key	108 x 28 x 16 mm	steel	1	USD 9,00	USD 9,00
11	Bronze Bar - racks	400 x 20x 15 mm	Bronze	8	USD 7,00	USD 56,00
12	Bolts	Bolts ¼-20 1"	Steel	8	USD 4,00	USD 32,00
13	Shaft	Φ 100 mm	Steel	1	USD 75,00	USD 75,00
14	Rotor Disc	Φ 460mm x 50 mm	7075 Aluminum	1	USD 135,00	USD 135,00
15	Retarder Socket		Plastic	1	USD 8,00	USD 8,00
16	Cable	500 mm	Copper	1	USD 15,00	USD 15,00
17	Socket screw	¼-20 6" cap screw	Steel grade 8	2	USD 1,00	USD 2,00
18	Spacer washer	Φ 1" x Φ 1.25" 1/32	Aluminum	4	USD 2,00	USD 8,00
19	Bracket	Thickness 13	Steel	2	USD 11,00	USD 22,00
20	Bracket Bolts	Bolts ¼-20 1"	Steel	4	USD 2,00	USD 8,00
21	Gears on magnets		Bronze	4	USD 32,00	USD 128,00
22	Worm Gear		Bronze	1	USD 15,00	USD 15,00
23	Worm Gear Shaft		Steel	1	USD 26,00	USD 26,00
24	Nuts on flange yoke	¼-20 flange nuts	Steel	4	USD 3,00	USD 12,00
					Sub Total	**USD 1 330,00**
					Labour (Approximately 30% of materials)	**USD 399,00**
					Overheads (Approximately 20% of materials)	**USD 266,00**
					Total	**USD 1 995,00**

The bill of quantities for producing the proposed electromagnetic retarder is given in Table 1 showing an estimated cost of $1,995.00. Performance evaluation for the developed chosen solution was based on the torque magnitude from equation (5) using the various parameters and designed values and dimensions, some of which were obtained from literature.

$$\text{Braking torque } \tau_{diss} = n\frac{\pi\sigma}{4}D^2dB^2R^2\omega$$

$$\tau_{diss} = 16\times\frac{\pi\times35500}{4}\times0.04^2\times0.05\times1.2^2\times\frac{0.346^2}{4}\times = 17\ 842Nm$$

The target braking torque for controlling a 26,500 kg bus at 30km/hr was 8 220.07Nm (Gay, 2005), hence the derived torque from the proposed design provides a sufficiently safe mechanism. In the event that a higher torque is required, the proposed retarders can be mounted in series.

5. Discussion and Recommendations

The proposed eddy current retarder consists of a number of components which are pivotal in the braking system of heavy vehicles. Attention was paid on the retarder mechanical design to ensure that its interface with other driving aids and controls were synchronized. Braking on the transmission shaft may cause uneven braking distribution on the vehicle which results in locking or skidding. The designed eddy current retarder system has to be equipped with the electronic interface which will work with ABS on the vehicle to automatically turn off the eddy current retarder in the event of skidding or locking allowing the ABS to control the friction brakes with no interference from the retarder, after which the electronic interfacing system should reactivate the retarder progressively for proper braking. Connection designs are also recommended as effective controls especially mountainous terrain where the retarder activation is on long gradients, an independent brake pedal control is required. This can be built either in the dashboard or mounting to the steering column to enable the activation of the retarder in the different positions. An accurate thermal model is also required for modelling the conductive, convective, and radiant heat transfer in the brake. The modelling of the gradients inside the brake may also be necessary for accurate performance prediction, especially in heavy duty applications where the brake heats up significantly and fast response is required. The results can be used to determine the importance of these gradients and uneven and damaged roads. The retarder should also be preserved from the metal debris since this will be attracted by the magnets and may result in malfunctioning. Further research, fabrication and experimentation with the prototype of this conceptual model may be useful to determine practical performance against the proposed model. Regular maintenance and checking as well as pressure washing periodically will ensure that the retarder is free of debris and hence longer life spans, the exact periods of which vary depending on the usage of the vehicles. Further analysis of the application of the integrated brake in heavy vehicles can be pursued by using complete dynamic models of the vehicles and actual driving situations to give precise understanding of the dynamic operation of the integrated brake in anti-lock, traction, dynamic stability control applications and allow for a complete design of the integrated brake controller.

6. Conclusions

This research was motivated by observations made at a company that specializes in the service and backup support for heavy vehicles. The frequent servicing and replacement of hydraulic friction brakes purportedly owing to the damaged road infrastructure in Zimbabwe required innovative solutions to cut down on the costs for maintenance. Based on the developed concept for electromagnetic brakes, 3 concepts were analyzed and the chosen option was developed further to incorporate positive attributes of the other concepts coupled with improvements leading to the proposed frictionless electromagnetic retarder that employs permanent magnets mounted on the transmission shaft of the vehicle to supplement the hydraulic friction brakes as well as reduce the amount of wear on the brake pads and their frequent replacement. Analysis of the proposed design showed that it would be able to provide sufficient braking torque to control a heavy vehicle such as a bus or truck. The estimated cost of the proposed retarder was $1,995.00, a reasonable amount that can adequately be covered by the savings on maintenance costs. However, further work will be required to develop the proposed design into a prototype that can be experimented on to determine practical performance on different terrains and road conditions.

Acknowledgements

The authors are grateful to the service company for allowing access to their operations to carry out this research and indeed hopeful that the company will adopt the proposed electromagnetic retarder for their heavy vehicles.

References

Boisvert, M., Mammosser, D., Micheau, P., and Desrochers, A., Comparison of two strategies for optimal regenerative braking, with their sensitivity to variations in mass, slope and road condition, *Proceedings of 7th IFAC Symposium on Advances in Automotive Control The International Federation of Automatic Control*, pp 626-630, Tokyo, Japan, September 4-7, 2013.

Fancher, P.S., O'Day, J., Bunch, H., Sayers, M., Winkler, C.B., *Retarders for Heavy Vehicles: Evaluation of performance characteristics and in-service costs*, Technical Report for the Highway Safety Research Institute, Michigan, 1981.

Gay, S.E., *Contactless Magnetic Brake*, Texas A&M University, Texas, 2005.

Hayt, W.H, and Buck, J.A., *Engineering Electromagnetics 8th Edition*, McGraw Hill, New York, 2012.

Hollowell, T.C., Kahl, J.T., Stanczak, M.D., and Wang, Y., *Eddy Current Brake Design for Operation with Extreme Back-drivable Eddy Current Motor*, University of Michigan, Michigan, 2010.

Jou, M., Shiau, J.K., and Sun, C.C., Design of a magnetic braking system, Journal of Magnetism and Magnetic Materials, vol. 304, pp 234–236, 2006.

Karakoc, K, Suleman, A., and Park, E.J., Analytical modeling of eddy current brakes with the application of time varying magnetic fields, *Applied Mathematical Modelling*, vol. 40, pp 1168–1179, 2016.

Karakoc, K., Park, E.J, and Suleman, A., Improved braking torque generation capacity of an eddy current brake with time varying magnetic fields: A numerical study, *Finite Elements in Analysis and Design*, vol. 59, pp 66–75, 2012.

Lee, K. and Park, K., Optimal robust control of a contactless brake system using an eddy current, Mechatronics, vol. 9, pp 615-631, 1999.

Lu, X., Li, Y., Wu, M., Zuo, J., and Hu, W., Rail temperature rise characteristics caused by linear eddy current brake of high-speed train, Journal of Traffic and Transportation Engineering, vol. 1, no. 6, pp 448-456, 2014.

MotorIndia, Telma thrust on Indian Retarder Market, Component Zone Feature in *MotorIndia Magazine*, Chennai, Dec 2012.

Puttewar, A.S., Kakde, N.U., Fidvi, H.A., and Nandeshwar, B., Enhancement of Braking System in Automobile Using Electromagnetic Braking, IOSR Journal of Mechanical and Civil Engineering, vol. 11, pp 54-59, 2014.

Ruwende, I., Harare roads declared a state of national disaster, *The Herald*, Zimpapers, Harare, 2017, Available: http://www.herald.co.zw/harare-roads-declared-a-state-of-disaster/, Accessed 26 Feb 2017.

Telma Incorporated, Telma Driver's Manual, How does a Telma Retarder work?, Telma, Illinois, 2015, Available: https://www.youtube.com/watch?v=5FMoUEmSsdE, Accessed: 27 Feb. 2017.

Thompson, M.T., Permanent Magnet Electrodynamic Brake Design Principles and Scaling Laws, *Online Symposium for Electronic Engineers*, Worcester, 2015.

Tshuma, M., Zimbabwe's rundown road network dangerous, *Financial Gazette*, Zimbabwe Financial Gazette, Harare, 2016. Available: http://www.financialgazette.co.zw/zimbabwes-rundown-road-network-dangerous/, Accessed: 26 Feb 2017.

Yasa, Y., Sincar, E., Tugrul, Ertugrul, B.T., and Mese, E., A multidisciplinary design approach for electromagnetic brakes, *Electric Power Systems Research*, vol. 141, pp 165–178, 2016.

Biographies

Wilson R. Nyemba holds a BSc Honors degree in Mechanical Engineering from the University of Zimbabwe and an MSc in Advanced Mechanical Engineering from the University of Warwick in England. He held several positions in industry ranging from product development to engineering management and has served as a Lecturer, Chairman of Department and Dean of Engineering at the University of Zimbabwe. He also served as Chairman of WaterNet and Project Manager for the Royal Academy of Engineering Project on Enriching Engineering Education, both in Southern Africa. He is currently on sabbatical at the University of Johannesburg in South Africa, pursuing research focusing on Manufacturing Process Flow Modelling and Simulation using Engineering Systems Thinking.

Chris Pote Chris Pote is currently a final year undergraduate student in the Department of Mechanical Engineering at the University of Zimbabwe. On several occasions he has been attached at a Zimbabwean company that specializes in the supply, service and backup of Scania heavy vehicles where he gained some experience, during which time he collected data and developed an interest in braking systems. He is keen and interested in specializing in the automobile sector to share his experiences and knowledge. He is currently pursuing research on converting used vehicle oils into diesel.

Tauyanashe Chikuku is currently a Lecturer in the Department of Mechanical Engineering at the University of Zimbabwe. He holds a Bachelor of Engineering Honors degree in Mechanical Engineering and a Master of Science degree in Manufacturing Systems and Operations Management both from the University of Zimbabwe. His main areas of research and teaching are in Engineering Design and Appropriate Technology.

Charles Mbohwa is currently a Full Professor of Sustainability Engineering and Engineering Management as well as the Vice Dean of Postgraduate Studies responsible for Research and Innovation in the Faculty of Engineering and the Built-Environment at the University of Johannesburg, South Africa. He holds a BSc Honors degree in Mechanical Engineering from the University of Zimbabwe, an MSc in Engineering Management from the University of Nottingham in England and a PhD in Engineering and Environmental Impact Assessment from the Tokyo Metropolitan Institute of Technology in Japan. His main areas of research interest are: manufacturing and production systems, sustainable manufacturing, re-manufacturing and resource efficiency, manufacturing technology-laser-based additive manufacturing, organizational development and management services; humanitarian operations and operations research.