Vehicle's Fuel Consumption Modelling Under Various Conditions

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ABSTRACT.

The response surface methodology technique is implemented to get a better response for minimizing fuel consumption. This paper explores external factors that affect fuel consumption while also building a prediction model for various drivers based on driving data. Fuel consumption rate is an important issue which needs addressing if energy management is of concern. This is because of its impact on the environment and also because the amount of fuel in this planet is dwindling. The response surface methodology (RSM) results showed that the performance of a standard engine without any modifications tends to be satisfactory. The aim is to find an area of minimum fuel consumption by modelling a response surface to some preprocessed data. Some of these data were collected by on-board diagnostics units. And, some of these required variables such as the speed and the brake specific fuel consumption (BSFC) were extracted from an engine model that matches a two litre, four-cylinder engine. The influences of various external factors on consumption are analyzed after the usage of a linear model. We also wanted to model a response surface to find the minimum BSFC.The results from this model can help vehicle drivers' with the reduction of their fuel consumption's usage during various external driving conditions.

Keywords: Fuel Consumption, Speed, Energy Management, RSM, BSFC

1.Introduction

Researchers around the worlds are trying to find ways to minimize environmental pollution and degradation. These pollutions contribute to the amount of carbon emissions into the atmosphere. The current study focuses on power generation through internal combustion engines (ICE). Many studies have been done on the brake specific fuel consumption (BSFC). The brake specific fuel consumption (BSFC) is a parameter that reflects the efficiency of a combustion engine that produces rotational power at either the shaft or the crankshaft by burning fuel. bsfc Is used to evaluate the efficiency of the internal combustion engines (ICE) in automotive applications. Yesilyurt and Aydin (2020) examined diesel engine characteristics for various fractions of diethyl ether (DEE) as an oxygenated fuel additive in cottonseed oil biodiesel-diesel fuel blends. Firstly, several tests performed for diesel and B20 blend. Then, 2.5%, 5%, 7.5%, and 10% of DEE by volume was mixed with biodiesel-diesel fuel to prepare the ternary blends. All the fuel samples were run on in a single-cylinder, four-stroke, and direct-injection diesel engine at five different engine loads and fixed engine speed conditions. Tshivhase and Kainuma (2018) identified the existing literature gaps and possible future research focus with respect to carbon emission reduction by looking at literature done between 1995 1nd 2018. In the 1990s due to improved computer models a consensus was formed that stated that greenhouses gases were deeply involved in most climate changes and emissions were bringing discernable global warming. During the same decade, scientific research in emissions has included multiple disciplines. Tshivhase and Kainuma (2019) designed and solved a mathematical model with the help of a software package to optimize the costs. The problem was solved using a mixed integer linear program (MILP) which required a binary which was applied between the customer bases and the warehouses.

Yesilyurt and Aydin (2020), experimental results showed that BTE was decreased by 17.39% while increasing in BSFC by 29.15% for 10% addition of DEE in the blend as compared to diesel fuel. Besides, the engine fueled with ternary blends revealed mitigation up to 12.89%, 4.12%, and 8.84% in the HC, smoke, and NOX emissions, on an average, respectively than those of diesel fuel. CO emission exhibited increasing trends with the diesel fuel at higher proportions of DEE despite up to 40.09% dropdown remarked for lower concentration at the maximum load. By the way, the CO2 also dropped under high loads. However, the combustion behaviors vaguely deteriorated when the CI engine run on all ternary blends. As a consequence, DEE can be evaluated as an auspicious aspect to remove the main issues with the usage of cottonseed oil biodiesel. Tshivhase and Kainuma (2019) addressed the emissions of carbon into the atmosphere by proposing a single period, multi-supplier low carbon mixed integer model. This model was proven to reduce carbon emissions in the supply chain and also find the optimum distribution levels among different facilities including factories.

Bharadwaz et al. (2016) obtained results that inferred that the VCR engine has maximum performance and minimum emissions at 18 compression ratio, 5% fuel blend and at 9.03 kg of load. At this optimized operating conditions of the engine the responses such as brake thermal efficiency, brake specific fuel consumption, carbon monoxide, unburnt hydrocarbons, nitric oxide, and smoke are found to be 31.95%, 0.37 kg/ kW h, 0.036%, 5 ppm, 531.23 ppm and 15.35% respectively. It is finally observed from the mathematical models and experimental data that biodiesel methanol blends have maximum efficiency and minimum emissions at optimized engine parameters. Yesilyurt and Aydin (2020) stated that the addition of DEE up to 10% (by vol.) could be considered as a promising technique for the utilization of biodiesel/diesel blend efficiently in the CI engines without any major modifications. Bharadwaz et al. (2016) wanted to improve the performance of biodiesel–methanol blends in a VCR engine by using optimized engine parameters. For optimization of the engine, operational parameters such as compression ratio, fuel blend, and load are taken as factors, whereas performance parameters such as brake thermal efficiency (Bth) and brake specific fuel consumption (Bsfc) and emission parameters such as carbon monoxide (CO), unburnt hydrocarbons (HC), Nitric oxides (NOx) and smoke are taken as responses. Tshivhase (2018) studied the airport industry which is a well-known contributor to carbon emissions. Tshivhase and Vilakazi 2018) focused on the mining industry which is also a strong contributor of carbon emissions

Bharadwaz et al. (2016) experimented per the design of experiments of the response surface methodology. Optimization of engine operational parameters is carried out using Derringers Desirability approach. Tshivhase and Kainuma (2019) reviewed the literature of what has been studied with respect to carbon emissions and also identify the gaps in the literature using a systematic literature review approach. Content analysis was used to categorize existing literature on the various topics and methods over time in the area of carbon emissions in the supply chain. The word brake is related the use of the dynamometer to measure the engine parameters such as the fuel mass flow rate and the torque. An ICE requires fuel and air to produce energy. This amount of fuel used is usually measured on a dynamometer as a mass flow rate in kilograms per second (kg/s). However, this parameter cannot be used to measure the efficiency of the engine because it is not obvious how much power we can extract from the fuel. So by dividing the fuel mass rate to the engine output power we can obtain the brake specific fuel consumption which is measured in kilogram per joules. Since the fuel mass flow rate is measured in usually measured in grams per second and the engine power in Kilowatt, this f=gives the brake specific fuel consumption in gram per kilowatt-hour. The engine power is the product between the engine speed and the torque So the BSFC can be expressed as a function of the engine speed and torque. The engine torque which is measured in newton meter can also be defined as function of the mean effective pressure (MEP) of the engine. The lower the BSFC the more efficient the engine is.

Based on previous studies, the main aim of this work is investigate the relationship between the speed, load and the BSFC in a four-cylinder engine.

2.Methodology

2.1 The 4-cylinder engine

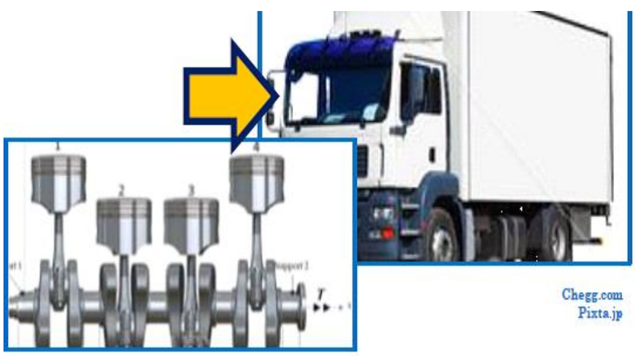


Figure 1: The four-cylinder engine make up

The number of cylinders that an engine contains is an important factor in the overall performance of the engine. Each cylinder contains a piston that pumps inside and those pistons connect to the crankshaft. The more pistons there are pumping, the more combustive events. That means that more power can be generated in less time. Four-cylinder engines commonly come in either straight or inline configurations while 6-cylinder engines are usually configured in the more compact "V" shape, and thus are referred to as V6 engines. V6 engines are powerful and quiet, but turbocharging technologies have made four-cylinder engines more powerful and attractive. Modern four-cylinder engines use lighter materials and turbocharging technology. Advanced aerodynamics and technologies put less stress on these smaller turbocharged engines, further increasing their efficiency and performance.

2.2. Navier-Stokes Equations

The three-dimensional unsteady form of the Navier-Stokes Equations. These equations describe how the velocity, pressure, temperature, and density of a moving fluid are related. The equations were derived independently by G.G. Stokes, in England, and M. Navier, in France, in the early 1800's. The equations are extensions of the Euler Equations and include the effects of viscosity on the flow. These equations are very complex.

The equations are a set of coupled differential equations and could, in theory, be solved for a given flow problem by using methods from calculus. But, in practice, these equations are too difficult to solve analytically. In the past, engineers made further approximations and simplifications to the equation set until they had a group of equations that they could solve. Recently, high speed computers have been used to solve approximations to the equations using a variety of techniques like finite difference, finite volume, finite element, and spectral methods

Coordinates: (x,y,z)
Velocity Components: (u,v,w)
Time : t Pressure: p
Density: ρ Stress: τ
Total Energy: Et
Heat Flux: q
Reynolds Number: Re
Prandtl Number: Pr

Continuity: $$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0$$

X – Momentum: $$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} = -\frac{\partial p}{\partial x} + \frac{1}{Re_r}\left[\frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z}\right]$$

Y – Momentum: $$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho uv)}{\partial x} + \frac{\partial(\rho v^2)}{\partial y} + \frac{\partial(\rho vw)}{\partial z} = -\frac{\partial p}{\partial y} + \frac{1}{Re_r}\left[\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z}\right]$$

Z – Momentum $$\frac{\partial(\rho w)}{\partial t} + \frac{\partial(\rho uw)}{\partial x} + \frac{\partial(\rho vw)}{\partial y} + \frac{\partial(\rho w^2)}{\partial z} = -\frac{\partial p}{\partial z} + \frac{1}{Re_r}\left[\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z}\right]$$

Energy:
$$\frac{\partial(E_T)}{\partial t} + \frac{\partial(uE_T)}{\partial x} + \frac{\partial(vE_T)}{\partial y} + \frac{\partial(wE_T)}{\partial z} = -\frac{\partial(up)}{\partial x} - \frac{\partial(vp)}{\partial y} - \frac{\partial(wp)}{\partial z} - \frac{1}{Re_r Pr_r}\left[\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z}\right]$$
$$+ \frac{1}{Re_r}\left[\frac{\partial}{\partial x}(u\tau_{xx} + v\tau_{xy} + w\tau_{xz}) + \frac{\partial}{\partial y}(u\tau_{xy} + v\tau_{yy} + w\tau_{yz}) + \frac{\partial}{\partial z}(u\tau_{xz} + v\tau_{yz} + w\tau_{zz})\right]$$

(Courtesy of NASA)

This area of study is called Computational Fluid Dynamics or CFD. The Navier-Stokes equations consists of a time-dependent continuity equation for conservation of mass, three time-dependent conservation of momentum equations and a time-dependent conservation of energy equation.

2.3. Response Surface Methodology

Response surface methodology gathers statistical based mathematical methods and is among the most relevant multivariate techniques for optimization and engine modelling. This method also measures the assembly among the engine input factors and the engine output responses.

$$\boldsymbol{b} = \boldsymbol{f}(\,\boldsymbol{a_1}\,,\ \boldsymbol{a_2}, \boldsymbol{a_3}\,,\ \boldsymbol{a_4} \ldots \boldsymbol{a_n}) \qquad (1)$$

Where , $\boldsymbol{a_1}$, $\boldsymbol{a_2}, \boldsymbol{a_3}$, $\boldsymbol{a_4} \ldots \boldsymbol{a_n}$ are the engine input factors and $\boldsymbol{b}$ is the engine output .

$$\boldsymbol{b} = \boldsymbol{j_0} + \sum_{\boldsymbol{i=1}}^{\boldsymbol{k}} \boldsymbol{j_i}\ \boldsymbol{B_i} + \cdots \qquad (2)$$

Linear regression modelling by response surface methodology

Where, , $\boldsymbol{j}$represents regression coefficients

It is also presumed that the engine input parameters are uninterrupted.

The RSM is a widely used mathematical and statistical method for modeling and analyzing a process in which the response is affected by various variables and the objective of this method is to optimize the response. The parameters that affect the process are called dependent variables, while the responses are called dependent variables. For example, the hardness of a porridge is affected by cooking time X_1 and cooking temperature X_2. The porridge hardness can be changed under any combination of treatment X_1 and X_2. Therefore, time and temperature can vary continuously. If treatments are from a continuous range of values, response surface methodology is useful for developing, improving, and optimizing the response variable. In this case, the hardness of meat Y is the response variable, and it is a function of time and temperature of cooking. It can be expressed as the dependent variable y is a function of X_1 and X_2.

3.Results and Discussions

The 3D plot of (x,y)axes that is the load and speed against the z axis which is the BSFC. The preprocessed data is fitted with a fuel efficiency surface using the locally weighted smoothing linear regression (lowess) computed from p which is the coefficient structure and x and y are normalized by mean and standard. The plot of speed, load and BSFC is then plotted and problematic points are then removed as the BSFC cannot be negative. The BSFC can only start from 0. x and y are still normalized between the mean and the standard. In order to have a clear picture of the BSFC it is necessary to zoom into the axis. A contour plot is created to see the region where the BSFC is really low, this is necessary since we want to operate the engine efficiently.

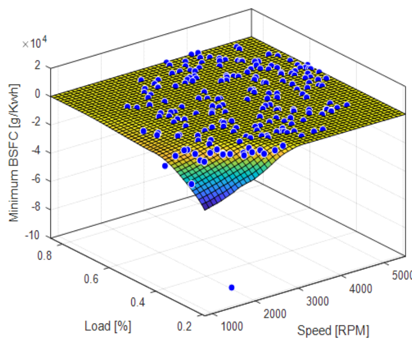


Figure2(a)

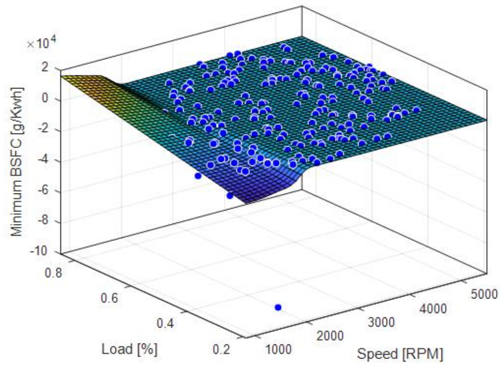
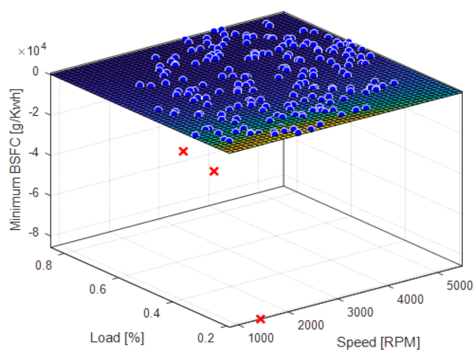


Figure3(a)



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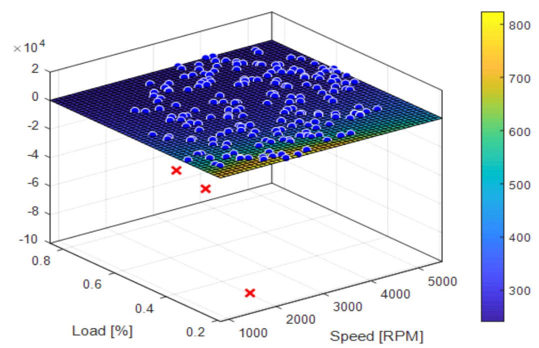
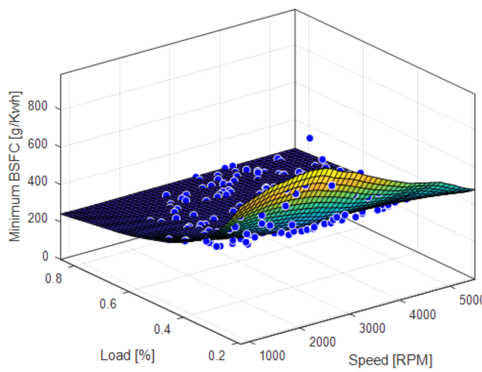


Figure3 (b)



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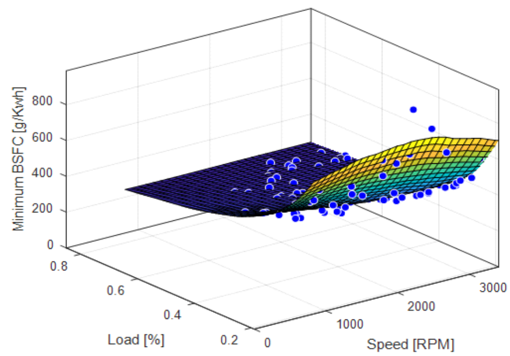

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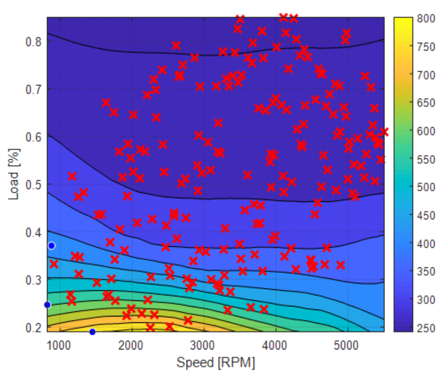
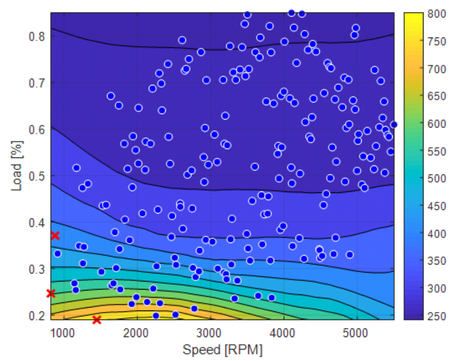


Figure2 (d)



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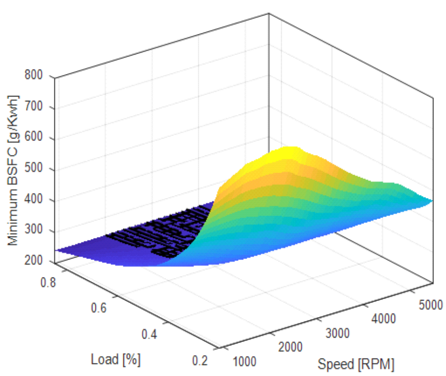

Figure2 (e)

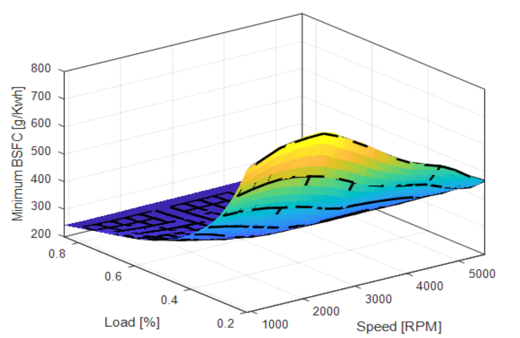

Figure3(e)

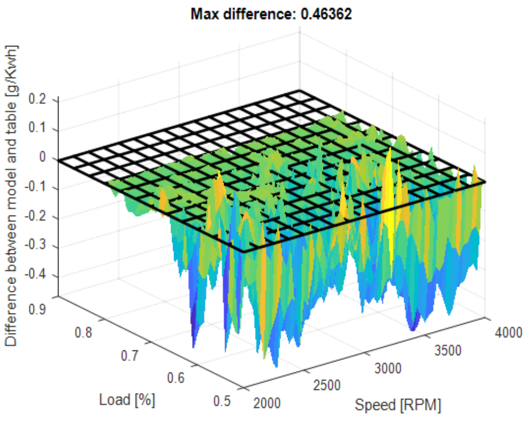

Figure2 (f)

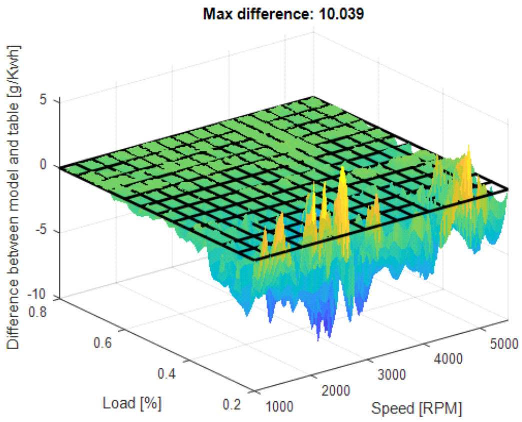

Figure3(f)

Based on the developed model based optimization, the performance of an engine is computed different speeds and loads.

Fig.2 (a) and Fig.3(a) presents the speed, load and BSFC plots for BSFC is between the minimum possible value and the maximum possible. The effect of normalizing the surface produces a surface that looks almost flat at higher BSFC values. And not normalizing the surface has a wrinkled kind of effect. BSFC can never be negative and hence the negative points are eliminated by keeping the limits of the z axis to between zero and infinity, bearing in mind the one surface Fig.2 (b) is normalized and the other Fig.3(b) is not.

Fig.2(c) and Fig.3(c) allows for us to zoom in on the part of z-axis of interest. Fig.2(c) shows the same speed and load axis as before as. Fig.3(c) also limits the speed axis to between zero and the mean which is 3000.

The problem points which indicate negative BSFC are for the z-axis is between minimum and zero as in Fig.2(d) and for between zero and maximum BSFC as in Fig.3(d). These are clearly shown on contour plots which are basically 2D plots. For the two conditions above tables are created from the contour plot surface by evaluating the model over a grid of points, speed and load breakpoints have variables created for them. The difference between the two is the value of the breakpoints with Fig.2(e) smaller than Fig.3(e). The tables that are created are then plotted against the original model with the grid showing the table breakpoints. Slight difference between model and table can be used to determine efficient table size.

The table accuracy is checked by first viewing the difference between the model and the table by plotting their difference on a smoother grid. This difference is then used in the prediction accuracy between these two products to determine the accurate table size. Fig.2(f) has the maximum difference as 0.46 and Fig.3(f) as 10.04.

4.Conclusions

The influence of engine parameters that is engine load and engine speed in modelling a response surface are investigated. At very high engine loads the fuel consumption tends to be very low. The BSFC is also favorable at very high speeds. At lower speeds, the fuel consumption is really high especially and super low speeds.

At mid loads, the fuel consumption tends to be neither critical nor little. The ICE generates the power required for propulsion and depending on the driving scenario and road load the engine will operate at a certain speed and torque (load).100 kW wheel power, can be obtained in 2nd gear, 4th gear and 5th gear. In the 2nd gear, the engine speed is the highest and the engine torque the lowest. By shifting up to 5th gear, we maintain the same output power but with higher engine load and lower speed. Vehicles with automatic transmissions have shift schedulers designed to keep the engine in the most efficient operating points through the selected gear. On a manual transmission vehicle is up to the driver to make the right gear shifts in order to minimize the fuel consumption.

References

Bharadwaz Y.D., Rao B.G.,Rao V.D.. (2016). Improvement of biodiesel methanol blends performance in a variable compression ratio engine using response surface methodology. *Alexandria Engineering Journal*. 55 (-), 1201-1209.

Box,G.E.P. and Wilson,K.B.. (1951). On the Experimental Attainment of Optimum Conditions. *Journal of the Royal Statistical Society. Series B (Methodological)*. 13 (1), 1-45.

Tshivhase , T.. (2018). Does Operational Efficiency Depend on the Airport's Size?. *International Journal of Management Science and Business Administration*. 4 (4), 28-37.

Tshivhase,T. and Kainuma,Y.. (2019). Current Carbon Emission Reduction Trends for Sustainability - A Review. *Journal of Sustainable Development*. 12 (4), 147-165.

Tshivhase,T. and Kainuma,Y.2018. *Reduction of Carbon Emissions in the Supply Chain: A Systematic Literature Review* . The 19th Asia Pacific Industrial Engineering and Management Systems, 5-8 December , Hong Kong

Tshivhase,T. and Kainuma,Y.2019. *Emission-distribution model development under the cap-and-Trade Policy*. The 20th Asia Pacific Industrial Engineering and Management Systems, 2-5 December , Japan

Tshivhase,T. and Kainuma,Y.2019. *Optimization of Production and Transportation scheduling using an MILP*.The 9th International Symposium on Operations Management and Strategy 2019, 4-6 September , Tokyo Japan

Tshivhase,T. and Vilakazi,L.. (2018). Job Satisfaction: What factors in the Coal Mining Industry will lead to Higher Satisfaction?. *International Journal of Management Science and Business Administration*. 4 (6), 17-25.

Yesilyurt M.K , Aydin M.. (2020). Experimental investigation on the performance, combustion and exhaust emission characteristics of a compression-ignition engine fueled with cottonseed oil biodiesel/diethyl ether/diesel fuel blends. *Energy Conversion and Management*. 205 (-), 112355.