Industrial and Systems Engineering
Vol. 1, No. 1, 2016, pp. 1-9
http://www.aiscience.org/journal/ise

Comparison of Aluminium Wheel to Steel Wheel in Relation to Weight and Fuel Consumption (Energy) in Automobiles

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Abstract

The kinetic energy of a car is enabled by one of its most important components known as the wheel and depending on the weight and strength of the wheel, the car may require more or less torque to overcome the drag force acting in opposite direction of the car. In principle, a car with heavy body parts such as the wheel may have some limitation in terms of the speed, general performance, fuel consumption, CO_2 emission etc compared to wheels produced from light weight materials. However, fuel consumption has remained a major concern to automobile industries in recent times, as this requires huge operational cost to enable auto users shuttle the required distance (kilometres). Consequently, CO_2 which is a major Green House Gas (GHG) that results in global warming is generated at the detriment of public health and surrounding environment. This paper presents a cradle to gate life cycle assessment of two car wheel produced from aluminium alloy and high strength low alloy steel. CES software 2014 was used to conduct a full Eco-audit for cradle to gate life cycle of both auto wheels and the result was used to calculate energy consumption and CO_2 emission at the USE phase of the aluminium and steel wheel in a distance of 180,000Km. From the energy breakeven point which occurred at a distance of 28,000Km with energy consumption of 850MJ (in terms of fuel consumption), aluminium alloy wheel consumed energy of 322MJ and 851MJ by steel wheel to cover a distance of 180,000Km. Also, from the CO_2 breakeven point which occurred at a distance of 28,000Km with CO_2 emission of 60Kg, aluminium alloy wheel constituted CO_2 emission of 22Kg and 60.7Kg by steel wheel to cover a distance of 180,000Km. However, aluminium alloy wheel saved 529MJ of energy and 38.7Kg of CO_2 to cover 180,000Km distance. Hence, it was concluded that aluminium alloy wheel is more economical in terms of fuel consumption and CO_2 emission compared to steel wheel, though steel wheel has a higher strength than aluminium alloy wheel in real life applications.

Keywords

Automobile Wheel, Energy, Environment, Emission, Fuel Consumption, Global Warming, Weight

Received: May 27, 2016 / Accepted: June 4, 2016 / Published online: June 28, 2016

1. Introduction

It is of utmost priority for humans to preserve or protect the environment from destruction, and more importantly to protect the interest of the future generation from any harmful effects resulting from human activities. This will be a perfect description of what sustainability is all about as it relates to the context which implies that both natural and artificial habitat should be free from global warming which the entire world is fighting towards minimizing. The word sustainability is an attribute of not harming the environment or squandering of available natural resources thus aiding global ecological balance [13]. For example, Wilson [15] suggested advancement in activities related to production and consumption of resources, such that it does not impact negatively on inhabitants and the environment. The question arises "should the world advance with unsustainable growth such as harmful emissions in manufacturing or use phase of

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products and ignore the negative footprint on the environment?" To attain sustainability it is imperative for the elimination of unsustainable patterns of consumption, production and the use of appropriate demographical policies [16]. Therefore, sustainability with respect to engineering has a similar approach that relates to Allen's [1] definition of sustainable engineering, as a basic design of industrial systems by preventing the use of natural resources, such that it does not result in lower standard of living, loss of opportunities for future generation or adverse impacts on environmental, social and human health condition. This clearly implies that the role of engineers is to ensure compatibility between the design and operation of industrial systems and the environment, thereby eliminating negative effect on present and future generations [5]. A number of engineering components and structures comprise other essential feature within the frame works of the component which the performance strength is built upon for support throughout the life time of the component. This implies that if the supporting arms of the component are deficient in any aspect of design, construction and development, certain criteria designed for the component may likely not be achieved. For example, if automobile wheel which is the major area of focus in this paper lacks the essential features needed to transform the potential energy of a car to kinetic energy, motion may likely be a problem. Quadling [10] defined automobile wheel as a circular device firmly fixed within the tire rim on the front and rear axle, enabling motion as the gear is engaged. According to Taiwan Turnkey [14], the essential component that makes up a wheel includes the hub, spokes and rim which depending on the manufacturers specification may exist in one piece, two or three in some cases. The hub is the midpoint of the wheel and represents the section in which the wheel is connected to the suspension via the steering knuckle. Similarly, the spokes extends outwards from the hub and attaching to the rim while the rim serves as the external part of the wheel that clings to the tyre. Prasad [9] expressed emphatically that automobile wheel is designed to carry the entire load of the car, where it bears not only the force exerted vertically on the wheel but also the random forces arising from pitch and roll during acceleration of the vehicle, cornering, speed bumps, and breaking. The wheel as a result of these forces suffers a huge impact which undermines the durability and life cycle of the wheel. In this case, lightweight materials may be advantageous in the reduction of unsprung weight as well as the entire weight of the vehicle. Meghashyam et al. [8] discuss that the tyre only performs its required functions only when fixed appropriately on the rim. However, a wheel and a tyre works hand in hand as a single component when coupled together in order to enable motion. Therefore, attention should be given to material properties and design concepts when manufacturing an automobile wheel. Using CES software, Eco-Audit will be conducted for the Cradle-to-Cradle life of automobile wheel and the report generated will be used to analyse the energy consumption, CO_2 footprint and the End of Life (EOL) potentials.

2. Estimation of Loads and the Component Duty Cycle

During acceleration of a vehicle, the wheels are subjected to angular or rotational acceleration which is achieved by angular force (referred to as torque) deployed by the vehicle engine on the front and back axle. On the base of the tyre, the torque behaves like a force in the backward direction which can be in opposition with the road surface, but the base of the tyre continuously remains stationary without accelerating, provided the tyre does no slip (skid) [7, 11].

Stearns et al. [12] reported that dynamic conditions can be achieved as a result of the forces a vehicle is exposed to, at different case scenarios as shown in Figure 1. In real life applications, the loads acting on the car wheel varies significantly as follows;

i. Longitudinal direction such as acceleration and breaking.

ii. Lateral direction such as cornering forces.

iii. Vertical direction such as compressive or tensile loading.

iv. Axial direction

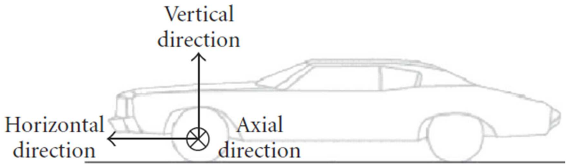


Figure 1. Significant directions of the load acting on automobile wheels.

Guler [6] also noted different operating conditions that can possibly result in various loading condition in automobile wheels. Such operating conditions can be summarised as follows;

i. The vehicle braking on level ground (Longitudinal weight transfer).

ii. The vehicle at the point of cornering (Lateral load transfer on braking).

iii. The vehicle at a downhill grade.

iv. The vehicle at the point of breaking at a downhill grade.

2.1. Radial Load

Radial load in a vehicle explains the vertical reaction forces applied by the surface of the road on all the tyres to balance the entire weight of the vehicle in the longitudinal direction when the car is in motion. In this case, radial load is applicable to the bead seat of a wheel in a car. For a rotating wheel that is radially loaded, the tensile strength of rim can extensively influence the wheel's fatigue life [11, 12]. Stearns et al. [12] in their illustration showed the radial loading conditions of a given automobile wheel as schematically represented in Figure 2.

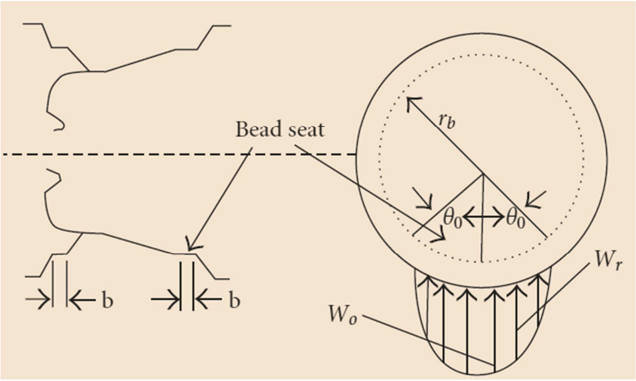


Figure 2. Schematically representation of radial loading condition of a car wheel.

Due to the loading condition that is radially acting on the rotating wheel, pressure distribution W_r acts (loaded) directly along the bead seat, in which pressure in the circumferential direction is presume to have a cosine function distribution as represented in Figure 2 [12]. Consequently, the pressure distribution can be expressed as

$$W_r = W_0 * \cos\left(\frac{\pi}{2} * \frac{\theta}{\theta_0}\right) \tag{1}$$

From equation 1 above, the radial load acting on a car wheel can be determined as follows

$$F_r = 2b\int_{-\theta_0}^{\theta_0} W_n * r_b d\theta = 8 * b * r_b * \theta_0 * \frac{W_n}{\pi} \tag{2}$$

Where,

W_n = Natural frequency

W = Radial Load

θ_0 = Angle of Loading

F_r = Radial Force

b = Width of the bead Seat

W_r = Pressure Distribution

2.2. Axial Load

Axial Load implies the resultant force travelling across the centroid of a certain segment in a direction perpendicular to the surface of the segment [10]. This type of load often acts laterally on the wheel in a manner that tends to oppose motion of the wheel. Axial loading on automobile wheel induce stresses which can result in major influence on the wheel geometry and can be determined using the following equations;

$$\sigma = \frac{F}{A} \tag{3}$$

Where;

σ = Normal Stress

F = Total Weight of the car acting vertically on the wheel

A = cross sectional area of the wheel

Deflection can be determined using the following equation;

$$\delta = \frac{FL}{AE} \tag{4}$$

Where;

δ = Deflection

L = Length of the plane inconsideration

E = Young's Modulus of the wheel material

The two load conditions on automobile wheels in most scenario results in rotating bending moment which can be expressed as

$$M_b = F_r * d + F_l * r \tag{5}$$

$$\text{Where } F_l = \mu * F_r \tag{6}$$

F_r = Radial force acting on the wheel

F_l = Lateral force acting on the wheel

μ = Coefficient of friction between the ground and the tire

r = Radius of the wheel

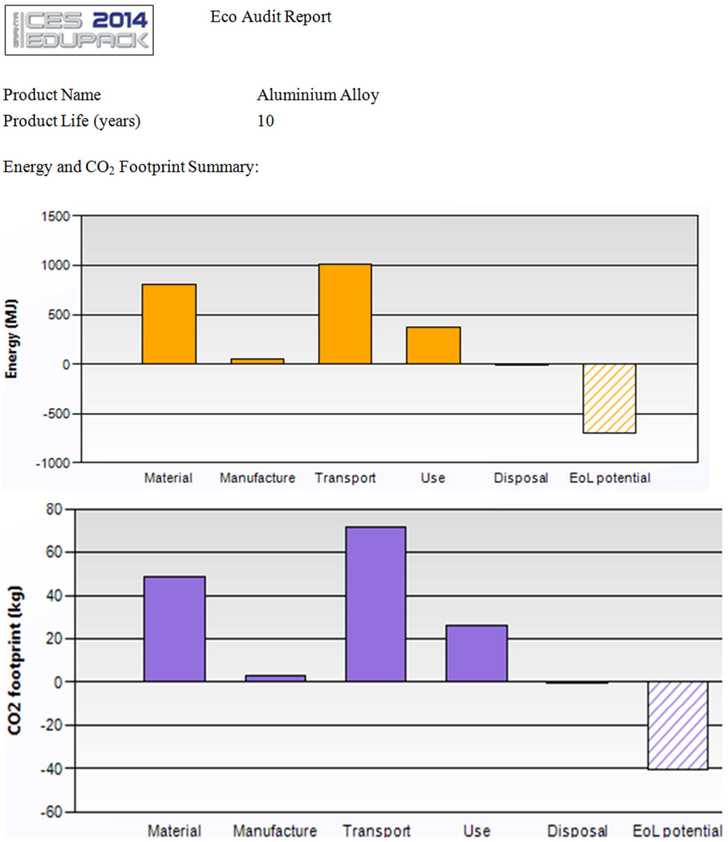
d = Wheel offset

3. Methodology

In this paper, Eco-Audit was carried out using CES in order to determine the magnitude of energy (MJ) exhausted for a period of 10 years and the amount of CO_2 footprint as well as the end of life (EOL) potential through the life time of aluminium alloy wheel and high strength low alloy steel wheel. The life cycle for both wheels was estimated at a duration of 10 years, while the estimated travelling distance throughout the USE Phase was assumed at 180,000Km (11184.7miles) for 365 days per year and 18x8.5 (diameter/width) specification wheel size will be selected for both aluminium alloy and steel wheel. Bolten [3] evaluates the weight ratio of aluminium alloy to steel as 1:2.8. Andy's Auto shop [2] evaluates the weight of a standard Mercedes Benz steel wheel as 11.2kg. Hence, the weight of aluminium alloy in that ratio can be expressed as 4kg.

3.1. Eco-Audit Explanation with Regards to Energy (MJ), CO_2 Footprint and EOL Potential of Alloy Wheel

As shown in Figure 3, the following graphs illustrates the Eco-Audit result for aluminium alloy wheel for a period of 10 years at various phases respectively while Table 1 represents the summary of energy and CO_2 footprint of the Eco-Audit graphs at various phases such as the material manufacturing phase, USE phase etc.


Eco Audit Report

Product Name Aluminium Alloy
Product Life (years) 10

Energy and CO_2 Footprint Summary:

Figure 3. Eco-Audit Report for Aluminium Alloy Wheel (CES Edupack, 2014).

Table 1. Energy and CO_2 Footprint Summary extracted CES from Eco-Audit Report.

Phase	Energy (MJ)	Energy (%)	CO_2 (Kg)	CO_2 (%)
Material	803	36.1	48.3	32.5
Manufacture	45.5	2.0	2.73	1.8
Transport	1.01e+03	45.3	71.6	48.0
Use	368	16.5	26.1	17.5
Disposal	2.8	0.1	0.196	0.1
Total (for first life)	2.23e+03	100	149	100
End of life Potential	-703		-40.4	

3.2. Criteria for Choosing a Second Material for Automobile Wheel

Due to the adverse effect of CO_2 (on the environment) which is the dominant gas that constitutes ozone layer depletion, changes in earth's temperature, climate change etc, critical safety criteria and energy saving have recently become a major concern for automobile manufacturing industry due to CO_2 emission during manufacturing and USE phase of vehicles car wheel and its components. However, increasing emphasis on the minimisation of greenhouse and improvement of fuel efficiency in transportation section, automobile industries are undergoing research and development on lightweight materials which is the conventional material that has significantly facilitated the greenhouse gas minimisation approach [4]. As mentioned earlier, aluminium alloy wheels and steel wheels are mainly used in vehicles nowadays but while aluminium A356 has emerged as conventional material for alloy wheels due to its light weight, but the expensive nature of the material, fatigue strength, in-service temperature, stiffness, and ruggedity seems not to be a better option for the alloy wheel service life of 10 years. However, high density of the steel material seems to be a challenging factor in steel wheels despite the excellent properties which outperforms aluminium alloy wheels in terms of durability [9]. The second material for the car wheel in this case was chosen by evaluating the essential properties of high strength steels in CES software and comparing with that of A356 alloy of aluminium. Comparing the properties from CES software as shown in Table 2, it can be observed that high strength low alloy steels are still suitable for this application because high amount of energy (electrolytic reduction for example) is required for extracting the raw material for aluminium and CO_2 emission is involved in the process, whereas steel is produced from a mixture of iron ore and coal which minimal energy is required in the process.

Table 2. Material Properties for Aluminium Alloy Wheels and Steel Wheels (CES Edupack, 2014).

Material Properties	Aluminium Alloy (A356)	High Strength Low Alloy Steel
Price	1.35-1.48 GBP/Kg	0.345-0.377 GBP/Kg
Density	2.66e3-2.71e3 Kg/m^3	7.8e3-7.9e3 Kg/m^3
Young's Modulus	71.5-74.5 GPa	200-221 GPa
Yield Strength	105-116 MPa	550-650 MPa
Tensile Strength	172-190 MPa	600-670 MPa
Fatigue Strength at 10^7 cycles	74.7-91.3 MPa	280-315 MPa
Max Service Temperature	150°-170°C	473°-502°C

From Table 2, it can be observed that the density of high strength low alloy steel significantly outweighs that of aluminium alloy and this has a great influence on the use phase of the car wheel in terms of fuel efficiency. Despite the high density of high strength low alloy steel which is the major factor that limits the component efficiency in terms of good breaking systems when used in the manufacturing route of a car wheel, it can be observed that the yield strength, maximum service temperature, fatigue strength, and Young's Modulus are all perfect. Also, the price of 1Kg of high strength low alloy steel compared to aluminium alloy is quite minimal. Therefore, the justification of selecting high strength low alloy steel as a second material for automobile wheel is because of the low price and the above mechanical properties which makes a steel wheel stronger and more durable in rough terrain throughout the USE phase.

3.3. Eco-audit of Alloy Steel Wheel

High strength low alloy steel has been selected based on the criteria discussed above. The following references/assumptions with regards to the wheel is as follows; The life cycle for the steel wheel will be estimated at a duration of 10 years, while the estimated travelling distance throughout the USE Phase will be assumed at 180,000Km (11184.7miles) for 365 days per year and 18x8.5 (diameter/width) specification wheel size will be selected for the steel wheel. The wheel for Mercedes Benz E-class W124 (EVOII) with the weight given as 24.7lbs (approximately 11.2kg) will be considered [2].

3.4. Eco-Audit explanation in relation to Energy (MJ) CO_2 Footprint and EOL potential for High Strength Low Alloy Steel

As shown in Figure 4, the following graphs illustrates the Eco-Audit result for aluminium alloy wheel for a period of 10 years at various phases respectively while Table 3 represents the summary of energy and CO_2 footprint of the Eco-Audit graphs at various phases such as the material manufacturing phase, USE phase etc.

CES 2014 EDUPACK

Eco Audit Report

Product Name	Steel Wheel
Product Life (years)	10

Energy and CO_2 Footprint Summary:

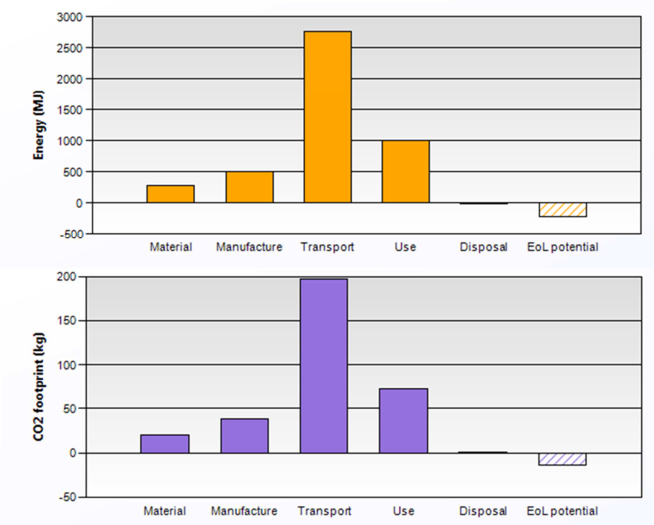


Figure 4. Eco-Audit Report for High Strength Low Alloy Steel Wheel (CES Edupack, 2014).

Table 3. Energy and CO_2 Footprint Summary from Eco-Audit Report (CES Edupack, 2014).

Phase	Energy (MJ)	Energy (%)	CO_2 (Kg)	CO_2 (%)
Material	290	6.3	19.9	6.1
Manufacture	511	11.1	38.3	11.7
Transport	2.77e+03	60.4	197	60.1
Use	1.01e+03	22.0	71.8	21.9
Disposal	7.7	0.2	0.539	0.2
Total (for first life)	4.59e+03	100	327	100
End of life Potential	-210		-13.6	

3.5. Calculating the Total amount of energy consumption and CO_2 Emission in the USE Phase of Aluminium Alloy (A356) Wheel

The values for energy consumption and CO_2 emission in the USE phase of the aluminium alloy wheel was determined as follows;

Energy consumption at the USE phase of the alloy wheel = 368MJ (Refer to Table 1)

Total distance = 180000km

Duration = 10 years

Duration for 1 year = 18000km

Therefore;

$$\frac{368}{180000} = 0.002$$

$$0.002 * 18000 = 36$$

$$36 + 848 = 884\text{MJ}$$

This value (848) was obtained by adding the enrgy consumption at the material extraction and processing phase and the energy consumption at the component manufacturing phase for the aluminium alloy wheel. 884MJ was the value obtained for energy consumption at a distance of 18,000km in the USE phase of the alloy wheel and this was used to calculate for subsequent values as shown in Table 4.

Table 4. Energy and CO_2 Values for Alloy Wheel.

Distance (Km)	Energy (MJ)	CO_2 (Kg)
18000	848	59.3
36000	884	61.9
54000	920	64.4
72000	956	66.9
90000	992	69.44
108000	1028	71.96
126000	1064	74.48
144000	1100	77.0
162000	1136	79.5
180000	1172	82.0

Similarly, Values for CO_2 Emission was obtained as follows;

CO_2 emission in the USE phase of the alloy wheel = 26.1kg (Refer to Table 1)

Energy consumption at the USE phase of the alloy wheel = 368MJ (Refer to Table 1)

Total distance = 180000km

Duration = 10 years

Duration for 1 year = 18000km

Therefore,

$$\frac{26.1}{368} = 0.070$$

0.070*884 = 61.9kg

61.9kg was the value obtained for CO_2 emission at a distance of 18,000km in the USE phase of the alloy wheel and this steps was used to calculate for subsequent values of CO_2 emission in the USE phase as shown in Table 4.

3.6. Creating a USE Graph for High Strength Low Alloy Steel Wheel

The values for energy consumption and CO_2 emission in the USE phase of the steel wheel was determined as follows;

Energy consumption at the USE phase of the alloy wheel = 1010MJ (Refer to Table 3)

Total distance = 180000km

Duration = 10 years

Duration for 1 year = 18000km

Therefore;

$$\frac{1010}{180000} = 0.0056$$

$$0.0056 * 18000 = 100.8$$

$$100.8 + 801 = 901\text{MJ}$$

901MJ was the value obtained for energy consumption at a distance of 18,000km in the USE phase of the steel wheel and this steps was used to calculate for subsequent values for energy consumption in the USE phase as shown in Table 5.

Table 5. Energy and CO_2 Values for Steel Wheel.

Distance (Km)	Energy (MJ)	CO_2 (Kg)
18000	801	56.8
36000	901	63.9
54000	1001	71.0
72000	1101	78.1
90000	1201	85.2
108000	1301	92.3
126000	1401	99.4
144000	1501	106.5
162000	1601	113.6
180000	1701	120.7

Similarly, Values for CO_2 Emission was obtained obtained as follows

CO_2 emission in the USE phase of the alloy wheel = 71.8kg (Refer to Table 3)

Total distance = 180000km

Duration = 10 years

Duration for 1 year = 18000km

Therefore,

$$\frac{71.8}{1010} = 0.071$$

$$0.071*901 = 63.9\text{kg}$$

63.9kg was the value obtained for CO_2 emission at a distance of 18,000km in the USE phase of the steel wheel and this steps was used to calculate for subsequent values for CO_2 emission in the USE phase as shown in Table 3. Graphically, energy consumption and CO_2 with respect to the distance covered by both alloy and steel wheel are shown in Figure 5 and Figure 6 respectively.

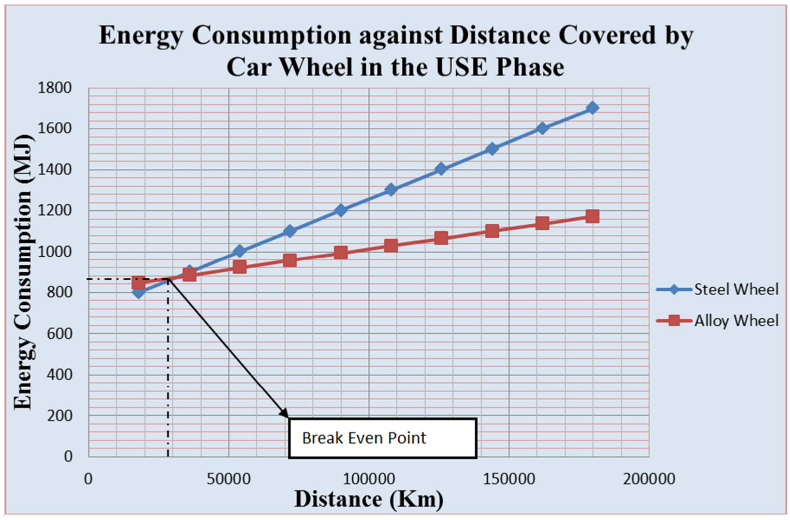


Figure 5. Graph of Energy Consumption against Distance Covered by Car Wheel in the USE Phase.

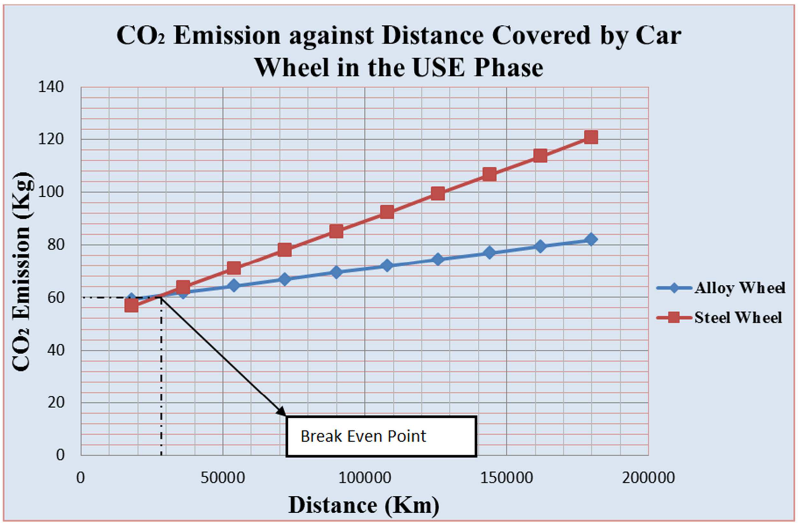


Figure 6. Graph of CO_2 Emission against Distance Covered by Car Wheel in the USE Phase.

4. Discussion

Aluminium alloy wheel has a low density which makes it advantageous in the aspect of minimal fuel consumption at each phase as well as less impact potentials on the environment, whereas the density of high strength low alloy steel significantly outweighs that of aluminium alloy and this has a great influence on the use phase of the car wheel in terms of fuel efficiency. This correlates with the analysis carried out by Meghashyam [8] and Andy [2] on various automobile wheel weigh. Despite the high density of high strength low alloy steel (which is the major factor that limits the component fuel efficiency), in terms of performance such as braking, rugged nature, yield strength, maximum service temperature, fatigue strength, cost and stiffness [3], steel wheel may be the preferred material. For example, 1Kg of high strength low alloy steel is about 0.345-0.377 GBP compared to 1Kg of aluminium alloy which is about 1.35-1.48 GBP (CES Edupack software 2014). As shown in Figure 5, the breakeven point for aluminium alloy wheel and steel wheel intercepts at a distance of 28,000Km with energy consumption of about 850MJ by both wheels. The breakeven point in this case indicates a point where equal amount of energy (in terms of fuel consumption) is consumed by both aluminium alloy wheel and steel wheel at a distance of 28,000Km. Beyond the breakeven point, it can be observed that the energy of 1701MJ is consumed by using steel wheel to cover a distance of 180,000Km and this shows additional energy of 851MJ from the breakeven point. However, aluminium alloy wheel consumed energy of about 1172MJ to cover the same 180,000Km distance, with additional energy consumption of 322MJ as shown in Figure 5. Comparing these values, it obvious that aluminium alloy wheel consumed less energy by saving a total amount of 529MJ. This is due to the low density of aluminium alloy wheel which in principle requires the car to develop less torque to overcome the drag force acting against the car in motion. This is disadvantageous in the case of steel wheel as the torque needed to overcome the drag force (acting in opposite direction to the moving car) is much as a result of the high density of the steel wheel which may have a slight effect on the speed of the car and as well result in more fuel consumption (energy). However, this implies that a car with less weight on the wheels can accelerate faster than a car with heavier weight on the wheel. Similarly, as shown in Figure 6, the breakeven point for aluminium alloy wheel and steel wheel intercepts at a distance of about 28,000Km with CO_2 emission of 60Kg. The breakeven point in this case signifies the point where equal amount of CO_2 is emitted into the atmosphere at a distance of 28,000Km by a car using either aluminium alloy wheel or steel wheel. Beyond the breakeven point, it can be seen that CO_2 emission of 120.7Kg is emitted by using steel wheel to cover a distance of 180,000Km, showing additional 60.7Kg from the breakeven point. However, using aluminium alloy wheel to cover a distance of 180,000, CO_2 emission of 82Kg is consumed, showing additional CO_2 emission of 22Kg from the breakeven point as shown in Figure 6. Comparing these values, it obvious that aluminium alloy wheel emitted less CO_2 by saving a total amount of 38.7Kg. This is due to the low density of aluminium alloy wheel which in principle requires the car to develop less torque to overcome the drag force acting against the car in motion. This is disadvantageous in the case of steel wheel as the torque needed to overcome the drag force (acting in opposite direction to the moving car) is much as a result of the high density of the steel wheel which may have a slight effect on the speed of the car and as well result in more CO_2 emission [4]. However, this implies that a car with less weight on the wheels can accelerate faster than a car with heavier weight on the wheel. Summary of the evaluation is shown in Table 6 and Figure 7.

Table 6. Summary of Energy consumption and CO_2 emission by Alloy and Steel Wheel.

Energy Consumption (MJ)		**Energy Savings by Alloy Wheel (MJ)**	**Additional CO_2 Emission (Kg)**		**CO_2 Savings by Alloy Wheel (Kg)**
Alloy Wheel	Steel Wheel		Alloy Wheel	Steel Wheel	
322	851	529	22	60.7	38.7

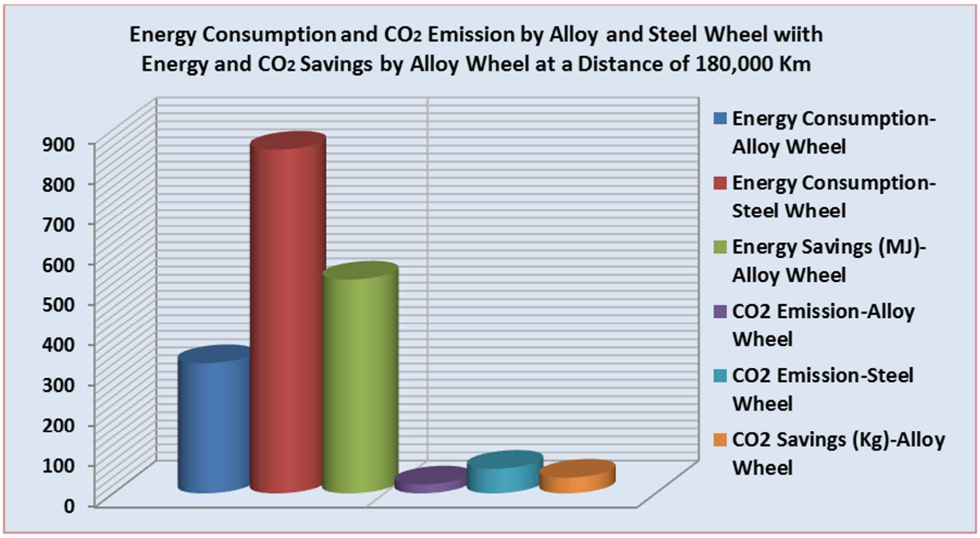


Figure 7. Energy Consumption and CO_2 Emission by Aluminium Alloy Wheel and Steel Wheel with Energy and CO_2 Savings by alloy Wheel at a Distance of 180,000 Km

5. Conclusion

From the following analysis, it can be concluded that aluminium alloy wheel is more economical in terms of fuel consumption and CO_2 emission compared to steel wheel. Whereas, steel wheel has a higher yield strength than aluminium alloy wheel in real case applications, making it more suitable in tough, rough, and rugged terrain than alloy wheel. Hence, for higher performance, minimal CO_2 emission and fuel efficiency, reference should be made to alloy wheel.

References

[1] Allen, D. T. and Shonnard, D. R. (2012) Sustainable Engineeing: An Introduction to Sustainability. [online] available from <http://www.informit.com/articles/article.aspx?p=1828432> [20 December 2015].

[2] Andy's Auto shop (N.d) Wheel Weight. [online] available from <http://www.wheelweights.net/> [24 November 2014].

[3] Bolten, W. (1998) Engineering Materials Technology. Butterworth-Heinmann-Linacre-Jordan Hill, Oxford OX28DP, 225 Wildwood Avenue, Woburn.

[4] Chiaberge, M. (2011) New Trends and Developments in Automotive Industry. Intech, China. [online] available from <http://cdn.intechopen.com/pdfs-wm/13343.pdf> [23 November 2014].

[5] Ezeonu, C., Tagbo, R., Anike, E. N., Oje, O., Onwurah, I. (2012) Biotechnological Tools for Environmental Sustainability: Prospect and Challenges for Environments in Nigeria, A Standard Review. International Journal of Biotechnological Research, Volume 2012.

[6] Guler, D. (2006) Dynamic Analysis of Double Wishbone Suspension. Izmir Institute of Technology, Turkey. [online] available from <http://library.iyte.edu.tr/tezler/master/makinamuh/T000523.pdf> [20 November 2014].

[7] Math Library (2013) Newton's Laws Applied to an Accelerating Car. [online available from <http://mathforum.org/library/drmath/view/67379.html> [20 November 2014].

[8] Meghashyam, P., Girivardhan, S., and Sayed, N. (2013) Design and Analysis of Wheel Rim using CATIA & ANSYS. International Journal of Application or Innovation in Engineering and Management 2 (8), 2319 – 4847.

[9] Prasad, B. and Kumar, M. (2013) Topology Optimisation of Alloy Wheel. Altair Technology Conference, India. [online] available from <http://altairatc.com/india/previous-events/2013/images/presentations/OS-15_TOPOLOGY_OPTIMIZATION-Hyundai.pdf> [29 October 2014].

[10] Quadling, D. (2002) Advance Level Mathematics Mechanics 1. Published by Cambridge University Press. The Edinburgh building, Cambridge CB2 8RU, UK.

[11] Schnubel, M. (2014) Today's Technician: Automotive Suspension and Steering Class Room Manual and Shop Manual. Cengage Learning, p 607. ISBN: 9781305178410.

[12] Stearns J., Srivatsan T., Gao, X., and Lam, P (2006) Understanding the Influence of Pressure and Radial Loads on Stress and Displacement Response of a Rotating Body: The Automobile Wheel. International Journal of Rotating Machinery 2006, 1-8.

[13] Tester, T. W., Dreak, E. M., Driscoll, M. J., Golay, M. W., Peter, W. A. (2005) Sustainable Energy: Choosing Among Options. Publisher: PHI Learning Limited, New Delhi-110001.

[14] Taiwan Turnkey (2014) Aluminum Alloy Wheel Making Plant. [online] available from <http://file:///F:/Second%20semester%20courses/Design%20and%20sustainbility/Taiwan%20Turnkey-Project%20Information%20%20-Aluminum%20Alloy%20Wheel%20Making%20Plant.html> [24 November 2014].

[15] Wilson, W. and Sasseville, D. (1999) Sustaining environmental management success. New York: Wiley.

[16] World Steel Association (2014) Sustainability. [online] available from <http://file:///F:/Second%20semester%20courses/Design%20and%20sustainbility/World%20Steel%20Association%20-%20Sustainability.html> [24 November 2014].