The Lighter the Better: Weight Reduction in the Automotive Industry and its Impact on Fuel Consumption and Climate Change

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Abstract

The automotive industry is growing faster than any other industry and neck on neck with this growth is the demand for lightweight components. This is a pull factor, which is primarily influenced by the drive towards reducing fuel consumption and emissions to the atmosphere. The stakes are very high in the quest to satisfy the insatiable customer hunger for reduced fuel consumption. Stringent emission regulations have also been put in place in order to mitigate the adverse effects of global warming. This has placed tremendous pressure for an increased production of light vehicle components. Hence the lighter the better, and this paper focuses on the lightweighting technologies that are being implemented in the automotive industry, and how weight reduction is vital in reducing vehicle fuel consumption and global warming. Two weight reduction methods, material substitution and topology optimization are reviewed and analyzed based on cost, strength and stiffness. The paper also discusses the contribution that vehicle mass has on the driving cycle when compared to other parameters that affect fuel consumption.

Keywords

Lightweighting, automotive industry, fuel consumption, topology optimization and material substitution.

1. Introduction

The automotive industry is the quickest growing industry today (Bangde et al. 2020). The demand for lightweight components in this industry keeps on burgeoning (Grand View Research 2018), and it is happening in the midst of an intensely competitive industry where the stakes are always high in the quest to satisfy the ever-changing needs of the customer. This is influencing sustainability, which can also be referred to as eco-friendly design. This is happening at a time when the world is going green and countries seek to minimize the negative effects of global warming. The increasing awareness about reducing emissions and the stringent emission regulations has placed tremendous pressure on automotive companies to turn to lighter parts in order to reduce the weight of cars (Chebolu, 2020; Kobayashi et al. 2009; Fontaras et al. 2017). The lighter the better, and practical application has proven that reducing a motor vehicle's weight by 10% not only reduces raw material consumption, which is material efficiency, but also cuts car fuel consumption by between 6% to 8% (Joost 2012; Bangde et al. 2020; Wang et al. 2020). Thus, lightweighting supports sustainability. This is due to the fact that the lighter vehicle will have to overcome lesser tractive forces during motion. The weight of the car is the most significant tractive force. 75% of the fuel consumption is dependent on the weight (Saidpour 2004). The more the weight reduction, the lesser the tractive forces encountered by the vehicle when it is in motion and the lesser the fuel consumption. This is beneficial to both the company and the customer. Research has also proven that every 100 kg removed from a motor vehicle reduces CO_2 emissions by 9 grams per kilometer (Hirsch 2011). Lightweight parts also have high energy efficiency (Dudek and Zagórski 2017). It is against this background that this paper presents the lightweighting strategies that have been implemented on vehicle components and the impact on fuel consumption and on emissions, which subsequently impacts climate change.

2. Material substitution and topology optimization in vehicle component weight reduction

Since the turn of the new millennium, the automotive industry has experienced a surge in the development of lightweight vehicle components. An example is in the race cars designs, where in addition to reduced emissions and fuel savings; there is an improvement in the performance of the vehicle. This makes acceleration and breaking easier, and provides stability (Li et al. 2013). An important question that an engineer has to answer is how to meet the ever-changing market demand for lightweight products while at the same time reducing the design's manufacturing cost and enhancing product compressive and tensile strength, stiffness and durability. Two main approaches have been used to reduce vehicle component weight. The first one is replacing existing material with a lighter one, and it is called material substitution. The second approach is to optimize the performance of the component through redesign, and it is referred to as topology optimization.

2.1 Material Substitution and its cost benefit analysis

Today, lighter materials such as aluminum, magnesium, titanium and composites are being used to substitute heavier materials like steel. Taking aluminium as an example, its advantage is that it is lightweight, recyclable and absorbs twice as much crush energy as compared to materials like mild steel (Khademian and Peimaei, 2020). As for titanium, previous research has suggested weight reduction through material substitution on bolts and nuts. Froes et al. (2004) and Croccolo et al. (2012) both agree that significant weight savings can be achieved by replacing steel bolts and nuts with titanium. These weight savings go a long way in reducing fuel consumption for the motor vehicle and consequently reduce CO_2 emissions to the atmosphere. Froes et al. (2004) goes on to look at the use of titanium in some sections of the components which were traditionally manufactured using steel. These components are:

- *The chassis:* although there is acknowledgement of the prevention of its use on pivot bearings, wheel carriers, steering linkage, and axle stubs due to the high cost associated with it being used there.
- *Exhaust systems:* where unlike steel which needs to be replaced after 7 years, grade 1 or grade 2 titanium can last the entire lifetime of a vehicle (12 to 14 years).
- *Springs:* where its low density and high yield strength are utilized.

However, despite offering the benefits of lightweighting and bringing in excellent strength to weight ratio and high product efficiency, material substitution has a trade-off between the benefit of lightweighting and high production costs (Hagnell et al. 2020. The lightweight material itself is generally expensive. Taking composites as an example, the different grades of carbon fiber costs between US$33/kg and US$67/kg to manufacture (Carberry 2008). This is very expensive and can only be implemented when there are very high expected returns, for example, in the case of race car drivers as they place more value on performance as compared to price (Hällgren et al. 2016). Other materials such as titanium, have a good combination of lightweight and high strength, but at the same time very expensive both to acquire and process (Bodunrin et al. 2020). Some materials are associated with negative environmental impact during their production (Kim and Wallington 2013; Witik et al. 2011). Furthermore, some materials, for example, magnesium, have a low yield strength and will fail in areas where high strength and stiffness is needed. Some are not easily recyclable, for example, the glass-fiber reinforced polymer composite (Cheah 2010).

2.2 The rise of topology optimization and its application so far

While material substitution replaces the material without necessarily changing the geometry of the part, topology optimization changes the geometry of the part without replacing the material. Topology optimization is a mechanical design tool, which aims to employ the stiffest material distribution in a way that is as light as possible (Topaç et al. 2020). As a numerical approach, it comes up with material placing within a given domain in order to achieve the desired functionality, such as stiffness, that is the resistance to deformation, under particular loads, subject to given constraints while at the same time reducing material usage, weight of the product and providing uniform stress distribution (Thompson et al. 2016). The purpose is to determine the optimal layout of the material in a given domain (Bendsoe and Sigmund 2013). Topology optimization has been applied throughout the industry as the researchers keep on finding ways of reducing vehicle component weight without compromising on compressive and tensile strength, stiffness and durability.

According to Metal AM (2018), the mini cooper suspension trailing arms were redesigned through topology optimization and the optimized designs weigh 48% less with the strength and performance not compromised. With the help of additive manufacturing, a design that uses less raw materials was achieved and the entire design process was reduced from days to hours. Figure 1 below shows a conventional mini cooper suspension trailing arm (left) and the optimized one (right) weighing 48% less:

Figure 1: Conventional (left) and optimized (right) mini cooper suspension trailing arm (Metal AM 2018)

Karadere et al. (2020) also came up with a redesign of automobile suspension components and achieved 35.203% weight reduction through shape and topology optimization techniques. Roper et al. (2018) implemented multi-material topology optimization methods on a complex McPherson suspension structure, placing focus on the lower control arm. The results show that a 30% weight reduction was achieved while stiffness was increased by 9%.

Li et al. (2020) optimized suspension uprights for an electric car using the topology optimization mathematical model. The results show a 60.43% mass reduction from 1.2056 kg to 0.4771 kg. This was validated through testing for strength, stiffness and safety factor under the conditions of turning braking, emergency braking and sharp turning. The initial geometric model, the model after topology optimization and the manufactured part are shown in Figure 2 below:

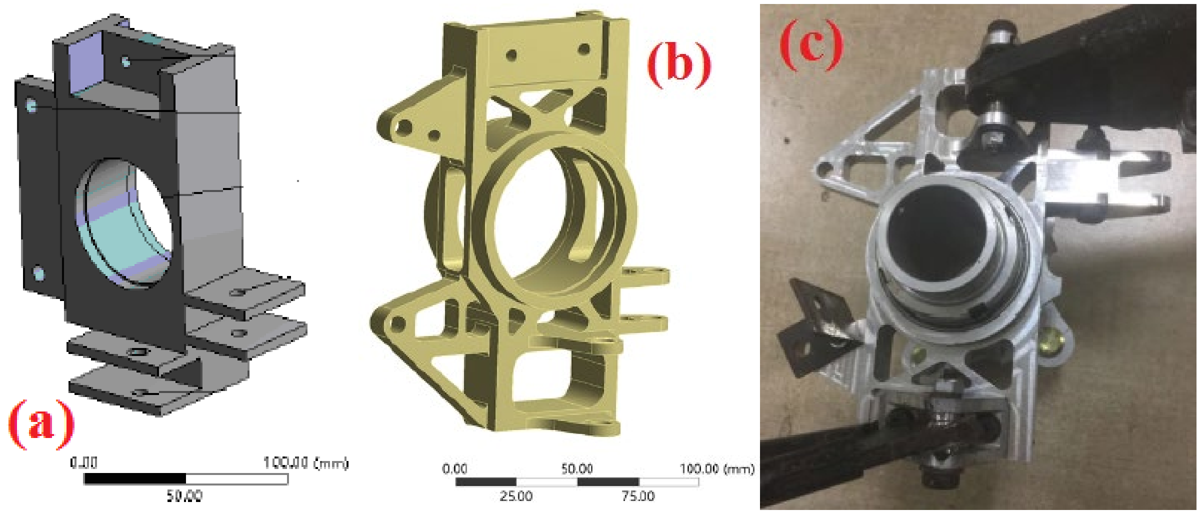

Figure 2: Suspension upright: initial geometric model (a), model after topology optimization (b), the manufactured new model (c) (Li et al. 2020)

Earlier on, 15% reduction in mass had been obtained by Riordan et al. (2010) on a research whose aim was to topologically optimize the Formula SAE upright through the use of an OptiStruct software. These are shown in Figure 3 below:

Figure 3: Formula SAE upright current design (left) and topologically optimized design (right) (Riordan et al. 2010)

Cavazzuti et al. (2011) proposed a methodology that uses topology optimization and topometry optimization together with size optimizations to reach an optimum design of a rear-central engine high-performance vehicle chassis. Ferrari standards were used for the structural performance constraints, paying particular reference to the Ferrari 458 Italia. These constraints were modelled using Finite Element Analysis (FEA). Boundary conditions were applied to test the stiffness of the redesign. The outcome of the research showed a significant reduction in weight, torsional and bending stiffness. Razak et al. (2017) also discussed topology optimization on chassis but focusing on electric racing cars for FV Malaysia. The objective function was to minimize weight compliance subject to a constraint of a maximum of 30% of design space volume. The results showed an improvement on the weight reduction by 11.07% and the maximum von Mises stress by 21.74%.

Sudin et al. (2014) employed the topology optimization technique on a brake pedal with a goal of reducing the weight without sacrificing the performance. Through the use of the Altair Optistruct software under linear static stress, an optimal design was achieved at 22% weight reduction. This is shown in Figure 4 below:

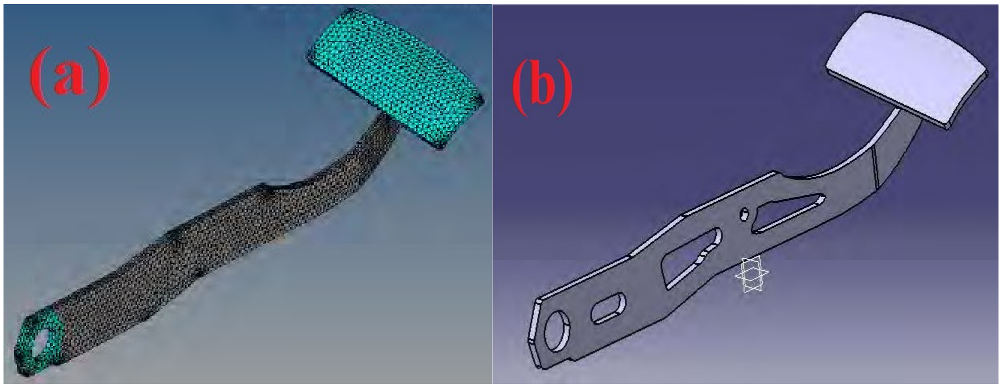

Figure 4: Original brake pedal geometry (a) and topologically optimized (b) (Sudin et al. 2014)

Li et al. (2015) focused on topology, shape, and size optimization of an automotive engine cradle. This is a very important component as it supports the engine, transmission and the suspension, while at the same time distributing the chassis loads over a wider area and reducing the vibrations caused by the engine. The main thrust was to minimize the weight subject to stiffness, natural frequency and durability. Topology optimization was applied first, and the mass was reduced from 82.6 kg to 26.7 kg. After that, size and shape optimization were applied and the mass was further reduced to 21.4 kg. The last stage was to validate the redesigned component for durability using Finite Element Analysis (FEA) and it passed the test. This diagrammatically represented in Figure 5 below:

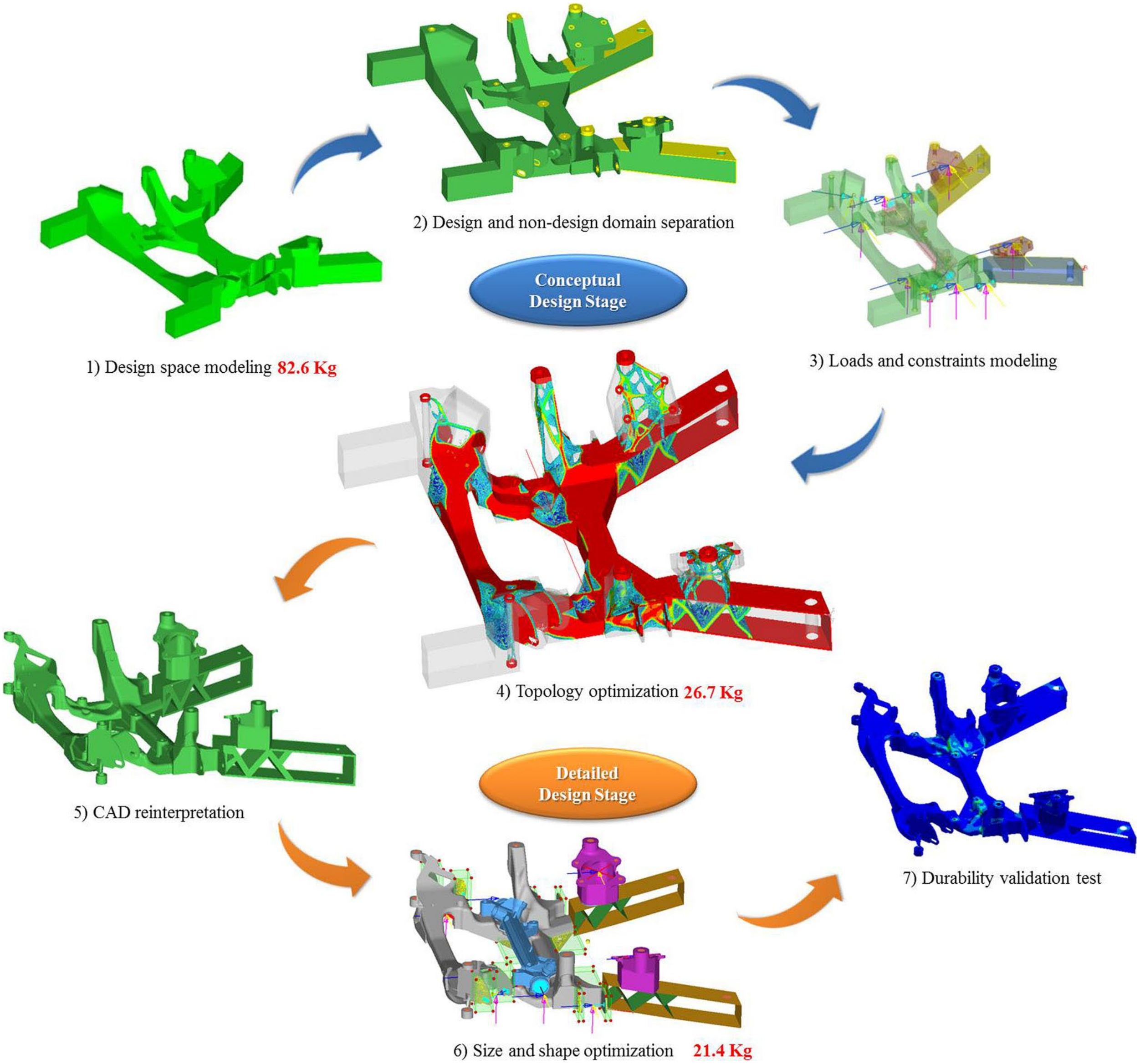

Figure 5: Structural design process of an engine cradle (Li et al. 2015)

It is critical to consider the structural performance and the total cost of production in the early stages of the design process. Yildiz et al. (2004) did a research on weight reduction of engine mount brackets using topology optimization. Both the topology and shape optimization approaches were used to demonstrate how optimal design of vehicle structural components could be achieved without compromising on stiffness and performance under dynamic loading conditions. 75% material usage was achieved and fatigue life evaluation validated the design. In another research, Wu et al. (2016) used the OpiStruct software to topologically optimize an engine bracket and results show that the weight was reduced by 40%.

3. Lightweighting for reduced fuel consumption

Before exploring the effect of lightweighting for reduced fuel consumption, it is imperative to note that even though weight is the most important factor, there are many other parameters that affect fuel consumption. These are diagrammatically represented in Figure 6 below:

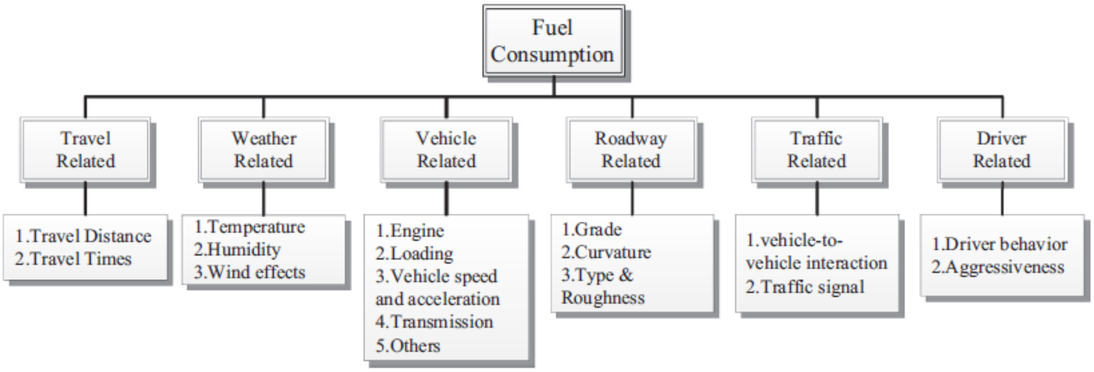

Figure 6: Factors that affect vehicle fuel consumption (Zhou et al. 2016)

Key points to note from the diagram are:

- Weather related – the colder it is, the more the fuel consumption. The weather elements such as ambient temperature, humidity and wind affect the fuel consumption through attachments such as the air conditioning system and the water pump. As an example, a drop in temperature from 24℃ to 7℃ can increase fuel consumption by 16% (Natural Resources Canada, 2014). Air conditioning increases vehicle energy consumption (Khayyam et al. 2011). It can consume about 10% of the fuel (Yu et al. 2020).
- Vehicle related section is the major fuel consumer, and includes the useful energy consumption that is used to overcome the tractive forces to propel the vehicle forward plus the losses that occurs in the engine. This is largely dependent on vehicle weight.
- Roadway related refers to the physical condition of the road (Zhou et al. 2016). Poor, uneven terrain increases rolling friction in the wheels (Kamal et al. 2011). A vehicle moving on a flat road uses between 15% and 20% less fuel than the one moving on a rocky, uneven road (Boriboonsomsin and Barth, 2009).
- Driver related – speeding, driving at an inconsistent speed, extended idling increases fuel consumption. This is one of the main factors that affect the rate at which fuel is consumed in a vehicle (Yao et al. 2020). Experiments at Ford Motor Company showed that improving driving behaviour can improve fuel economy by an average of 24% (Berry 2010). Opening windows in summer makes a vehicle to be less aerodynamic, thereby increasing fuel consumption (Huff et al. 2013).

The customer benefits from weight reduction through reduced fuel consumption. Research in the aviation industry has revealed that removing one pound (0,45 kg) of aircraft mass saves up to 53 000 litres of fuel per year (Civil Aviation Authority - Qatar 2018). As for the automotive industry, reducing a motor vehicle's mass/weight by 10% cuts car fuel consumption by between 6% to 8% (Joost 2012; Bangde et al. 2020; Wang et al. 2020). Figure 7 shows a schematic of the forces acting on a vehicle accelerating on a level road:

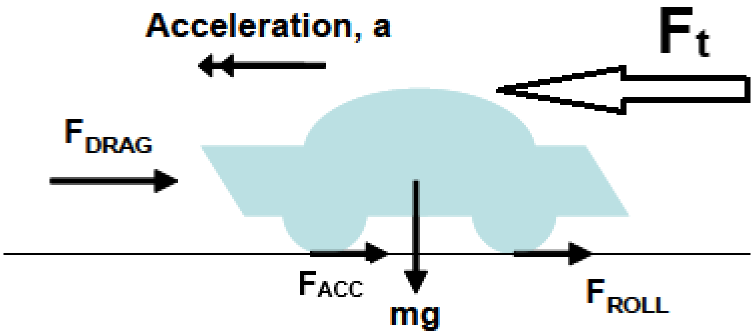

Figure 7: Forces acting on a vehicle accelerating on a level road (Cheah 2010)

The total tractive force F_t, which propels the vehicle forward (Saleem et al. 2020) is given by:

$$F_t = F_{ROLL} + F_{ACC} + F_{DRAG} \qquad \textbf{\textit{(1)}}$$

The rolling resistance at the wheels, is given by:

$$F_{ROLL} = f \cdot mg \qquad \textbf{\textit{(2)}}$$

From Newton's second law of motion, the acceleration resistance is given by:

$$F_{ACC} = m\,a \qquad \textbf{\textit{(3)}}$$

The aerodynamic drag, is given by:

$$F_{DRAG} = \tfrac{1}{2}\, C_D \cdot \rho_{AIR} \cdot v^2 \cdot A \qquad \textbf{\textit{(4)}}$$

Therefore, equation 2 translates to:

$$F_t = (f \cdot mg) + (m\,a) + (\tfrac{1}{2}\, C_D \cdot \rho_{AIR} \cdot v^2 \cdot A) \qquad \textbf{\textit{(5)}}$$

Where:

F_t : Total tractive force [N]
F_{ROLL} : Rolling resistance [N]
F_{ACC} : Acceleration resistance [N]
F_{DRAG} : Aerodynamic drag [N]
f : Rolling resistance coefficient
m : Vehicle plus payload mass [kg]
g : Acceleration due to gravity [m/s^2]
a : Vehicle acceleration [m/s^2]
C_D : Drag coefficient
ρ_{AIR} : Air density [kg/m^3]
v : Instantaneous vehicle speed [m/s]
A : Vehicle frontal area [m^2]

Therefore, using equation 5, increasing vehicle mass/weight increases the tractive force and vice versa (Cheah 2010). Figure 8 below shows the fuel use in a driving cycle.

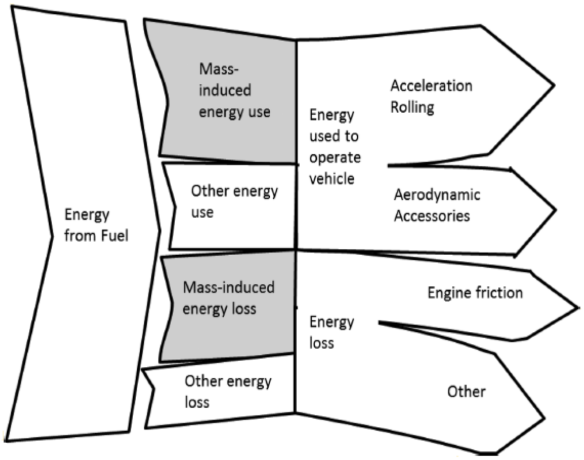

Figure 8: Fuel use in a driving cycle (Kim and Wallington 2013)

The diagram above, although not drawn to scale, illustrates that mass/weight is the greatest contributor to fuel consumption. Weight alone takes 75% of the fuel consumption (Saidpour 2004). Fuel consumption can be broken into the following:

1. Fuel used to operate the vehicle

This is the fuel that goes to the engine and drivetrain and is used to propel the vehicle forward. It includes (Lutsey and Sperling, 2005):

- The inertial energy that causes the vehicle to accelerate forward.
- The energy to keep the vehicle at a desired speed in spite of aerodynamic drag.
- The energy to overcome rolling resistance at the wheels.

The weight of the vehicle directly affects the inertial acceleration of the vehicle and the rolling resistance. A point to note however is that although Figure 8 classifies it under other energy uses, the aerodynamic drag can also be affected by weight. This is if an increase in weight results in an increase in the frontal area of the vehicle, which then increases the air resistance to the forward motion.

2. *Fuel needed to overcome losses*

This is the fuel which is lost inside the engine and on components such as the differential, axle and bearings (Kim and Wallington 2013). The losses include the following (Lutsey and Sperling, 2005):

- The exhaust heat.
- The cooling system.
- Mechanical losses due to friction in the engine.
- Braking losses.
- Pumping losses.

The weight of the vehicle directly affects the size of the engine required. Vehicle mass also affects the friction required during breaking. The energy previously used to overcome inertia and propel the vehicle forward is lost as friction and heat in the brakes. Heavier vehicles have greater inertia, which results in the need for more friction during breaking, hence more fuel is lost (U.S. Environmental Protection Agency 2015). When the weight is reduced the engine can be resized, leading to further reduction of weight, heat and frictional losses (Casadei and Broda 2008). Figure 9 below displays the weight-fuel consumption relationship for an average car and a light truck:

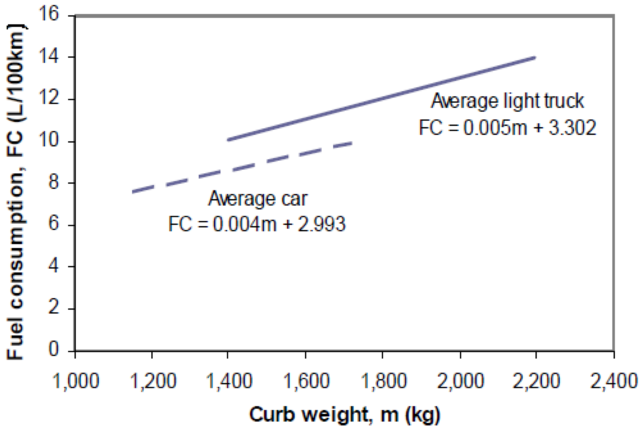

Figure 9: Simulation results for curb weight-fuel consumption relationship (Bandivadekar et al. 2008)

The fuel consumption (FC) for an average car is given as FC = 0.004m + 2.993; where m is the mass/weight of the car. According to the simulations done on the AVL© ADVISOR vehicle simulation software, every reduction in the weight of a car by 100 kg will result in a decrease in fuel consumption by 0.4 litres /100km for cars, and 0.49 litres /100km for light trucks (Bandivadekar et al. 2008). This agrees with the findings of many researchers such as Joost (2012); Bangde et al. (2020); and Wang et al. (2020), whose findings are that every 10% weight reduction cuts car fuel consumption by between 6% to 8%.

4. Lightweighting for reduced emissions

The mass of the vehicle is closely associated with the amount of emissions (Soo et al. 2015). Every 100 kg reduced from a vehicle through either topology optimization or material substitution reduces CO_2 emissions by 9 grams per kilometer (Hirsch 2011). Vehicle mass is also tightly linked to the energy consumed during the production processes. The production of non-sustainable products, that is, products which consume more energy/fuel during use, has increased the levels of NO_x, SO_2, CO_2, HC, PM, CO in the atmosphere. Taking CO_2 as an example, its safe level in the atmosphere is 350 parts per million (Guerra et al. 2020). However, the year 2013 marked the first time when the atmospheric concentration of CO_2 passed 400 parts per million (ppm), climbing from 316 ppm in 1958 (Jones 2017). The 2019 data which was measured by Yale University showed that the level was very high at 415.39 ppm (Yale School of the Environment 2019).

Temperatures have been constantly rising. In the year 2019 alone the world, as examples, witnessed the following:

- The burning of the Amazon rainforest (Lizundia-Loiola et al. 2020). Over 7 million hectares were burnt.
- The 2019-2020 veld fires in Australia. At least 445 deaths were linked to the veld fires, and more than 4 000 people were hospitalized (BBC, 2020a). In addition to that, 3 000 homes were lost, 7.3 million hectares of land burnt, property was lost, and half a billion of the wildlife was affected (Yeung 2020).
- The June 2019 record breaking heat wave in Europe which led to hot weather-related deaths, veld fires and the closing of thousands of schools. Countries like France experienced record-breaking temperatures of up to 45℃ and issued the red weather alert for the first time in history (Xu et al. 2020).
- The rising sea levels causing cities like Jakarta to sink to below 2 meters below sea level to date, and predictions are that 95% of the city will be covered by the sea in 2050, which has forced the Indonesian government to make plans to change the capital city to the Borneo's East Kalimantan province between Samarinda City and the port city of Balikpapan by 2025 (Lin and Hidayat 2018).
- The melting of the arctic (Bhattacharyya et al. 2019) and the July 2020 heat waves in the arctic where temperatures reached 38℃ (Freedman 2020).

Even though there are many contributions to the above-mentioned predicament, industrialization is the main contributor. Save for the electric cars, all the other vehicles use fossil fuels which then releases the greenhouse gases, meaning that if the vehicle weight is reduced so will be the emissions. In countries such as England, people are now being encouraged to use public transport or cycle to their workplaces (BBC, 2020b). Others are being encouraged to reduce the number of times they board flights and stay at home if possible. In a situation where inevitability is concerned, people are being encouraged to avoid connecting flights since the most fuel intensive parts of an airplane is during take-off and landing (Center for Climate and Energy Solutions, 2020).

The 2020 COVID-19 lockdown period brought an opportunity to evaluate the transport sector's contribution on emissions. Le Quéré et al. (2020) did a study on the temporary reduction in daily global CO_2 emissions during the COVID-19 forced confinement. A comparison was made between the atmospheric level of CO_2 during the peak of the lockdown versus the previous levels. In most countries, the lockdown was at its peak during the period from March 2020 to May 2020. Many international borders were closed and everyone who was not involved in essential services like hospital employees was confined to their homes under strict lockdown rules. Figure 10 below represents the global daily fossil CO_2 emissions from 1970 to the end of April 2020. Starting with graph (a) on the left, the black cumulative line shows the mean daily emissions between the years 1970–2019 at an uncertainty of ±5%, which is represented by the grey shading. The red dropping line shows the dropping daily emissions from January up to end of April 2020. Using graph (b) on the right, the red line represents the daily CO_2 emissions from January to end of April 2020.

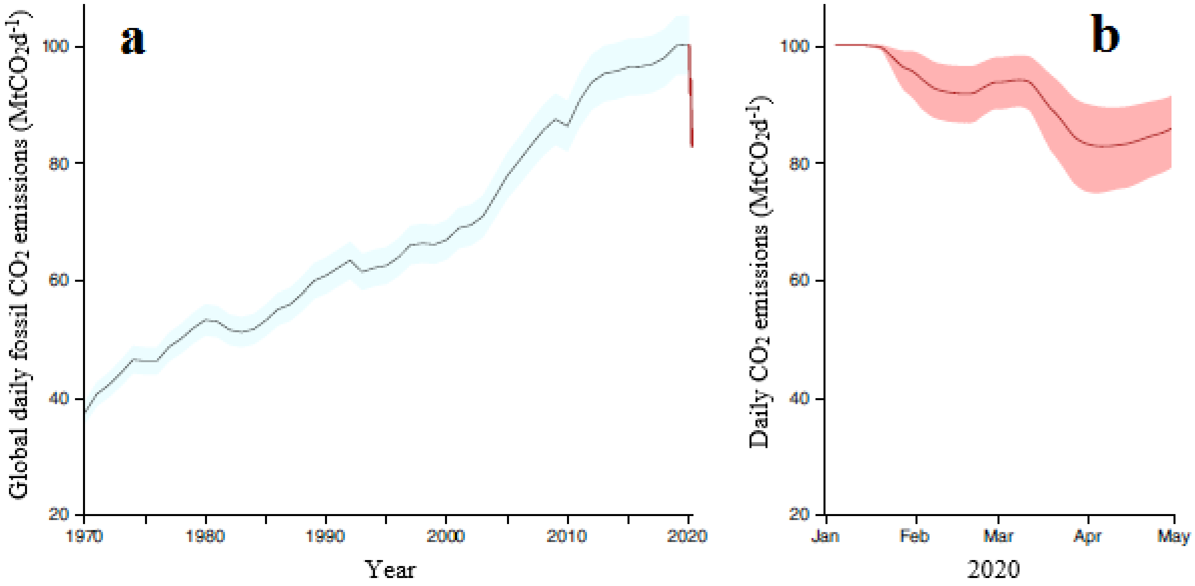

Figure 10: Global daily fossil CO_2 emissions from 1970 to the end of April 2020 (Le Quéré et al. 2020)

The average daily global CO_2 emissions dropped by 17% when compared with the 2019 mean levels. About half of this total change was directly influenced by the changes in surface transport. Figure 11 further shows the changes in the global 2020 daily fossil CO_2 emissions made by the power, industry (manufacturing sector) and surface transport.

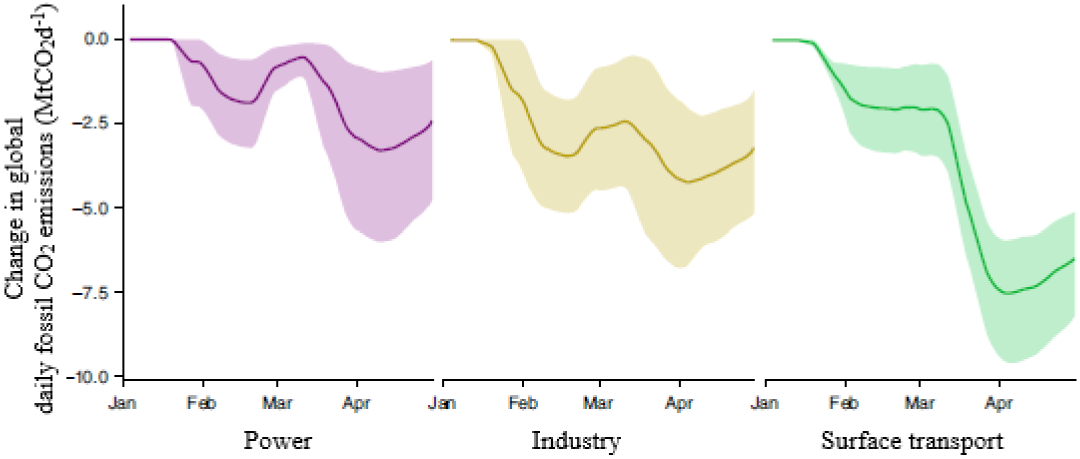

Figure 11: Change in global 2020 daily fossil CO_2 emissions by sector (Le Quéré et al. 2020)

From Figure 11 it can be seen that surface transport made the most significant change. The emissions however rebounded to within an average of 5% lower than the 2019 average values in early June as the easing of the lockdown restrictions started. Again, surface transport had a major contribution to the upsurge. More personal vehicles started to be in use as people avoided public transport with a view of protecting themselves from the corona virus. This proves that lightweighting in the automotive sector has a significant contribution in curbing the negative effects of climate change.

5. Discussion

The main objectives of the paper were to present the different lightweighting technologies that have been implemented in the automotive industry, and how weight reduction is key in reducing vehicle fuel consumption and global warming. In terms of the technologies used to date, there is no outright solution in as far as weight reduction is concerned. One cannot do a total substitution of materials due to the high costs associated with materials such as composites. On the other hand, extreme caution has to be taken when topologically optimizing a component in order to avoid compromising on its compressive and tensile strength, stiffness and durability. One has to strike a balance between lightweighting and performance. Some researchers have adopted a hybrid approach where both technologies are utilized.

Other than weight, the other factors which affect fuel consumption are the physical condition of the road, weather and driver behaviour. However, 75% of the fuel consumption is dependent on the weight. Weight actually affects the entire lifecycle of the vehicle. Starting at the initial stage, there is increased raw material input requirements, to the production line where there is high energy usage, to the after-production stage where high fuel consumption and emission are the order of the day. The negative impact has caused an upsurge in lightweighting as a counter measure. The relationship between vehicle mass and tractive force has been discussed and that a heavier vehicle has to overcome more tractive forces. The paper has also shown how an increase in weight increases the inertia (product of mass and velocity), aerodynamic drag (due to the greater frontal area) and rolling resistance (due to increase in rolling friction). This tends to increase the amount of power required to propel the vehicle forward. Also, due to the heaviness of the vehicle, there is more heat generated in the engine and increased mechanical losses both in the engine and the drive train.

The issue of global warming cannot be overemphasized. Application of weight reduction technologies play a huge role in ensuring that the world does not get any warmer. A 100 kg weight reduction has the potential of reducing CO_2 emissions by 9 grams per kilometer.

6. Conclusion

The following can be concluded from the research:

1. Even though there are many factors that affect fuel consumption, weight stands out with the most significant contribution.
2. Of the two main weight reduction techniques, which are: material substitution and topology optimization there is no outright best method. Material substitution has a tradeoff between lightweighting and high production costs. Also, the material used may not be able to withstand the high forces encountered during use. Topology optimization offers a solution but needs extreme caution so as not to compromise performance. Some researchers have adopted a hybrid of the two technologies in order to maximize the benefits of each technology and minimize on the limitations.
3. Reducing vehicle weight is of paramount importance in reducing fuel consumption. This is because the weight reduction reduces tractive forces encountered in the forward motion of the vehicle, weight is the most significant tractive force and 75% of the fuel consumption is dependent on weight.
4. Weight reduction is also important in curbing the negative effects of global warming which are being experienced world over. This is through reduced emissions to the atmosphere.

The benefits of lightweighting are experienced by the companies, the customer and the world at large, and therefore, the lighter the better.

7. Acknowledgements

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References

Bandivadekar, A., Bodek, K., Cheah, L., Evans, C., Groode, T., Heywood, J., Kasseris, E., Kromer, M. and Weiss, M., *On the Road in 2035: Reducing Transportation's Petroleum Consumption and GHG Emissions.* Available at: http://web.mit.edu/sloan-auto-lab/research/beforeh2/otr2035/, 2008.

Bangde, S., Kini, C. R. and Pai, A., Reconfigurable body exterior panels: a review, *Journal of Mechanical Engineering Research and Developments*, vol. 43. no. 4, pp. 14–23, 2020.

BBC (2020a) Australia bushfires: Hundreds of deaths linked to smoke, inquiry hears, [Online]. Available at: https://www.bbc.com/news/world-australia-52804348#:~:text=Smoke from the massive bushfires,Tasmania told the Royal Commission. (Accessed: 15 November 2020).

BBC (2020b) How our daily travel harms the planet, [Online]. Available at: https://www.bbc.com/future/article/20200317-climate-change-cut-carbon-emissions-from-your-commute (Accessed: 15 November 2020).

Bhattacharyya, U., Borse, P., Bochetty, S. and McBride, M., *Glaciers Melting in the Arctic,* 2019.

Bendsoe, M. P. and Sigmund, O., Topology optimization: theory, methods, and applications, *Springer Science & Business Media,* 2013.

Berry, I. M., The effects of driving style and vehicle performance on the real-world fuel consumption of U.S. light-duty vehicles, *Masters Thesis.* Massachusetts Institute of Technology, pp. 1-140, doi: 10.1016/j.trd.2015.10.003, 2010.

Bodunrin, M. O., Chown, L. H. and Omotoyinbo, J. A., Development of low-cost titanium alloys: A chronicle of challenges and opportunities, *Materials Today: Proceedings.* Elsevier Ltd, pp. 1–6. doi: 10.1016/j.matpr.2020.02.978, 2020.

Boriboonsomsin, K. and Barth, M., Impacts of road grade on fuel consumption and carbon dioxide emissions evidenced by use of advanced navigation systems, *Transportation Research Record: Journal of the Transportation Research Board,* vol. 2139, no. 1, pp. 21–30. doi: 10.3141/2139-03, 2009.

Carberry, W., Airplane recycling efforts benefit Boeing operators, Boeing Aeromang, [Online]. Available: https://www.boeing.com/commercial/aeromagazine/articles/qtr_4_08/article_02_1.html, May 13, 2008.

Casadei, A. and Broda, R., Impact of vehicle weight reduction on fuel economy for various vehicle architectures, *The Aluminum Association, Inc.,* pp. 1–60, 2008.

Cavazzuti, M., Baldini, A., Bertocchi, E., Costi, D., Torricelli, E. and Moruzzi, P., High performance automotive chassis design: a topology optimization based approach, *Structural and Multidisciplinary Optimization,* vol. 44, no. 1, pp. 45–56. doi: 10.1007/s00158-010-0578-7, 2011.

Center for Climate and Energy Solutions (2020) Reducing Your Transportation Footprint. [Online.] Available at: https://www.c2es.org/content/reducing-your-transportation-footprint/ (Accessed: 15 November 2020).

Cheah, L. W., Cars on a diet: the material and energy impacts of passenger vehicle weight reduction in the U.S., *Doctoral dissertation.* Massachusetts Institute of Technology, pp. 1-121, 2010.

Chebolu, A., Automotive lightweighting: a brief outline, *Advanced Combustion Techniques and Engine Technologies for the Automotive Sector*, pp. 247–256. doi: 10.1007/978-981-15-0368-9_12, 2020.

Civil Aviation Authority – Qatar., Airline weight reduction to save fuel: The crazy ways airlines save weight on planes, [Online]. Available: https://www.caa.gov.qa/en-us/News/Pages/Airline-weight-reduction-to-save-fuel-The-crazy-ways-airlines-save-weight-on-planes-.aspx, May 13, 2018.

Croccolo, D., Agostinis, M. De and Vincenzi, N., Influence of tightening procedures and lubrication conditions on titanium screw joints for lightweight applications, *Tribology International,* vol. 55, pp. 68–76, 2012.

Dudek, P. and Zagórski, K., Cost, resources, and energy efficiency of additive manufacturing', *E3S Web of Conferences,* 14, pp. 1–8. doi: 10.1051/e3sconf/20171401040, 2017.

Fontaras, G., Zacharof, N.-G. and Ciuffo, B., Fuel consumption and CO_2 emissions from passenger cars in Europe – laboratory versus real-world emissions', *Progress in Energy and Combustion Science*, vol. 60, pp. 97–131. doi: 10.1016/j.pecs.2016.12.004, 2017.

Freedman, A., Siberian heat streak and Arctic temperature record virtually 'impossible' without global warming, study says, *The Washington Post.* Available: https://www.washingtonpost.com/weather/2020/07/15/siberian-heat-streak-arctic-temperature-record-virtually-impossible-without-global-warming-study-says/, July 17, 2020.

Froes, F. H., Friedrich, H., Kiese, J. and Bergoint, D., Titanium in the Family Automobile: The Cost Challenge, *Jom*, vol. 56, no. 2, pp. 40–44, 2004.

Grand View Research., Lightweight materials market size report analysis by product (Aluminium, Polymers & Composites), by application (Automotive, Aviation, Energy), by region, and segment forecasts, 2017 – 2024, [Online], Available: https://www.grandviewresearch.com/industry-analysis/lightweight-materials-market, May 12, 2018.

Guerra, D. D., Iakovleva, E. V and Shklyarskiy, A. Y., Alternative measures to reduce carbon dioxide emissions in the Republic of Cuba, *Journal of Ecological Engineering,* vol. 21, no. 4, pp. 55–60. doi: 10.12911/22998993/119800, 2020.

Hagnell, M. K., Kumaraswamy, S., Nyman, T. and Åkermo, M., From aviation to automotive - a study on material selection and its implication on cost and weight efficient structural composite and sandwich designs, *Heliyon.* Elsevier Ltd, vol. 6, no. 3, pp. 1–12. doi: 10.1016/j.heliyon.2020.e03716, 2020.

Hällgren, S., Pejryd, L. and Ekengren, J., (Re)Design for Additive Manufacturing, *Procedia CIRP*, vol. 50, pp. 246–251. doi: 10.1016/j.procir.2016.04.150, 2016.

Huff, S., West, B. and Thomas, J., Effects of air conditioner use on real-world fuel economy, *SAE Technical Paper,* no. 2013-01–0551. doi: 10.4271/2013-01-0551, 2013.

Hirsch., Aluminium in innovative light-weight car design, *Materials Transactions*, The Japan Institute of Light Metals, vol. 52, no. 5, pp. 818–824. doi: 10.2320/matertrans.L-MZ201132, 2011.

Jones, N., How the world passed a carbon threshold and why it matters. Yale Environment. Available: https://e360.yale.edu/features/how-the-world-passed-a-carbon-threshold-400ppm-and-why-it-matters, July 11, 2017.

Joost, W. J., Reducing vehicle weight and improving U.S. energy efficiency using integrated computational materials engineering', *Jom*, vol. 64. no. 9, pp. 1032–1038. doi: 10.1007/s11837-012-0424-z, 2012.

Kamal, M. A. S., Mukai, M., Murata, J. and Kawabe, T., Ecological vehicle control on roads with up-down slopes, *IEEE Transactions on Intelligent Transportation Systems*, vol. 12, no. 3, pp. 783–794, 2011.

Karadere, G., Düzcan, Y. and Yildiz, A. R., Light-weight design of automobile suspension components using topology and shape optimization techniques, *Materials Testing,* EDP Sciences, pp. 454–458. doi: 10.3139/120.111503, 2020.

Khademian, N. and Peimaei, Y., Lightweight materials (LWM) in transportation especially application of aluminum in light weight automobiles (LWA), *International Conference on Interdisciplinary Studies in Nanotechnology,* pp. 1–22, 2020.

Khayyam, H., Nahavandi, S., Hu, E., Kouzani, A., Chonka, A., Abawajy, J., Marano, V. and Davis, S., Intelligent energy management control of vehicle air conditioning via look-ahead system, *Applied Thermal Engineering.* Elsevier Ltd, vol. 31, no. 16, pp. 3147–3160. doi: 10.1016/j.applthermaleng.2011.05.023, 2011.

Kim, H. C. and Wallington, T. J., Life cycle assessment of vehicle lightweighting: a physics-based model of mass-induced fuel consumption, *Environmental science & technology,* vol. 47, no. 24, pp. 14358–14366. doi: 10.1021/es402954w, 2013.

Kobayashi, S., Plotkin, S. and Ribeiro, S. K., Energy efficiency technologies for road vehicles, *Energy Efficiency*, vol. 2. no. 2, pp. 125–137. doi: 10.1007/s12053-008-9037-3, 2009.

Li, C., Kim, I. Y. and Jeswiet, J., Conceptual and detailed design of an automotive engine cradle by using topology, shape, and size optimization, *Structural and Multidisciplinary Optimization,* vol. 51, no. 2, pp. 547–564. doi: 10.1007/s00158-014-1151-6, 2015.

Li, J., Tan, J. and Dong, J., Lightweight design of front suspension upright of electric formula car based on topology optimization method, *World Electric Vehicle Journal,* vol. 11, no. 1, p. 15. doi: 10.3390/wevj11010015, 2020.

Li, J., Yu, S., Zhang, N., He, H., Yang, Z. and Jia, Y., Formula SAE racecar suspension system design, *Applied Mechanics and Material*s**,** vol. 416–417, pp. 1840–1844. doi: 10.4028/www.scientific.net/AMM.416-417.1840, 2013.

Lin, M. M. and Hidayat, R., Jakarta, the fastest-sinking city in the world, BBC. Available: https://www.bbc.com/news/world-asia-44636934, July 11, 2018.

Lizundia-Loiola, J., Pettinari, M. L. and Chuvieco, E., Temporal anomalies in burned area trends: satellite estimations of the Amazonian 2019 Fire Crisis', *Remote Sensing*, vol. 12, no. 1, p. 151. doi: 10.3390/rs12010151, 2020.

Lutsey, N. and Sperling, D., Energy efficiency, fuel economy, and policy implications, *Transportation Research Record: Journal of the Transportation Research Board*, vol. 1941, no. 1, pp. 8–17, 2005.

Metal AM., *The magazine for the metal additive manufacturing industry,* [Online], pp. 1–162, 2018.

Natural Resources Canada., *Learn the facts: Cold weather effects on fuel efficiency,* Auto$mart. [Online], Available: https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/oee/pdf/transportation/fuel-efficient-technologies/autosmart_factsheet_3_e.pdf, July 17, 2014.

Le Quéré, C. et al. (2020) 'Temporary reduction in daily global CO2 emissions during the COVID-19 forced confinement', Nature Climate Change. Springer US, 10(7), pp. 647–653. doi: 10.1038/s41558-020-0797-x.

Razak, M. S. bin A., Hasim, M. H. bin and Ngatiman, N. A. bin., Design of electric vehicle racing car chassis using topology optimization method, *MATEC Web of Conferences,* vol. 97, p. 01117, 2017.

Riordan, C., Tovar, A. and Renaud, J., Topology optimization of a Formula SAE upright using OptiStruct, *SAE Technical Paper,* no. 2010-01–0396, 2010.

Roper, S., Li, D., Florea, V., Woischwill, C. and Kim, I. Y., Multi-material topology optimization: a practical approach and application, *SAE Technical Paper,* pp. 1–10. doi: 10.4271/2018-01-0110, 2018.

Saidpour, H., Lightweight high performance materials for car body structures, *NTI Technology Conference, CEME, Ford Motor Company*, pp. 14–19, 2004.

Saleem, A., Liu, N., Junjie, H., Iqbal, A., Hayyat, M. A. and Mateen, M., Modelling of an electric vehicle for tractive force calculation along with factors affecting the total tractive power and energy demand, *3rd International Conference on Computing, Mathematics and Engineering Technologies (iCoMET). IEEE,* pp. 1–5, 2020.

Sudin, M. N., Tahir, M. M., Ramli, F. R. and Shamsuddin, S. A., Topology optimization in automotive brake pedal redesign, *International Journal of Engineering and Technology (IJET),* vol. 6, no. 1, pp. 398–402, 2014.

Soo, V. K., Compston, P. and Doolan, M., Interaction between New Car Design and Recycling Impact on Life Cycle Assessment, *Procedia CIRP.* Elsevier B.V., vol. 29, pp. 426–431. doi: 10.1016/j.procir.2015.02.055, 2015.

Thompson, M. K., Moroni, G., Vaneker, T., Fadel, G., Campbell, R. I., Gibson, I., Bernard, A., Schulz, J., Graf, P., Ahuja, B. and Martina, F., Design for additive manufacturing: trends, opportunities, considerations and constraints, *CIRP Annals*, vol. 65, no. 2, pp. 737–760. doi: 10.1016/j.cirp.2016.05.004, 2016.

Topaç, M. M., Karaca, M., Aksoy, B., Deryal, U. and Bilal, L., Lightweight design of a rear axle connection bracket for a heavy commercial vehicle by using topology optimisation: a case study, *Mechanics,* vol. 26, no. 1, pp. 64–72. doi: 10.5755/j01.mech.26.1.23141, 2020.

U.S. Environmental Protection Agency., Office of Energy Efficiency and Renewable Energy, Where the Energy Goes: Gasoline Vehicles. Available: https://www.fueleconomy.gov/feg/atv.shtml, July 6, 2015.

Wang, L., Di, C., Liu, Q., Song, L. and Jiao, F., Energy saving and emission reduction of study on lightening of dump truck carriage, *IOP Conference Series: Earth and Environmental Science,* vol. 512, no. 1, pp. 6–13. doi: 10.1088/1755-1315/512/1/012003, 2020.

Witik, R. A., Payet, J., Michaud, V., Ludwig, C. and Månson, J. E., Assessing the life cycle costs and environmental performance of lightweight materials in automobile applications, *Composites Part A.* Elsevier Ltd, vol. 42, no. 11, pp. 1694–1709. doi: 10.1016/j.compositesa.2011.07.024, 2011.

Wu, P., Ma, Q., Luo, Y. and Tao, C., Topology optimization design of automotive engine bracket, *Energy and Power Engineering,* vol. 8, no. 04, pp. 230–235. doi: 10.4236/epe.2016.84021, 2016.

Xu, P., Wang, L., Liu, Y., Chen, W. and Huang, P., The record-breaking heat wave of June 2019 in central Europe, *Atmospheric Science Letters,* vol. 21, no 4, pp. 1–7. doi: 10.1002/asl.964, 2020.

Yale School of the Environment., CO_2 concentrations hit highest levels in 3 million years. Available: https://e360.yale.edu/digest/co2-concentrations-hit-highest-levels-in-3-million-years, July 11, 2019.

Yao, Y., Zhao, X., Liu, C., Rong, J., Zhang, Y., Dong, Z. and Su, Y., Vehicle fuel consumption prediction method based on driving behavior data collected from smartphones, *Journal of Advanced Transportation,* pp. 1–11. doi: 10.1155/2020/9263605, 2020.

Yeung, J., Australia's deadly wildfires are showing no signs of stopping. Here's what you need to know, CNN. Available: https://edition.cnn.com/2020/01/01/australia/australia-fires-explainer-intl-hnk-scli/index.html, July 12, 2020.

Yildiz, A. R., Kaya, N. and Öztürk, F., Optimal design of vehicle components using topology design and optimisation, *Inernational Journal of Vehicle Design*, vol. 34, no. 4, pp. 387–398, 2004.

Yu, H., Liu, Y., Li, J. and Liu, H., Real-road driving and fuel consumption characteristics of public buses in southern China, *International Journal of Automotive Technology,* vol. 21, no. 1, pp. 33–40. doi: 10.1007/s12239, 2020.

Zhou, M., Jin, H. and Wang, W., A review of vehicle fuel consumption models to evaluate eco-driving and eco-routing, *Transportation Research Part D: Transport and Environment.* Elsevier Ltd, vol. 49, no. 5, pp. 203–218. doi: 10.1016/j.trd.2016.09.008, 2016.

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