An analysis of new materials and their effects on improving fuel efficiency

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Abstract: This paper introduces the use of new materials in the replacement of traditional materials in automotive vehicles. Firstly, the properties such as tensile strength, elongation at break, Young's modulus, density were discussed and analyzed. Also, the benefits of using new materials are discussed by comparing the physical properties. Then the advantages of AZ91D magnesium alloy, T1000G carbon fiber were compared with traditional automotive materials and the improvements that were achieved where the new materials were proven to have increased strength and decreased weight. Furthermore, the concept of automotive lightweight is applied to demonstrate the relationship between new materials and fuel economy. Finally, the internal and external structures of the materials are analyzed such as the anisotropy of carbon fiber, and it was found that the benefits outweigh the drawbacks like the high production cost of carbon fiber, then suggestions are given for future investigations.

1. Introduction
Vehicle fuel economy has been a hot topic of discussion in recent years. With the increase in fuel prices due to inflation, driving has become less affordable for many households [1]. Climate changes and greenhouse gases is also a major issue that our society faces today. Transport accounts for over 24% of global CO₂ emission, where a typical passenger vehicle produces about 4.6 metric tons of carbon dioxide a year [2]. This means improving fuel economy will also bring benefits for our environment.

New materials have been researched to reduce the mass of the vehicle and maintain costs in achieving fuel economy. Lightweight materials were shown to have great effect in reducing fuel consumption as it directly correlates to energy consumption. However, safety must also be ensured in a vehicle, which means materials must be selected based on their physical and chemical properties such as strength, ductility, hardness, reactivity, and melting points to derive a suitable candidate [3]. Other attributes that must be considered with new materials are their durability (warranty), damageability, repair, and crashworthiness [4].

Efforts have been made to analyze the use of different materials for components of the body. Masaaki Saito reviewed various physical properties of aluminum, which shows that using aluminum for the vehicle body will reduce its weight by 50% [5]. While Eneyw Gardie has focused on carbon fiber, in which 80.4% percent of the weight of wheel application was reduced [6]. P.K. Mallick shows the advantages of magnesium alloy, such as high special mechanical properties, high castability [7]. B.R.
Powell, P.E. Krajewski, A.A. Luo’s article introduces magnesium, the lightest automotive metal structure [8], the appropriate amount of magnesium in the automotive metal. Although studies have been made in analyzing a specific material to ensure the stability and safety of the car while also improving fuel efficiency by reducing the body weight, this paper has put together 2 commonly discussed new materials to compare their use in vehicle production. This paper starts off introducing the properties of magnesium alloy (AZ91D) and Carbon Fiber (T1000G) under experimental conditions. Then a detailed analysis of various kinds of carbon fibers was also made to derive the most suitable candidate for automotive manufacturing. Furthermore, the data was compared with those from the traditional materials to derive an optimal material for each of the bumper, chassis, and door panels of a vehicle. Limitations were discussed on current production of these new materials and possible future steps were offered to ensure the accessibility in the automotive industry.

2. Discussion

2.1 Properties of new materials

AZ91D is a magnesium alloy that is newly introduced into the automobile industry due to its excellent mechanical properties, corrosion resistance, and castability. The corrosion resistance comes from the composition of the alloy, in which over 90% is magnesium as mentioned in Table 1 and the use of iron and nickel is limited to under 0.005% limiting oxidation. AZ91D has a relatively high tensile strength of 230MPa, with a Young’s Modulus of 44.8GPa. This makes the alloy strong and ductile to ensure safety and castability. It has a low density of 1.81 g/cm3 means that the alloy is lightweight and would effectively reduce the weight of the whole vehicle if AZ91D is widely used. Magnesium is currently being used in gearbox, front end and IP beams, steering column, airbag housings as well as in steering wheels, seat frames, and fuel tank covers. Steel components in vehicles can be replaced by a single cast piece of magnesium adding to the strength of the material and allowing for housings to be cast into place. This castability also requires less tooling and gauges which lowers manufacturing consumption.

| Table 1 The composition of AZ91D (MAGNESIUM ALLOY) [9]. |
|-----------------------------------------------|
| AZ91D | Percentage (%) |
|-------|----------------|
| Aluminum | 8.30-8.90 |
| Magnesium | 90 |
| Iron | 0.005 |
| Nickel | 0.002 |
| Zinc | 0.35-0.10 |
| Silicon | 0.10max |

Carbon fiber is a new type of fiber material with high strength and modulus. It contains more than 95% of carbon, consists of flake graphite microcrystalline organic fibers stacked along the axial direction of the fiber after carbonization and graphitization treatment of microcrystalline stone ink material. The biggest advantage of carbon fiber is its lightweight. Carbon fiber has a strength 20 times greater than that of iron, and it is the only material whose strength does not decrease at high temperatures up to 2000°C. Its impact absorption capacity is 4-5 times than that of the ordinary metals and has the desirable characteristics of fatigue resistance and corrosion resistance. Carbon fiber has a low coefficient of thermal expansion, allowing it to drop from temperatures of several thousand degrees Celsius to room temperature without bursting. Carbon fiber composites have a large thermal expansion coefficient, so when they are under the same heat as other materials, they are less likely to deform, making it a useful material in many high-precision structural parts [10]. In fig 1, there is a comparison of different kinds
of materials where carbon fiber has shown to have a higher tensile strength and lower density. T1000G carbon fiber (T1000G) has the highest tension strength, along with other remarkable performances in elasticity and density as shown in table 2, which makes it a good substitute and improving the quality of the frame also guarantees the vehicle safety. Therefore, this paper will be focusing on T1000G as it is a better choice for vehicle production.

![Fig 1 the density, elongation at break, Elasticity modulus and Tension strength of different materials.](image)

2.2 A comparison of traditional with new materials
The traditional material that was used for the vehicle’s chassis was aluminum alloy but compared to the new materials, it has a higher density of 2.67 g/cm³ compared to AZ91D and T1000G of around 1.8 g/cm³, this means that by replacing the traditional material, the chassis would become lighter. Carbon fiber is over 27 times stronger than the current aluminum alloy while AZ91D isn’t significantly stronger it shows that it does have enough strength to replace the current material while significantly reduce the weight to achieve better fuel economy. The Young’s modulus shows the resistance to damage and deformation, after comparing the data, the aluminum alloy has only a modulus of 27.2GPa whereas AZ91D is 44.8GPa and T1000G is sitting at 294GPa, making the new materials far safer options to use.

TPO was commonly used in vehicle bumpers today, but our new materials are better replacements because although their densities are very similar varying between 1.80-1.82 g/cm³, but the purpose of a
bumper is to protect the vehicle and the passengers in a crash. Therefore, the significant increase in
tensile strength and young’s modulus of AZ91D and T1000G improves the safety and quality of the
vehicle and reduces the likeliness that the bumper is damaged in small accidents, which reduces
replacement costs and waste production.

The door panels on the vehicle are mainly built with Q235 steel, it has a high tensile strength of
420MPa and young’s modulus of 210GPa, which is far stronger than the AZ91D, but not as much as
T1000G. However, it does have a high density of 7.85 which is over 4 times as dense as the new
materials, adding a significant amount of weight to the vehicle considering its size. In this case, the use
of T1000G would decrease the weight of the vehicle significantly, hence increasing fuel efficiency, but
research must be done to reduce the costs of producing the carbon fiber on a large scale, or else it would
be impractical.

Table 2 the data of traditional materials of chassis, bumper, doors and new materials

| Components | Materials | Chassis | Bumper | Doors | AZ91D | T1000G | Gen3AHS |
|------------|-----------|---------|--------|-------|-------|--------|---------|
| Density (g/cm³) | Aluminum alloy | 2.67 | 1.82 | 7.85 | 1.81 | 1.80 | 7.83 |
| Tensile strength (MPa) | Thermoplastic Polyolefins (TPO) | 234 | 57 | 420 | 230 | 6370 | 980 |
| Young’s modulus (GPa) | Q235 Steel | 27.2 | 2.10 | 210 | 44.8 | 294 | 200 |

2.3 Effects of using new materials
Weight reduction has a significant effect on improving vehicle fuel economy. A 10% reduction in
vehicle weight will lead to an approximately 8% to 10% increase in power performance at 100km, and
a 2-7m reduction in braking distance which can bring many advantages such as the reduction in fuel
consumption and so on.

Lightweight materials are necessary for propelling the fuel economy of modern cars while ensuring
their safety and performance. Less energy will be used for the acceleration of a lighter car than a heavier
one, thus, lightweight materials are more promising for both automakers and auto buyers. Magnesium
and carbon fibers have better energy absorption than the traditional metal materials such as steel, thus
providing more protection upon impact. Beyond that, lightweight vehicles enhance performance,
especially steering. They are usually more maneuverable to park in limited space. Assembling vehicles
with the components made of light-weight materials normally can reduce the weight of any vehicles
from10% to 60%. Life cycle assessment (LCA) is the most common methodology for assessing how the
products or services influence the environment. Plenty of the examples of comparative LCAs which
related to automotive lightweight context has been exist already [11] and they provide two main
approaches: Proportions-based and FRV-based.

The proportions-based approach is founded on the assumption of a linear dependence between the
quota of FC saving with respect to total vehicle FC and mass saving with respect to total vehicle mass
through a proportionality constant, as shown by the equation below:

\[ \frac{\Delta FC}{\Delta M} = \frac{FC_{ref veh}}{M_{ref veh}} \times c \]  (1)

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Where $\Delta FC$ is Fuel Consumption reduction achieved through vehicle mass reduction [l/100 km], $\Delta M$ is vehicle Mass reduction [kg]. $FC_{\text{ref.veh}}$ is Fuel Consumption of reference vehicle [l/100 km], $M_{\text{ref.veh}}$ is Mass of reference vehicle [kg]. $c$ is proportionality constant [12].

In this approach the proportionality constant fixed which has a value 0.6, as suggested by Lynne Ridge. And adopting the same value of $c$ means the ratio still unaltered ignoring vehicle technical features of each specific application, thus, it may lead to a high degree of uncertainty.

In the FRV-based approach FC reduction achievable through light weighting is determined by the following relation:

$$\Delta FC = \Delta M \times FRV \times 0.01 \quad (2)$$

FRV is Fuel Reduction Value coefficient [l/100 km$\times100$ kg] [12]

Unlike proportions-based approach, which is founded on a rigid proportionality, FRV-based approach is more accurate estimation. With these two algorithms the fuel economy can be calculated whether it’s in large quantities or in specific cases, so the data can be clearly compared to get the highest fuel economy.

Magnesium alloys have a high strength-to-weight ratio. 30-70% weight is reduced if replaced with the traditional material, specifically, they are 36% lighter per unit volume than aluminum and 78% lighter than iron and 75% lighter than steel withstand 10 times more strength than aluminum, titanium, or steel. This will likewise cause a 24-60% increase in fuel efficiency.

If the traditional steel were replaced with magnesium or carbon fiber composite materials, the weight of the car could be reduced by approximately 300 kilograms. According to Francesco Del Pero, Massimo Delogu, Marco Pierini [12], the number of FRV is between 0.02 and 1, use the averaging formula, FRV is 0.707, so $\Delta FC$ would be 2.12.

2.4 Analyze

The increase in the utilization of magnesium in automobile production will bring positive effects to the environment. Magnesium is the eighth-most abundant element of around 2.5% of the Earth’s crust, which represents an unlimited supply that is sustainable. Magnesium is recyclable, therefore, instituting a recycling system would extend supplies, reduce waste, and save energy. This is especially important when around 12 million cars are destroyed around the world each year, producing over 15 million tons of metal wastes. In addition, magnesium can also reduce vibration and overall noise through the tuning of parts, so it also benefits the environment in reducing noise levels. However, the strength, hardness, and modulus of elasticity of magnesium-based materials decrease with increasing temperature. Therefore, if the vehicle is constantly under high temperatures, it will speed up the aging and reduce its life span.

Carbon fiber can be distinguished from the isotropic properties of steel and aluminum alloys because it can be customized due to orientation. For example, an object made of steel can withstand the same amount of pressure from any direction. When a force is applied perpendicular to the fibers, the material can withstand a great deal of force, which means the geometry of the fiber can be engineered for the best application for some vehicle components like a bumper beam. While carbon fiber is light and strong, it also has a weakness: it can be pierced by sharp objects because carbon fiber material is essentially a cloth woven with thread. Its hardness and toughness are based on its large area of stress, when confronted with sharp objects making it is easy to puncture. The other weakness is that carbon fiber is not only expensive but also impossible to repair. If the original material is damaged, the entire carbon fiber will have to be replaced. So even if there’s a small accident, it costs the vehicle owner a great deal to fix, for this reason, currently only 0.007% of carbon composites are used in vehicle as shown in fig 2.
Fig 2 Composition of automobile parts

Another reason why carbon fiber components are not widely used is their high cost of production, they are about 20 times more expensive to produce than steel as shown in fig 3, making it impractical to produce at an industrial level. However, these issues can be addressed when further research and developments are made so that carbon fiber can be standardized to lower the costs of production.

Fig 3 Cost breakdown of carbon fiber body (right) versus steel body (left) for 2009, from Rocky 2011 Mountain Institute's Industry Report.

3. Conclusion
After close analysis of the two new materials: AZ91D and T1000G, it was shown that they can be used as excellent substitutes for traditional automotive materials. They both have the desirable high strength, low density, and good ductility that will work together to reduce the weight of the vehicle by over 30-70% and enhance its performance. This will achieve the goal of increasing fuel efficiency by approximately 25-60% while ensuring safety. In turn, this improvement can promote the protection of the environment by saving energy and reducing emissions, which is beneficial for addressing the
constant environmental issues that society is facing today. Overall, through the comparison of data for the traditional and new materials, it was found that the replacement of traditional materials in automobile production with new lightweight materials will bring positive social and environmental impacts, however, future studies are encouraged for solutions in reducing the cost of production.

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