Journal of
Nanoscience and Nanotechnology
Vol. 12, 6621–6630, 2012

RESEARCH ARTICLE

Nanotechnology in Automotive Industry: Research Strategy and Trends for the Future—Small Objects, Big Impacts

Margarida C. Coelho[1,*], Guilhermina Torrão[1], Nazanin Emami[2], and José Grácio[1]

[1] *Centre for Mechanical Technology and Automation, Department of Mechanical Engineering, University of Aveiro, Aveiro, 3810-193, Portugal*
[2] *Department of Engineering Science and Mathematics, Luleå University of Technology, Luleå, 971 87, Sweden*

The goal of this paper is to emphasize and present briefly the nanotechnology science and its potential impact on the automotive industry in order to improve the production of recent models with an optimization of the safety performance and a reduction in the environmental impacts. Nanomaterials can be applied in car bodies as light weight constructions without compromising the stiffness and crashwortiness, which means less material and less fuel consumption. This paper outlines the progress of nanotechnology applications into the safety features of more recent vehicle models and fuel efficiency, but also emphasis the importance of sustainable development on the application of these technologies and life cycle analysis of the considered materials, in order to meet the society trends and customers demands to improve ecology, safety and comfort.

Keywords: Automotive Industry, Fuel Consumption, Life Cycle Analysis, Nanomaterials, Safety, Vehicle.

1. INTRODUCTION AND OBJECTIVES

The world budget from different governments for research on nanotechnologies research was about $4.6 billion in 2005 and which will accelerate up to $1 trillion by 2015.[1] Vehicle safety, performance, and fuel efficiency provide a demand for new and advanced materials in automotive applications. Nanomaterials for automotive applications are intended to pursue reductions in engines emissions, safe driving, quiet vehicles, self-healing body and windscreens.[2] The idea of using nano-fluids to improve coolant performance was presented long time ago.[3] The outcome of that proposal was 100% increase in liquid thermal conductivity, using nanometer scale particles resulted in many more scientific research projects in this area.[4] Even so, the improvements in coolants performance may provide drive and motivation for further improvements in engine efficiency and reduced size and weight of cooling systems. Also, there is research with focus on the improvement of thermal and rheological properties of lubricants, using nano-particles.[5]

An improvement in vehicle's weight reduction is an important issue for motor vehicles since reducing weight is the principal way to increase fuel economy. Global expectations for fuel economy and low emissions for manufacturing and transportation are creating a demand for new low-cost, high-performance lightweight materials to replace metals. Nanocomposite is the name used for final solid matrix that contains nano-objects (for example a novel class of polymeric based materials exhibiting superior mechanical, thermal, and processing properties, suitable to replace metals in automotive and other applications).[6] The effectiveness of the nanoparticles is such that the amount of material added is normally only 0.5–5% by weight. Such a nanocomposite has properties that are superior to conventional microscale composites and can be synthesized rather inexpensive and using simple techniques.[7] The use of nanocomposites in vehicle parts and systems is expected to improve manufacturing speed, enhance environmental and thermal stability, promote recycling, and reduce weight. Applying this technology only to non critical structural parts of vehicles such as front and rear parts, cowl vent grills, valve/timing covers, and truck beds could yield several billion kilograms of weight saved per year.[6]

Nanotechnology is already in mass production for automobile components: antireflection, coating based on multiple nanolayers on glass is used for instruments by Audi and by Daimler Chrysler.[2] General Motors Corp.

*Author to whom correspondence should be addressed.

began using a thermoplastic olefin (TPO) nanocomposite in an optional step-assist for the Chevrolet Astro and the GMC Safari mini-vans. Substituting reinforced polymers in vehicle body components is a promising approach to weight reduction, but it is important to not compromise safety, cost or other desired attributes.[8] Also, sun protecting glazing with infrared reflecting nanolayers embedded into sheets of glass is used in buses. Thermoplastic nanocomposite with nanoflakes is used for stiff and light exterior parts like the step-assist by GM. Presting and Koning[2] predicted that a 30% improvement of roll-resistance, air-resistance, car-weight or of power train might reduce the fossil fuel consumption by 4%, 6%, 15%, or 28%. Hence, CO_2 emissions will decrease. Also, nanotechnology can contribute to fuel injection and reforming, to hydrogen storage, to the cell electrodes and to the proton exchange membrane (PEM). Further, efficient engine combustion can be achieved by applying nanojets which would decrease the losses by surface tension during aerosol formation.[2] An additional application of porous nanocomposites can be used as pollution filters, which mechanically and/or by catalytic reaction suppress emission of soot particles or toxic gases.[9,10]

This paper aims to address the contribution of nanotechnology in automotive components, in order to increase safety and environmental performance and state the research strategy in this field that must be addressed in the near future. Namely, the state of art of nanotechnology applications on the research of lightweight, safety and fuel efficiency in vehicles are analyzed in detail. Also challenges and weaknesses to guide further research in order to anticipate magnitude and nature of the impact of specific nanotechnology-based innovations in the automotive industry are outlined.

This paper is organized with the following sections: literature review, research strategies for nanomaterials applications and its risk assessment approach. Some guidelines are presented for future nanotechnology research to assist automotive industry to produce ecological friendly vehicles without compromising design and safety features.

2. LITERATURE REVIEW

Bauer et al.[11] has described nanotechnology as "an opportunity to influence the properties of materials in a way that smaller but more capable and more intelligent systems" components with improved or new functionalities can be produced. The automotive industry benefit from nanomaterials in several domains, such as: frames and body parts, engines and powertrain, tribological aspects, paints and coatings, suspension and breaking systems, lubrication, tires, exhaust systems and catalytic converters, and electric and electronic equipment, in addition to reducing car weight, enhancing material functions, increasing comfort degree and flexibility, raising cost efficiency. Almost all the automobile components can be improved by nanotechnology as illustrated in Figure 1.

The design and manufacturing of cars, trucks and buses can be affected by nanotechnology and related technologies up to 60% in 10 years.[12] Other authors have shown existing nanotechnologies in cars applications such as light-weight construction using carbon nanotubes.[6] Nanocomposites are new class of polymeric/non polymeric filled composites with unique mechanical, physical, and processing properties. They may potentially be manufactured at low cost and may offer other advantages on density and processing with respect to metals and polymeric composites currently used in the fabrication of parts for automotive applications. Nanocomposites can be made by the *in-situ* intercalation polymerization method, where the monomer is first intercalated in the clay, and subsequently polymerized *in situ*. This method was pioneered by Toyota Motor Company to create Nylon 6 ± clay hybrid (NCH), used to make a timing-belt cover, the first practical example of polymeric nanocomposites for automotive applications.[6]

Coating for engine applications has been studied by several investigators.[13,14] There are advantages and limitations of conventional materials systems and techniques such as chemical–vapor–deposited diamond-like carbon (DLC) coating, plasma sprayed metal matrix composite coating, etc. Nano-grains of crystalline phase have potential in solving several such problems present in conventional coatings. These coatings provide high hardness, low residual stress and high toughness and show very good tribological properties. Zeng et al.[15] have used nano zirconia powder (<50 nm), to coat various substrates by atmospheric plasma spray. Higher coefficient of thermal expansion (CTE), hysteresis and lower thermal diffusivity, higher hardness and toughness compared to the traditional (microscale) coating are some examples of benefits of using nanoscale coating in automotive engine. Thermal diffusivity reduces, due to extra phonon scattering by boundary defects. Small grain size give higher hardness and toughness, also grain-sliding plasticity would be expected.[16]

Not much work has been investigated in the field of nanomaterials in engine applications, except on DLC and TBC, especially for automotive engines. The outstanding properties (mentioned above) of nanoscale materials has the potential to speed up the transition from a limited fossil fuel to a virtually unlimited and renewable energy source, namely hydrogen.[13]

2.1. Nanotechnology: Applications in Automotive Industry

This section presents in more detail the nanotechnology applications in the automotive industry: weight reduction and vehicle safety and accordingly fuel economy, engine emissions, fuel cells and tribological aspect.

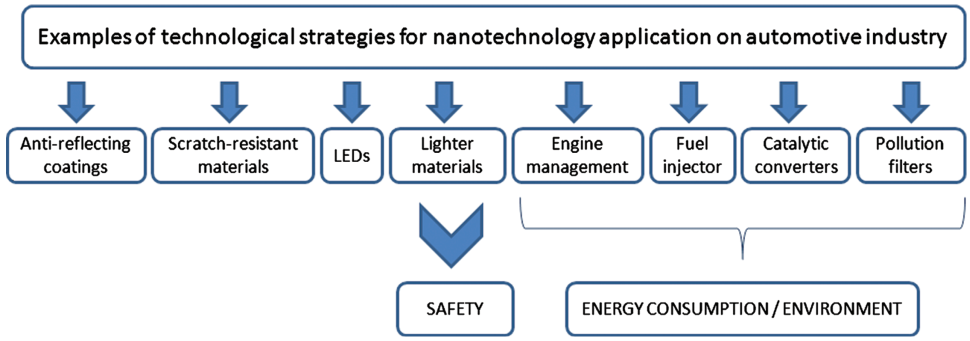

Fig. 1. Examples of application fields of nanotechnology in the automotive industry.

2.1.1. Nanomaterials for Vehicle's Weight Reduction, Safety and Fuel Economy

Nanotechnology application into the automotive industry leads to lighter car bodies without compromising stiffness and crashworthiness means less material and indirectly less fuel consumption. Nanocomposites based on various metal or plastic matrix material strengthened by metal or ceramic nanoparticles or nanoplatelets can improve the strength by 100%. Carbon Bucky fibers promise a tensile strength of 150 GPa, about 50 times that of steel with 1/5th of the weight. Even a polymer nanofiber would yield considerably thinner, stiffer and lighter parts for cars. That opens a huge research field for the next years.[2]

Nanocomposite plastic parts offer a 25% weight savings on average over highly filled plastics and as much as 80% over steel.[6] General Motors (GM) produced the electric Chevy Volt that uses 45.4 Kg of thermoplastics, including composites in the hood and doors, plus unreinforced polymeric materials in the rear deck lid, roof and fenders.[17] Among the plastics used in the Volt is a continuous glass fiber reinforced sandwich composite for lightweight horizontal body panels. Tesla sport car has high power-to-weight ratio tanks and sink of lightweight carbon fiber/epoxy composite. Also the British automaker Lotus has developed the new sport model Evora with mostly aluminum chassis along with a composite roof and stressed composite body panels that add to the car's high stiffness.

Vehicle mass is one of the most important design features that has a straight correlation with fuel consumption rate. The study conducted by Fontaras and Samaras[18] shows that the approximately reduction 13% of CO_2 could benefit from the following factors: 10% in average vehicle weight joined with 10% aerodynamic optimization, 20% reduced tirese rolling resistance and 7.5% increase in average powertrain efficiency. Hence nanotechnology offers advantages for automotive parts fabrications which will guide vehicles characteristics optimization and leads to uniform impact on emissions in order to reach average targets set for CO_2 emissions from the transportation sector. 5% and 10% reduction in vehicle weight will lead to a reduction in CO_2 emissions between 1.3–1.8% and 2.7–3.6% respectively.[18] This study shows that the benefit gained due to weight reduction reflects lower demand for engine power and a reduction in rolling resistance, as well as reduction of fuel consumption.

Advanced nanotechnologies applications are allowing the implementations of lightweight components hence resulting in vehicle weight savings. The common 900 kg of steel and other metals in cars can be reduced by up to 300 kg through the use of composites and hybrid solutions. Thermoplastic compounds are being broadly applied in the automotive leading to innovative challenges. Volkswagen uses long-fiber-reinforced thermoplastic (LFRT) Celstran®+, in the dashboard of the Golf Plus, leading to an elimination of metal and processing steps resulting in a weight reduction of about 8 kg as well as lower production costs. RTP Company announced the commercialization of polypropylene LFRT designed to meet automotive specifications. This impregnated concentrated combines 60% by weight very long glass fibre reinforcement and additives to a single pellet, allowing processors to easily blend it with precise polypropylene resin at the press. The concentrate can be used to increase stiffness, impact resistance, and long-term endurance of polyolefin materials when diluted to long glass fibre levels of 20–40% in finished goods.[17] These advanced thermoplastic, which have increased stiffness, impact resistance and long-term endurance, when applied in the automotive industry yields in weight reduction without compromising vehicle's safety features. Also these nanomaterials applications form leads to improve fuel economy.

LFRT when compared with metals offers higher strength-to-weight ratios and impact resistance, good design flexibility, and corrosion reduction. Also, glass mat thermoplastic (GMT) show a shorter moulding cycle times, longer shelf life offer a better resistance at a wide range of temperatures. These GMT characteristics make their selection by the automotive industry for exterior panels in the next years. Ford Motors Company suggested that an improvement of the fuel economy by 40% by 2010 requires an estimate of 340 kg vehicle weight reduction,

without compromising safety; to achieve this challenge the Company wants to develop paints, plastics, light metals and catalyst using nanomaterials.[17]

Since approximately 90% of the total energy used by an automobile during its life cycle is from fuel consumed, this weight reduction offers the potential of significant energy savings for the automotive industry and vehicle users.[6] Nano-scale reinforcement should enable part and system design of polymer composites that will be cost-competitive with other polymers, and eventually replace metals and glass, thus enabling the automotive industry to capture a leadership position in fuel-efficient, higher-quality, and durable vehicles.[6, 17]

Nanocomposites are also being applied to develop composites for hybrids. Recent investigation shows that using structural low-density composites in a one piece moulding in trunk compartments can reduce mass up to 50%.[17] Green resins, which include 30% recycled and renewable materials are being developed for automotive applications.

2.1.2. Applications to Engines and Catalysts for Automotive Emissions Cleaning

In 2009 a new average CO_2 emissions limit for passenger cars was introduced in the European Union imposing gradual average CO_2 emissions reduction to 130 g/Km until 2015.[18] In addition to light weighting vehicles, improvements in tires rolling resistance, engine efficiency and catalysts are necessary to reach European emissions goals.

The application of nanotechnology to develop new engines and powertrain requires an optimization of thermal and mechanical efficiency which it is possible by use of nanocrystalline structures that offer great strength and temperature resistance.[12] In the future engine fuel injector will incorporate thin diamond like carbon coatings and hence the wear resistance will be improved.[12]

During the last decades the development of heterogeneous catalysis was crucial to reduce emissions from vehicles engine combustion. The catalysis has been improved by using catalytically active nanoparticles onto a highly porous support material with very high surface are for automotive emission cleaning.[19] A further application of porous nanocomposites is related with the use as pollution filters, which mechanically and/or by catalytic reaction suppress emission of soot particles or toxic gases.[2]

2.1.3. Nanomaterials Applications to Energy Efficiency and Fuel Cells

Due to better nanomaterials, hydrogen production, storage and transformation into electricity in fuel cells are being improved with more efficient catalysts for water splitting, better nanostructured materials for higher hydrogen adsorption capacity and cheaper/simpler fuel cells.[20]

Solar cells on the vehicle roof are already an option; however they still have some limitations, so improvements are needed. To improve these cells, nanocomposites with semiconductor matrix might improve adsorption and increase efficiency. One idea may be the use of the complete car body as a solar cell. Various nanocomposites appeared, such as a photovoltaic paint composed of dye-sensitized TiO_2 nanoparticles embedded in an electrolyte or a flexible thin film semiconductor cell with multi nanolayers, or polymer cells either with carbon bucky balls or with semiconductor nano-rods.[2] Based on an envisaged efficiency of 10%, one can gain around 0.5 kW of electrical power for a limousine, enough to feed into the battery and thus saving power by the accompanying release of the vehicle's generator.

Fuel cells are regarded as the engines of the future with hydrogen as the energetic vector. Nanotechnology can contribute to improve fuel injection and reforming, to hydrogen storage, to the cell electrodes and to the proton exchange membrane (PEM).[2] An efficient aerosol formation in the methanol reformer, but also of fuel in the traditional combustion engine, can be achieved by means of nanojet arrays. High-pressure injection through nanojets lowers losses by surface tension. Porous compounds like foams with irregular nanopores may improve subcomponents of the fuel cell. The gas distribution layer (for H_2 and O_2) on both sides of the PEM or the electrodes need large surfaces.

In the long-term, fossil fuel engines can be substituted by those using hydrogen, either by direct combustion (BMW homepage) or by fuel cells (Toyota, GM and DaimlerChrysler homepages). An efficient storage medium for hydrogen is required in order to reduce the tank volume down to 10% of the present hydrogen pressure tanks. Adsorption to metalhydrides and alanates is presently investigated. However, great hope is directed to carbon nanotubes. Some authors state that the expected huge storage capacity of nanotubes for hydrogen is not proven and research would be needed to solve this topic in concerted action.[2] However, several other authors state that carbon nanotubes (CNTs) offer a great potential for solid hydrogen storage because of their thermal and chemical stability, large surface are and light weight [21 and references within]. For instance, Coelho et al.[21] used Hot Filament Chemical Vapor Deposition (HFCVD) to analyse hydrogen adsorption on multiwalled carbon nanotubes (MWCNTs) modified by nickel doping. An important finding of this work was to show a new hydrogen storage process using the HFCVD and that hydrogen adsorption onto CNTs results from catalytic activity of nickel.[21]

Nanotechnology can be applied to hydrogen fuel cell to reduce costs by improving the efficiency.[20] Carbon nanotubes and carbon nanofibers, mesoporous carbon and conductive oxides such as SnO_x/ITO, Ti_xO_y, TiO_2/ITO or WO_x are envisioned to be used in commercial electrodes,

both cathode and anode. For most of them, doping is the main strategy to further improve these nanomaterials for its application as supports of catalyst for membrane fuel cells.[20]

The future development of new electric vehicle models is strongly influenced by the advancement of long life, fast charging and better capacity batteries. Promising electrochemical properties including excellent kinetics and cycling stability have driven research interest in nanomaterials.[22] Ultracapacitors when compared with conventional batteries offer the ability to endure repeated cycles for many years without degradation and can tolerate cold weather conditions, shocks and vibration.[23] On the other hand, the ultracapacitors have the disadvantage of a limited capacity for storing energy. However, latest advance nanotechnology, in particular carbon nanotubes can significantly increase the ion-collecting surface area of the ultracapacitor, increasing its energy storage capacity upwards of 25% of a conventional Li-ion battery.[23] In addition, there have been developments in new electrode materials for lithium ion batteries in the past decade; namely, nanostructured materials have emerged as highly suitable candidates, including Si anode and $LiFePO_4$ cathode materials, and are starting to be used in the marketplace. This review highlights the major roles of nano size in lithium reactive nanomaterials for Li ion batteries, with the aim of providing nanomaterial scientists with a better understanding of electrochemical concepts that can be exploited for tailored design of electrode materials.

2.1.4. Nano-In-Tribology: Improvement of Tribological Aspects in Automotive Industry

Brake squeal is a well known problem caused by dynamic instability in vehicles, which is influenced by its instability of its structure and small disturbance due to the variation in friction force. Nishiwaki et al.[24] suggested that refinement of pad materials improved the performance of the brake materials, less brake squeal, based on their molecular dynamic approach and experimental validations. In recent years, brake effectiveness, as part of brake performance is required for vehicle safety. It is also affecting the comfort factor. Using nanomaterials in designing new brake material has shown to increase the brake's life time and reduce the brake squeal.

Nanocoating for engine application in automotive industry is another field nanotechnology which has attracted great deal attentions. Issues such as tribological behavior, lubrications, coefficient of friction, hot hardness, surface roughness and topography, residual stress, adherence, damage tolerance and resistance and so much more have been investigating. Advantages of conventional materials and their limitations and techniques such as chemical–vapor–deposition diamond-like carbon (DLC) coating, plasma sprayed metal matrix composite coating, tribologically functional ceramic coatings etc. is discussed thoroughly by Dahotre and Nayak.[25]

Mechanical friction is another concern in attempts to reduce friction and wear. Piston system in cars is major contributor to engine friction.[26] Nanoparticles or nanocrystals made of metals, semiconductors, or oxides are of particular interest. In PVC coating in automotive industry applications, nanoparticles are of great scientific interest as they are effectively bridging the properties between bulk materials and atomic or molecular structure. Prabhu and Vinayagam used CrN nano particles for surface engineering of piston ring and piston head to reduce the friction and improve their wear properties using PVD system.[27]

By averting the liners in automotive engine, the engine dimension reduces significantly. About 1 kg per engine easily can be saved according to Ebisawa and Rao, which helps in reduction of the overall engine dimension.[28–30] It is important to remember that each and every kilogram reduction of payload is essentially important for fuel efficiency.

According to US Department of Energy,[31] 100 kg reduction in a vehicle weighted about 1100 kg would affect the fuel economy by 7%. Considering the life time of an average vehicle this reduction is significant. By employing nanomaterials much of this objective can be achieved. The nano-world possess so much potential that Nobel laureate Dr. Richard Smalley predict that nanotechnology is the tool for solving the energy problem of the tomorrow's world.[32] Employment of nanotechnology in current and future automotive, aero and other engines will go long way in solving energy crisis.

Another aspect of application of nanotechnology in order to reduce the wear and friction in car tires. For decades, carbon black micro/nanoparticles are already integrated into tires' rubber. Developments of nano products into tires still attract many researcher attentions. Tires manufacturers (such as Michelin, Goodyear and Bridgestone) are adding nanoparticles to their products to improve wear to abrasion resistance and gas permeability.[33]

2.2. Nanomaterials: Their Potential Toxicity and Impacts in the Environment

Nanoproducts applications have uncertainties regarding environmental impacts. Nanoparticles can be released to the environment reaching water, soil and the air. As result, they can persist for a long time or be taken up by biological organisms. Also, they can act as ecotoxical hazard and undergo biodegradation or bioaccumulation in food chains. The main causes of nanoparticles toxicity are due to: the chemical toxicity of materials included into its structures; their small size allowing its penetration into the cellular membranes and its shape, like nanotubes that can easily penetrate cell membrane.[34] The effects of nanoparticles

(materials with dimensions between 1 to 100 nm) are still being investigated with regulatory concerns moving from the traditional PM10, PM5 and PM2.5 as the increased toxicity of the finer particles has been identified.[35] A critical feature of nanoparticles is their high surface-area-to mass ratio, which provides additional sites for bonding or reaction. Hence when inhaled they may penetrate cells allowing direct access to the bloodstream and possibly circumventing the blood-brain barrier or depositing in the other organs of the body.[36]

Vehicles still emit carbon-based aerosols nanoparticles as a result of incomplete combustion, as well as lead compounds. Currently, the new vehicles are equipped in catalysts containing noble metals, such as platinum. A few years ago, it was announced that platinum nanoparticles, with dimensions in the range 0.8–10 nm, were released from car catalysts during their life-time.[34] The newest catalysts, recently introduced by Mazda, also contain nanoparticles of metals such as platinum and palladium, but having size several times smaller than in conventional catalysts. Lately, it has been found that addition of Al or Al_2O_3 nanoparticles to diesel fuel improves its properties. Due to degradation of nanoparticles present in the environment, heavy metals may be released. For example, it has been shown that nanodispersed platinum group elements can be transferred to animal tissues.[34,37] Also, nanomaterials with very low solubility or degradability may accumulate in biological systems. The variables used by these authors to predict nanoparticles environmental risk include environmental persistence, bioaccumulation and toxicity. CNTs are some of the least biodegradable engineering nanomaterials since they are lipophilic and insoluble in water (and so have the potential to enter fatty cell membranes). These properties may be related with a tendency of CNTs to bioaccumulate.

Concerning the risks to humans, nanoparticles primarily enter the human body through inhalation or dermal contact.[34,37] Biodegraded nanoparticles in the cellular environment may accumulate within cells and lead to intracellular changes such as destruction of organelle integrity and gene alterations.[34]

A semi-analytical model describing by Högberg[38] where the motion of fiberus particles ranging from nano- to micro scale has been developed. Their results showed that particles with elongated shape has higher probability of reaching the vulnerable gas-exchange region in the deep lung compare to particles with diameters in the size-range 10–100 nm and lengths of several micrometers. It was noticeable that popular MWCNTs would fall into this size-range.

The exposure to single wall carbon nanotubes (SWCNTs) containing metal *in vitro* resulted in oxidative stress, as confirmed by the formation of free radicals, accumulative peroxidatives products, and depletion of cells antioxidants.[39] It is possible that the exposure to multi wall carbon nanotubes (MWCNTs) may play a significant potential role in human health effects associated with pulmonary and epidermal toxicity and genetics interactions. Both SWCNT and MWCNTs are non-biodegradable and resemble needle-like, carcinogenic asbestos fibers in size, shape and cellular persistence. The National Institute for Occupational Safety and Health (NIOSH) have reported data showing that MWCNTs can indeed migrate intact from the lungs of mice and into the tissue surrounding the lungs where asbestos induces a form of cancer known as mesothelioma. Further, to assess CNTs potential toxicity, human T lymphocytes, a possible targets cell that gain access to lymphoid tissue following interstitialization were found to be killed in a time- and dose-dependent manner. Also, studies using ultrafine particles and CNTs demonstrated an association with cardiovascular effects, such as platelet aggregation and enhance vascular thrombosis.[38,39]

Thus, as a consequence of widespread usage and their supposed persistence against degradation, human and environmental exposure to CNTs is likely to increase. However, the results of toxicological studies suggest that nanotubes may affect human health.[38,40] Köhler et al.[40] tracked CNTs throughout their life cycle as part of two types of consumer products: lithium-ion secondary batteries and synthetic textiles. The findings suggest that a release of nanotubes can occur not only in the production phase, but also in the usage and disposal phases of nanotube applications. Also, the likelihood and form of release is determined by the way CNT are incorporated into the material. In addition, as long as potential adverse effects of CNT cannot be ruled out, the authors recommend implementing precautionary measures along the value chain (including the end-of-life treatment) in order to reduce the release and possible negative environmental or human health effects of CNT.

Due to the explained toxicity concerns explained above, there is an urgent need for examination of environmental exposure that must take the following issues into account: identification and quantification of sources, determination of the environmental release pattern, establishment of concentrations in the environment, and examination of the potential bioaccumulation.[34]

2.3. Nanomaterials: Costs and Benefits

Despite the environmental impacts and toxicity of nanoparticles, nanotechnology presents great opportunities to develop new and improved consumer products for the benefit of society. Nevertheless, the benefits for society and industry related to nanomaterials applications and its consequences to the environment and humans, as well as other components (benefit, source chain, exposure and cost) must be taken into account during the assessment of the risk and life-cycle impacts of nanomaterials.[41]

Some benefits of the nanoproducts applications to the environment are: electronic components that allow

energy efficiency, also nanocomposites materials used in vehicle models which contributes to weight reduction and improves of materials properties, as hardness.[11] Hence these benefits represent environmental advantages of nanotechnology applications.

Despite of all advantages of nanomaterials applications, it is very important to balance the costs and benefits associated with nanotechnology. Some authors estimated potential selected economic and environmental impacts associated with the use of nanotechnology in the automotive industry;[8] they projected the material processing and fuel economy benefits associated with using a clay-polypropylene nanocomposite instead of steel or aluminum in light-duty vehicle body panels and they concluded that although the manufacturing cost is currently higher, a life cycle analysis (LCA) shows potential benefits in reducing energy use and environment discharges by using a nanocomposite design. Use of nanoparticles in medical procedures has shown successful results, for example as imaging tools, phototherapy agents and as gene or drug delivery carriers. Also, nanoparticles with magnetic properties will be valuable for transport of chemical factors, and hence it will allow an improvement of direct drug deliver in cancer therapy.[34]

Policy-makers need to understand the economic potential and environmental implications of a nanotechnology innovation to make informed judgments concerning research and development (R&D).[8] However, there are few analyses for the specific implications of nanotechnology for a given product, process, or market. A sufficiently broad perspective at the outset is required to understand economic and technical feasibility, estimate life cycle environmental implications, and minimize unanticipated negative impacts. The rapid rise in federally funded nanotechnology R&D dictates that consideration of societal benefits will have a large role in setting the R&D agenda.

Some authors estimated that using nanomaterials in vehicles body fabrication instead of steel with upper bound 67% efficiency the nanocomposites substitution would be worth a little more than $8/lb in materials and processing costs with assembly adding a further $2/lb. At lower bound 38% efficiency, this substitution would be worth just less than $4/lb in materials and processing costs with assembly adding a further $1/lb. Thus, even near the lower-bound value, the nanocomposite could be a competitive material that would increase fuel economy at low cost. This study states that aluminum costs less than nanocomposites and offers better performance than the lower bound compounds. Nonetheless, the major advantage of polymer composites over metals is the ability to fabricate aesthetically pleasing shapes. Even thought this argument does not represent environmental savings, its benefit joined with higher fuel economy could entice consumers to purchase the lower weight vehicles, thus reducing environmental impacts.[8]

3. RESEARCH STRATEGY

The application of nanomaterials and nanotechnology have significant contributions to sustainability, however some crucial instruments are required to achieve a strategic management of nanomaterials, namely Green Nanoscience and LCA linked to Risk Assessment. These instruments are discussed next.

3.1. "Green Nanoscience" Perception

Since nanotechnology products have already been introduced to the market, it is necessary to analyze how they will be treated and disposed of after the end of their use. It is necessary to develop a "green nanoscience" alert to provide a nanowaste management for the nanotechnologies and nanoproducts systems process. The "green nanoscience" emphasizes the need for continuous monitoring of the fate of nanoproducts (products containing nanoparticles) and suggests recycling as a way to reduce the amount of nanowaste released to the environment. This "green nanoscience" perception can be illustrated with the following example: silver nanoproduct applications. This nanoproduct is used for fridges, vacuum cleaners, and air conditioning amongst other industry applications. As example, a fridge for disposal could cause a release of silver to the environment. Therefore, the waste management for nanoproducts must be developed before the first nanoproducts starts to be disposed of.[34] Nanomaterials probably do not behave in the same way as normal waste and hence information about how to identify and how to analyze nanowaste is complex. Therefore legal regulations are a crucial issue. Nowadays, no nanowaste has been regulated as hazardous waste neither regulation of end-of life of nanotechnologies. However United States Environmental Protection Agency has recently restated its position on carbon nanotubes, confirming that they are chemically distinct from other forms of carbon, therefore should be treated separately under the Toxic Substances Control Act.[34] In November 2009, the EPA issued two proposed Significant New Use Rules (SNUR) of Toxic Substances Control Act (TSCA) for substances generically identified as single- and multi-walled CNTs; this directive requires protective measures to limit exposures and mitigate potential unreasonable risks, and also prohibits release of CNTs into water.[36]

3.2. Assessing Life-Cycle Risks of Nanomaterials

Life-cycle and risk assessments are instruments that approach different disciplines in order to provide a framework for decision making for nanoproducts management. A life cycle approach to manage the potential risks posed by nanomaterials must take into account all the stages, from production, through use, to disposal, which

should avoid making the nanowaste problem a legacy of nanotechnology.

For the nanotechnology industry, the life-cycle stages of resource extraction, raw material production, nanoproducts manufacturing, transportation, use and end-of life can together be connected with significant costs and benefits to the manufacturers, customers, environment, and organizations. Impacts on human health, ecosystem, and effects of pollutants release are evaluated for each life cycle. Currently it is difficult to predict the gap between the launch of nanoproducts and the time when nanowastes reach the environment. Therefore collaboration between specialists, manufacturers, and economists is crucial to predict the amounts of nanowaste that will be disposed.[34]

In the field of nanotechnology assessment, LCA offers an analysis of the potential life-cycle implications, optimizing its economic, environmental and society benefits, and minimizing risks. The introduction of the Amara's law (which adopts a continuous development of nanotechnology and nanoproducts) into LCA to assess the benefits and also risks from applications of nanotechnology in products and services, it reinforces the need for a joint assessment of ecological and human health risks with an assessment of all other aspects along the life cycle of nanocompounds.[11]

During this analysis the production process, the manufacturing, the product use and end of life are considered in a join assessment of the following process modules: materials, use of energy, and amount of transportation, recycling of parts and components as a feedback loop.

The functions of nanomaterials in LCA will enable researchers to relate the amount of a flow to a specific product, hence a reference unit for all flows would be considering for life cycle. The selection and definition of the functional unit is essential to perform meaningful LCA.[11]

For instance, some authors[8] analyzed the material processing and fuel economy benefits associated with using a clay-polypropylene nanocomposite instead of steel or aluminum in light-duty vehicle body panels. Although the manufacturing cost is currently higher, a life cycle analysis shows potential benefits in reducing energy use and environment discharges by using a nanocomposite design. The authors state that, if the costs of nanocomposites can become competitive with steel, this would lead to a cost reduction, fuel savings, emissions and greenhouse gases reduction by substituting nanocomposites for steel in the vehicle body.

Bauer et al.[11] suggested three areas to use the LCA in the context of nanotechnology: identifying those functions of nanomaterials, which have to be related to applications; modeling of nanomaterials that perform the desired functionality if the classical function of a material is not unambiguously assignable; and evaluating the interventions of the technical system with the environment due to the release of nanoparticles. These stages for LCA are discussed next for the applications of nanomaterials in the automotive industry such as: lightweight construction, paintings, catalysts, tires, sensors, coatings for windscreen and car bodies, amongst others. The first stage of LCA is the functionality of consumable products that must be compared by the conventional market products to establish a LCA. For components (such as catalysts, paintings), the discussion of the environmental impact of the analyzed product depends on the way: the nanomaterials are integrated into the final product; the product is actually used; and the recovery of resources at the end of the product life. The second stage of LCA is the modeling of nanomaterials, state that requires the development of inventory data for the materials or processes. For instance all material and energy inputs, waste amounts and emissions (to air, water, soil) for the production of 1 kg of the respective nanomaterial are collected and grouped together accordingly.[11] The third and last stage of LCA is the evaluation of nanomaterials interactions with the environment and during this step the analysis focus the risk of possible release of very small particles and their potential impacts on human health and environment. This stage of LCA requires the establishment of life cycle inventories with elementary data about the characterization to their particle size and to provide information about the nanomaterial that is used. For instance, use of carbon black in tires or the use as catalysts has a different risk assessment. A specific characteristic of all these use types is the fact that all of them use fixed nanoparticles. Under normal use conditions it can be assumed that such fixed nanoparticles are not emitted into the environment, hence no impact due to ultra fine particles (UFP) will occur. Here, more in-depth toxicological studies about these materials are of crucial interest.

Few studies have been published in the field of LCA for nanoproducts and those few did not give enough attention to end life phase.[11] In order to improve the application of LCA in the area of nanotechnology there is the need to develop a structural framework to establish modules that are appropriate for a variety of decision-making scenarios.

4. CONCLUSIONS

Nanomaterials have been used for automotive applications, namely for safety and energy consumption reduction purposes. It must be emphasized that the vehicles' weight decrease is a balanced result between the application of nanomaterials and the use of structures made from low-density materials.

Nanotechnology will allow a more efficient use of materials, as well as energy and therefore will reduce waste and pollution. For example, by using a very small amount of precious metals on carrier material of exhaust emission catalysts the emissions of hydrocarbons, carbon monoxides and nitrogen oxide could be reduced by

90%.[11] Therefore, nanotechnology developments for automotive applications should be considered when developing future policy scenarios and strategies and to develop eco-innovative and safer strategies.

Life cycle awareness for nanotechnology is currently in its beginning, and amongst other concerns potential impacts of nanoparticles are so far not well understood due to the complexity of these materials. There are still open questions regarding the effects of nanomaterials on human and ecological exposure. Potential advantages and improvements of nanotechnology are currently promoted disregarding the potential environmental impacts along the entire life cycle which should be assessed and diminished in total and not only for specific aspects in product use and consumption. In application cases where nanoparticles are released intentionally or accidentally the lack of reliable knowledge about potential impacts and risks impede a straightforward promotion of proven advantages.[11] There is the need to develop knowledge in the context of the manufacturing process to overcome the gaps of the producing process, including the raw materials being used and recycling scenarios could be helpful for comparative assessments of nanotechnology by means of LCA. Also, new nanocompounds and materials should be managed by LCA analysis to measure improvements, projections, risks and advantages of taking into account the full life cycle.

There is also the need of quantitative assessment of differences in the uptake and toxicity of chemically modified nanoparticles. LCA exercises are crucial to health effects of nanotechnology and LCA reports need to be made for different classes of nanoparticles and nanoproducts, so as to predict the real threat of nanowaste. However, at present, it is impossible to obtain a full-spectrum LCA for nanotechnology due to insufficient knowledge about the detailed inputs and outputs of the system.

Risk assessment and LCA must be applied to nanomaterials analysis in order to allow the development of products and services without compromising the environment from one of the most exciting and multidisciplinary fields, nanotechnology. Future research need requires the development of the following areas: develop procedures for product end-of-life analysis, develop analysis risk for human health and ecossystems effects from nanomaterials, as well as human exposure to nanoparticles from vehicle emissions, materials, technologies and processes for sustainable automotive electrochemical storage applications and electric and hybrid vehicles (advanced eco-design and manufacturing processes for batteries).

Nanotechnology holds a great promise to achieve environmental, economic and safety goals in the automotive industry; however, researchers, governments and industry must promote a common procedure to optimize LCA in the decision support and to transfer significant information in the nanotechnology and product development.

Acknowledgments: The authors acknowledge the support of the Portuguese Science and Technology Foundation (SFRH/BD/41530/2007 and SFRH/BPD/21317/2005).

References and Notes

1. M. C. Roco, National nanotechnology initiative—Past, present, future, Handbook on Nanoscience, Engineering and Technology, 2nd edn., Taylor and Francis **(2007)**, pp. 3.1–3.26.
2. H. Presting and U. Koning, *J. Mater. Sci. Eng.* 23, 737 **(2003)**.
3. S. U. S. Choi, Developments and Applications of Non-Newtonian Flows, edited by D. A. Singer and H. P. Wang, American Society of Mechanical Engineers, New York **(1995)**, Vol. FED 231, p. 99.
4. P. Keblinski, J. A. Eastman, and D. G. Cahill, *Mater. Today* 8, 36 **(2005)**.
5. F. D. S. Marquis and L. P. F. Chibante, *J. Minerals, Metals and Materials Society* 57, 32 **(2005)**.
6. J. Garcés, D. Moll, J. Bicerano, R. Fibiger, and D. McLeod, *Adv. Mater.* 12, 1835 **(2000)**.
7. Nano Science and Technology Institute, accessed January 2011 http://www. nsti.org/press/PRshow.html?id=3203.
8. S. Lloyd and L. Lave, *Environ. Sci. Technol.* 37, 3458 **(2003)**.
9. Y. Lin, W. Lee, H. Chao, S. Wang, T. Tsou, G. Chang-Chien, and P. Tsai, *Environ. Sci. Technol.* 42, 3849 **(2008)**.
10. Q. Hong, L. Gu, X. Jie, H. Wu, and P. Lei, *Adv. Mater. Res.* 148, 498 **(2011)**.
11. C. Bauer, J. Buchgeister, R. Hischier, W. Poganietz, L. Schebek, and J. Warsen, *J. Cleaner Prod.* 16, 910 **(2008)**.
12. F. Berger and J. Loeffler, NanoRoadSME SWOT Analysis Concerning the use of nanomaterials in the automotive sector, *Nanomaterials Roadmap 2015, 6th Framework Program of the European Commission* **(2005)**.
13. N. Dahotre and S. Nayak, *Surf. Coat. Technol.* 194, 58 **(2005)**.
14. S. Zhang, Y. Fu, H. Du, X. T. Zeng, and Y. C. Liu, *Surf. Coat. Technol.* 162, 42 **(2002)**.
15. Y. Zeng, S. W. Lee, L. Gao, and C. X. Ding, *J. Eur. Ceram. Soc.* 22, 347 **(2002)**.
16. H. Hahn, P. Mondal, and K. A. Padmanabhan, *Nanostruct. Mater.* 9, 603 **(1997)**.
17. R. Stewart, *Reinf. Plast.* 53, 14–16, 18–19, 21 **(2009)**.
18. G. Fontaras and Z. Samaras, *Energy Policy* 38, 1826 **(2010)**.
19. M. Zach, C. Hagglund, D. Chakarov, and B. Kasemo, *Curr. Opin. Solid State Mater. Sci.* 10, 132 **(2006)**.
20. E. Serrano, G. Rus, and J. García-Martínes, *Renewable Sustainable Energy Rev.* 13, 2373 **(2009)**.
21. M. C. Coelho, E. Titus, G. Cabral, V. Neto, J. Madaleno, Q. Fan, A. Sousa, and J. Grácio, *J. Nanosci. Nanotechnol.* 8, 4023 **(2008)**.
22. K. T. Lee and J. Cho, *Nano Today* 6, 28 **(2011)**.
23. S. Brown, D. Pyke, and P. Steenhof, *Energy Policy* 38, 3797 **(2010)**.
24. M. Nishiwaki, K. Abe, H. Yanagihara, I. Stankovic, Y. Nagasawa, and S. Wakamatsu, SAE International, Paper 2008-01-2581 **(2008)**.
25. N. B. Dahotre and S. Nayak, *Surf. Coat. Technol.* 194, 58 **(2005)**.
26. S. S. Lin and D. J. Patterson, SAE Paper No. 930794 **(1993)**.
27. S. Prabhu and B. K. Vinayagam, *J. Nanotechnol. App.* 3, 17 **(2009)**.
28. G. Wuest, G. Barbetaz, and S. Keller, SAE Paper No. 970016 **(1997)**.
29. M. Ebisawa, T. Hara, T. Hayashi, and M. Ushiko, SAE Paper No. 910835 **(1991)**.
30. V. D. N. Rao, D. M. Kabat, D. Yeager, and B. Zizitter, SAE Paper No. 970009 **(1997)**.
31. US DOE, http://www. fueleconomy.gov, accessed on January **(2011)**.
32. Beyond the Nanohype Technology Quarterly, *The Economist* London **(2003)**.

RESEARCH ARTICLE

33. A. Smith, Nanotechnology-Does It Have a Sporting Chance? *Chem. Int.*, New Zealand **(2006)**.
34. G. Bytrzejewska-Piotrowska, J. Golimowski, and P. Urban, *Waste Manage.* 29, 2587 **(2009)**.
35. S. Klaine, P. Alvarez, G. Batley, T. Fernandes, R. Handy, D. Lyon, S. Mahndra, M. McLaughlin, and J. Lead, *Environ. Toxicol. Chem.* 27, 1825 **(2008)**.
36. E. Wallner, B. Myers, D. Sarma, and R. Parker, SAE Paper No. 2010-01-1149 **(2010)**.
37. N. G. Dawson, *BioScience* 58, 690 **(2008)**.
38. S. M. Högberg, Modeling nanofiber transport and deposition in human airways, Ph.D. Thesis, Luleå University of Technology, Luleå, Sweden **(2010)**, p. 210.
39. T. Papp, D. Schiffmann, D. Weiss, V. Castranova, V. Vallyathan, and Q. Rahman, *Nanotoxicology* 2, 9 **(2008)**.
40. A. R. Köhler, C. Som, A. Helland, and F. Gottschal, *J. Cleaner Prod.* 16, 927 **(2008)**.
41. C. Robichaud, D. Tanzil, and M. Wiesner, Environmental Nanotechnology, Applications and Impacts of Nanomaterials, McGraw-Hill, New York **(2007)**.

Received: 25 February 2011. Accepted: 28 March 2011.

RESEARCH ARTICLE