Deployment of Affordable Diamond-like Carbon (DLC) Coatings to Improve Efficiencies in Transportation

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ABSTRACT

Greenhouse gas (GHG) emissions from the transportation sector have been on the rise at an increasing rate. The beginning of 2016 marked the first time in 40 years that GHG emissions from transportation surpassed those of electric power generation, becoming the largest GHG emitting energy sector. Globally, GHG emission from the transportation sector is rapidly increasing, while technologies to improve fuel efficiencies have not yet capable to deploy at an affective scale. To immediately address some of the issues associated with GHG emitted by the transportation sector TriboTEX has developed an easy to use drop-in formula. TriboTEX synthesizes dual-sided, flat nanoparticles with distinct functionality on each side (sticky/slick). When added to lubrication systems the sticky side attaches to metallic surfaces exposing a slick side that reduces friction. The reduction in friction has demonstrated improvements in fuel efficiency averaging between 4-8% in real world tests across different vehicle platforms. The deployment of TriboTEX coatings does not carry an overhead investment of time and capital and is compatible with existing vehicle fleets on the road today. TriboTEX smart coating solutions, to date, have been deployed in over 10,000 vehicles worldwide.

Keywords: diamond-like carbon (DLC) coatings, friction reduction, fuel efficiency, wear

1 INTRODUCTION

In the last 45 years greenhouse gas (GHG) emissions from the transportation sector have more than doubled [1]. Increasing at a faster rate than any other energy end-use sector, in 2010 transport GHG emissions reached 7.0 gigaton of carbon dioxide equivalents (CO_2 eq) [2]. Approximately 80% of this substantial increase is attributed to road vehicles. In 2010 global transport accounted for 28% of total end-use energy [3]; 40% of which were used in urban transport [4]. Fossil fuels are the dominant energy source, providing 94% of the total demand, resulting in over 53 % of global primary oil consumption [3]. Half of the energy consumed was attributed directly to transportation with the light duty vehicle (LDV) classification [5].

In the United States GHG emissions from transportation have increased above electrical power generation for the first time in 40 years (Figure 1). Comparisons between energy sectors of the US economy demonstrate the magnitude and scale that transportation emissions have mushroomed to over

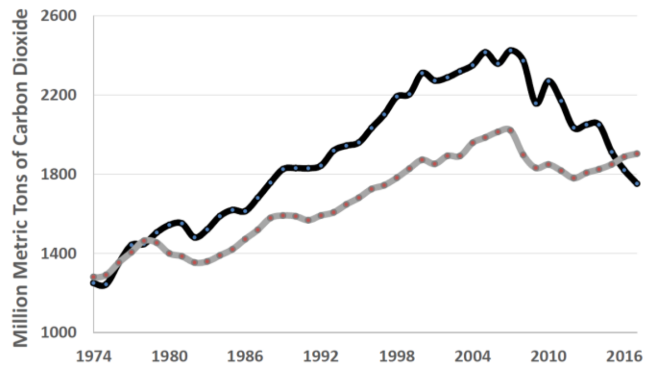

Figure 1. Carbon dioxide emissions from the US transportation sector (gray line) compared with electric power generation (black line), over a span of 40 years. Figure adapted from: DOE, EIA, May 2016 Monthly Energy Review

the last four decades (Figure 2). Alarmingly, the rapidly increasing emission of GHG from the transportation is occurring in spite of fuel efficiency technologies implemented by every major automobile manufacturer [6]. According to the IPCC, “without aggressive and sustained mitigation policies being implemented, transport emissions could increase at a faster rate than emissions from the other energy end-use sectors and reach around 12 Gt of CO2 eq per year by 2050]” [6]. To achieve an overall transition in the transportation sector the IPCC has recommended: rapid deployment of new and advanced technology developments, construction of new infrastructure, and the stimulation of change in consumer behavior and driver habits.

2 TARGETS FOR EMISSION REDUCTION

Meeting GHG reduction goals require 30 to 50% improvements in average energy efficiency and vehicle performance relative to metrics attained in 2010 [6]. Realizing these performance improvements will depend on large investments from vehicle manufacturers, which may require strong incentives and regulatory policies in order to achieve GHG emissions reduction goals.

A critical factor affecting vehicle fuel consumption and vehicle emissions is described by a metric termed, energy intensity. Energy intensity (energy/passenger mile or energy/ ton mile) is a combined descriptor of overall system performance combining effects of vehicle design, engine efficiency, driver behavior and vehicle usage patterns [7].

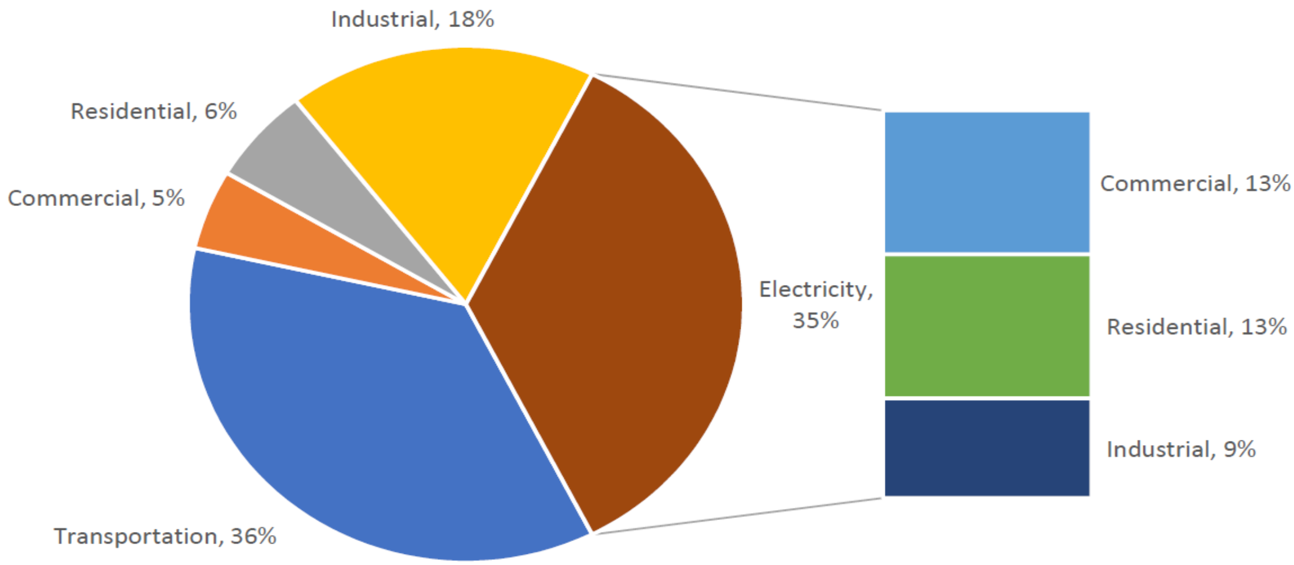

Figure 2. Greenhouse gas (GHG) emissions from individual sectors of the US economy in 2016. Figure adapted from: DOE, EIA, May 2016 Monthly Energy Review

Energy intensities can be lowered with improvements in engine performance, the use of lightweight materials, or increasing freight load factors and passenger occupancy rates [6]. Hybrid drive-trains, likewise, lower the energy intensity and have demonstrated fuel consumption reductions of up to 35%, although they lag in market penetration [6].

Generally, the strategy for improving fuel consumption is developed with the intention of reducing resistance the engine must overcome from: aerodynamic forces, auxiliary components (lighting and air conditioners), rolling resistance, internal friction and vehicle weight. For instance, if vehicle performance is held constant, a 10% reduction to vehicle weight produces approximately a 7% improvement in fuel economy [6].

Global Fuel Economy Initiative set a 50% reduction in average fuel use as a target for LDVs manufactured in the 2030s when compared to models in 2005 [9]. Combined incremental improvements in engine and drive-train systems could reduce overall fuel consumption for LDV powered with internal combustion engines to at least half by 2035, compared to average models of 2005 [8]. However, these saving in fuel consumption and reductions in GHG emissions do nothing to improve legacy vehicle platforms that will in operation for years to come. TriboTEX is proposes the deployment of self-forming, smart coatings to reduce the losses due to the parasitic effects friction and reduce cylinder blow-by to improve fuel efficiencies and reduce GHG emissions in vehicle fleets on the road today.

3 WHAT ARE SMART COATINGS ?

Smart coatings are defined as a self-generating and adaptive material layer that is produced during simulated operation of mechanical systems [10]. To meet these requirements, surface coatings must generate from special media, such as low viscosity carbohydrate, using nanoparticles during the run-in operation by a ‘tribochemical’ transformation. The coatings must significantly improve lubricating characteristics compared to the bare surface itself. Coatings must stop formation once the ideal thickness for desired low friction (elastohydrodynamic mode) is achieved.

The most prominent examples of smart coating technology in the past are nanoparticulate Borates (such as Boric Acid, Hexagonal Boron Nitride or Sodium Borate); dispersed in oil they react with surfaces to create lubricious boric oxide layers. The nano-boric acid technology was developed by Dr. Ali Erdemir at Argonne National Laboratory, and it has been through several improvements [11], [12]. Another smart coating example discovered in the 1960s by Dmitrii Garkunov is Selective Transfer. For Selective Transfer a bronze-steel frictional pair is lubricated by copper halides dispersed in glycerol and can achieve the sustained generation of a copper layer with superior lubricating properties [13].

4 TRIBOTEX COATINGS

The TriboTEX approach generates smart coatings in-situ (during operation) utilizing flat, ceramic nanoparticles with functionally different sides (slick/sticky). Current lubrication systems use active filtration with a typical cut-off size of 5-20 microns, TriboTEX powders that are significantly smaller than 1 micron, effectively pushing them to the nanoscale. The best candidates for such an approach are stratified silicates synthesized directly to single crystalline nanoparticles. As demonstrated previously, such ultrafine powders can dramatically reduce wear and promote the formation of thick (up to 30 microns) ‘tribofilms’ on the rubbing surfaces with extensive lubricating properties [14].

Figure 3. Coating formation (bottom strip) on cylinder ring. Formation of the DLC layer eliminates surface scratches, visible on upper portion of the ring.
Donor Vehicle: 1994 Infinity J30 with 234K miles.
Fuel Economy Improvement: 21 to 23.5 m
Component extracted: 15K miles after TriboTEX Engine Treatment application.

Due to the self-regulating mechanism of such film formation and the film's ability to compensate for wear, resulting in an effect called "self-repair" [11] and was featured in the book "Superlubricity" [15]. The material has been successfully tested in the field and TriboTEX is a leading expert in the fundamental mechanisms of action described in Dr. Pavlo Rudenko's PhD thesis and ongoing research on this topic with support from the National Science Foundation [14], [16], [17].

TriboTEX nanotechnologies facilitate the formation of friction reducing, protective coatings on internal components of lubricated mechanical systems, such as: engines, transmissions, gearboxes, differentials, and firearm barrels. Flat nanoparticles self-assemble, particle-by-particle, on working surfaces at frictional interfaces. TriboTEX nano-sheets attach to surfaces experiencing friction, covering the worn metal surface with a crystalline structure. The "slick" side is functionalized with catalyst and exposed to the lubricating oil to precipitate a carbon based DLC tribofilm on the surface during the course of normal operation. The surface begins to develop carbon deposit capping the coating layer with a silicon rich diamond-like coating [17]. Catalytically active nano-scale crystalline surfaces have been shown to demonstrate this phenomena of tribofilm formation through dissociative extraction of carbon from base oil molecules [18]. The coating formed on metal surfaces exhibits superior hardness, durability, and lubricity (Figure 3).

The typical formation time for the coating process to complete is fairly long (several hours of continuous operation). However, the end result is a superlubricious coating with the potential to achieve friction coefficient of below 0.01 with minimal investment of time and capital. Furthermore, when the lubricant is fully drained, the super lubricious properties are retained for some time (approximately 40K miles).

A brief overview of the demonstrated properties of magnesium hydrosilicate (MHS) generated coatings:

- Complex nanostructure, mainly consisting of nanograins from iron carbide, iron oxide and iron hydroxide.
- Crystalline nanograins are intermixed with an amorphous matrix of complex 3D structure of diamond-like nanocomposite (with DLC, amorphous silica, and silicon carbide as the main constituents).
- A plane alignment of nanocrystalline oxides and carbides is present, which is a typical characteristic of "superlattice" structures.

5 AFFORDABLE SOLUTION FOR EXISTING TRANSPORTATION PLATFORMS

TriboTEX aims to reduce GHG emissions by improving energy efficiencies in the transportation sector by providing an easy to use, drop-in engine coatings. The self-forming nano-sheets have been formulated to be compatible with conventional and synthetic motor oils for use in new and legacy vehicles platforms.

Tribofilm formation not only improves engine performance by reducing the parasitic effects of friction, but also adds a finite layer of material to surfaces compensating for existing wear. The ability to replace worn materials at contacting interfaces provides additional benefits of reduced blow by in the piston-cylinder pair. The immediate effect is improved compression and improved conversion of burned fossil fuel to mechanical energy. The synergistic combination of these effects result in improved fuel

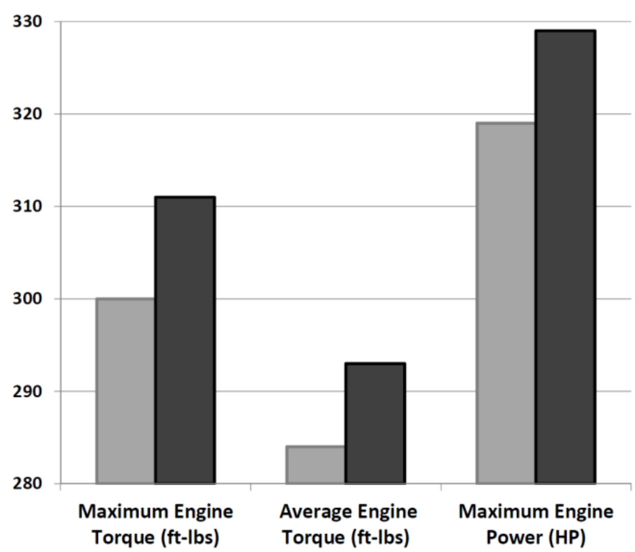

Figure 4. Dynamometer tested improvements in vehicle performance metrics, measured as torque and horsepower. Gray bars represent vehicle performance prior to treatment with TriboTEX Engine Coating. Black bars represent measured performance 500 miles after TriboTEX Engine Coating treatment. **Test Vehicle:** 2015 Ford Mustang

efficiency and increased power from the minimal effort of applying a drop-in coating into an existing engine platform.

Upgrading the existing legacy vehicle fleets in the transportation sector would have the immediate effect of reducing GHG emissions in the vehicle platforms fielded today. Independent researchers testing natural materials, improved by the TriboTEX synthesis process, have reported up to 5% reductions in fuel consumption, in close agreement with internal data collected.

TriboTEX nanomaterial coatings formulations are also being developed for use in gearboxes and manual transmissions. The combined benefits of friction reducing engine and gear surface coatings will provide compounded benefits of reduced fuel consumption and GHG emissions from vehicles on the road today.

6 CONCLUSION

Currently, only about 10% of the global population accounts for nearly 80% of the total motorized passenger-kilometers, meaning that much of the world's population hardly utilizes the transportation sector [6]. Transportation related GHG emissions as a percentage of total emissions typically range from above 30% in high income economies to as low as 3% in less developed ones [1], [2]. Nevertheless, GHG emissions from this sector are a major global concern that will continue to grow.

Over the next few decades incomes in developing and emerging economies are projected to rise contributing to increased demand for transportation and vehicle ownership [6]. This will result in further increased rates of GHG emission from the transportation sector placing additional demands to improve fuel economy and pressure from mandates to reduce consumption. Easy to use, drop in coating solutions provide an affordable, effective approach to reducing a portion of emissions from the transportation sector without major investments into new technologies or expensive engine overhauls.

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