**U.S. Department of Energy**
**Inventions & Innovation Program**
**Final Report**

Project Title: Improved Fuel Efficiency from Nanocomposite Tire Tread

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## Executive Summary

Rolling resistance, a measure of the energy spent (or lost as heat) as a tire rotates while moving, is a significant source of power and fuel loss. The continual compression and relaxation of a tire can consume nearly one third of a vehicle's available power. Tires with high rolling resistance are difficult to keep rolling, using more energy (and therefore fuel) to go a given distance. Recently, low rolling resistant tires have been formulated by adding silica to tire tread. These "Green Tires" (so named for the environmental advantages of lower emissions and improved fuel economy) have seen some commercial success in Europe, where high fuel prices and performance drive the selection of automotive components. Unfortunately, the higher costs of the silica (which is a partial replacements for very cheap carbon black) and a more complicated manufacturing process have prevented significant commercialization – and the resulting fuel savings – in the U.S.

Durability, wet traction, and rolling resistance are the key parameters describing tire performance and are known as the "Magic Triangle". Durability or resistance from abrasion is a measure of the structural integrity and lifetime of the tire. Wet adhesion or grip is crucial for the driver to control braking, cornering, and handling when driving in extreme conditions. It is easy to make improvements in one area at the cost of another. For example, improved traction can be obtained with softer tires, but this decreases durability and increases rolling resistance. Some silica compounds have been able to improve (or at least kept constant) all three of these areas in tires. This project sought to do the same, at a lower cost and with better compatibility with existing tire rubber compounding equipment.

In this project, TDA Research, Inc. (TDA) demonstrated that we can prepare an inexpensive alternative to silica that leads to tire components with lower rolling resistance. Additionally, these new tire composite materials were processed with traditional rubber processing equipment, without the viscosity increases seen with silica mixtures. We prepared specially designed nanoparticle additives, based on a high purity, inorganic mineral whose surface can be easily modified for compatibility with styrene-butadiene (SB) rubber – the major component of tire tread. When nanoparticles are dispersed down to their individual particle size and distributed throughout a polymer, the result is called a nanocomposite. We found that our rubber nanocomposites could decrease energy losses to hysteresis, the loss of energy from the compression (or expansion) and relaxation of an elastic material, by nearly 20% compared to a blank SB rubber sample (without nanoparticles). We also demonstrated better performance than a leading silica product, with easier production of our final rubber nanocomposite.

The reduction of dependence on foreign oil is a Priority 1 issue for DOE's Office of Energy Efficiency and Renewable Energy (EERE). Reducing rolling resistance is one way to significantly enhance energy efficiency, and is a focal point under the FreedomCAR and Vehicle Technologies Program. Specifically, this technology fits into the Propulsion Materials for Cars and Trucks sub-topic by leading to more efficient driving systems with lower emissions. Successful development of an improved rolling resistance tire would improve fuel economy and automotive safety, and would lower $CO_2$ emissions. It has been estimated that a 20% decrease in rolling resistance could give a 4% savings in fuel consumption and a roughly similar reduction in automotive $NO_x$, HC and CO emissions. By converting U.S. cars and trucks to these nanocomposite tires, we could see annual decreases of more than 4 billion gallons of fuel consumption and an annual reduction of over 22 million tons of $CO_2$ emissions.

## Actual Accomplishments versus Initial Project Goals and Objectives

Our Category 1 proposal was focused on preparing nanoparticles that were compatible with tire tread rubber, then forming a nanocomposite by the addition of those nanoparticles with rubber. The resulting rubber nanocomposites were then tested for hysteresis improvements. We had previously collected preliminary data that suggested that our nanoparticles could have this effect, but in another rubber system. This project has shown that those preliminary results are indicative of the hysteresis improvements we can introduce by the addition of our nanoparticles. We investigated SB rubber in a formulation recipe that modeled tire tread, and we found consistent hysteresis improvements up to 17% over a non-modified rubber sample. Additionally, we found that our nanoparticles were easier to mix with SB rubber than a competing silica product (currently used to make low rolling resistant tires.) We were able to achieve all of the objectives set out in the Category 1 proposal, and were able to establish the feasibility of using TDA's surface-modified nanoparticles as additives to improve the hysteresis in tire tread. The effort is currently poised for additional development, including scale-up of nanocomposite formation and testing, leading to formation of a prototype nanocomposite tire.

## Introduction

The U.S. leads the world in vehicle miles traveled per capita as well as total miles traveled. Passenger vehicles alone consume an average of 115 billion gallons of fuel per year, according to the Motor & Equipment Manufacturers Association (MEMA) (Bonsor 2001). When light trucks and SUV's are included, the number of miles traveled by Americans is over 2.6 trillion – enough to go to the sun and back 14,000 times (DeCicco and An 2002). All this travel comes with environmental costs as well. Emissions from cars and trucks represent the largest single source of carbon dioxide, and hydrocarbon, $NO_x$ and carbon monoxide emissions are significant even though automobile catalytic converters are extremely efficient. Because the use of personal vehicular travel is so widespread, small improvements in efficiency can have dramatic results in energy and economic savings, and result in significant environmental improvements. Efficiency improvements in cars and trucks have come from weight reductions, mechanical and aerodynamic optimizations, and improvements in the many materials that go into a car. Tires have been continually made more efficient through changes in design and formulation. By carefully selecting the rubber resins and additives that are mixed together to make tire tread, sidewalls and inner liners, tires can be manufactured that are more fuel efficient, longer lasting, and safer.

Durability, wet traction, and rolling resistance are the key parameters describing tire performance and are known as the "Magic Triangle". Durability or resistance from abrasion is a measure of the structural integrity and lifetime of the tire. Wet adhesion or grip is crucial for the driver to control braking, cornering, and handling when driving in extreme conditions. Rolling resistance is a measure of the energy lost as a tire rotates. Low rolling resistance results from tires that lose less energy, which translates into better fuel efficiency. It is easy to make improvements in one area at the cost of another. For example, improved traction can be obtained with softer tires, but this decreases durability and increases rolling resistance. Likewise, a less flexible tire would last longer and have low rolling resistance, but would have poor handling as it fails to grip the road with enough strength.

Tire tread – specifically, the tread cap – is the portion of a tire that has the greatest effect on durability, wet traction, and low rolling resistance. Other tire components contribute to overall performance, but the tread cap is the key section in contact with the driving surface (Figure 1). Tread caps are composed of styrene-butadiene (SB) rubber with many additives. Carbon black is used in large amounts (up to 35%) as a reinforcing filler. Without reinforcing fillers, tires would have very little structural integrity or durability. This structural framework is achieved by adding small obstacles (or fillers) to the polymer chains as they move against each other and against fillers like carbon black. This interaction helps a tire hold its shape, but also absorbs energy during the expansion / contraction cycle of tire rotation. This energy loss is known as hysteresis, and is the primary contributor to rolling resistance. One strategy to lower rolling resistance while maintaining the structural integrity of a tire has been to substitute some fraction of carbon black with high dispersible (HD) silicas.

HD silicas have smaller particle sizes, larger surface areas, and very different surface chemistries from carbon blacks (silicas have many polar –OH groups while carbon black contains primarily non-polar carbon). By themselves, HD silicas are not compatible with tire rubber and will form larger silica aggregates; however, when the silica surface is covered by a suitable compatibilizing agent, well-dispersed composites of silica in rubber are possible. These modified silica particles have different energy dissipation mechanisms in rubber as compared with un-modified carbon blacks and lose less energy during a compression / relaxation cycle. In this way, silica-containing tires can lower rolling resistance while maintaining flexibility and traction. Tires made with HD silicas have been termed "Green Tires" due to the environmental benefits by reducing fuel consumption and lowering $CO_2$ emissions. Silica-containing tires comprise 67% of passenger tires in Europe (in 1998) but less than 20% in North America. Green Tires have significant room for growth in both markets, especially in the light truck segment.

Unfortunately, the higher costs of the silica (which partially replaces very cheap carbon black) and a more complicated manufacturing process (these hybrid tires cannot be made on traditional tire formulating equipment due to higher mixing viscosities and require a substantial capital investment in new processing equipment) have prevented significant commercialization – and the resulting fuel savings – in the U.S.. The higher starting materials costs and more difficult processing are due primarily to the poor compatibility between silica and the rubber used in tire tread. By themselves, silicas are not compatible with tire rubber; however, when both the silica and a compatibilizing agent are added to the system, the compatibilizing agent covers the surface and well-dispersed composites of silica in rubber are possible. Suitable compatibilizing agents, like modified silanes, are expensive and the addition and mixing of silica and silane surface agents to tire recipes is not trivial. The resulting mixtures can be much more viscous than traditional tire mixtures. Additional mixing steps are needed to get sufficient silica coverage and distribution (increasing the time required to make a tire) and

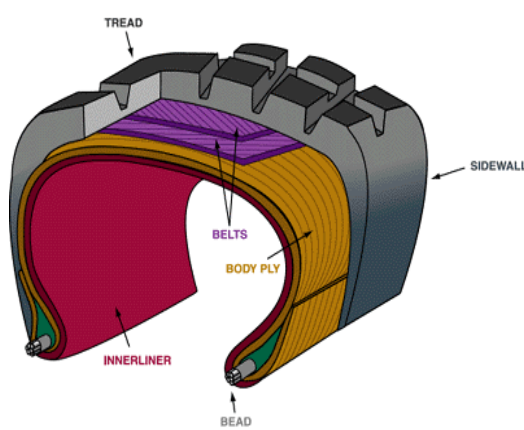


Figure 1. Tire components. (Photo courtesy of the Rubber Manufacturers Association.)

higher power mixing equipment must be used to handle the increased viscosities. All of these process changes and raw materials costs increase the final cost of a Green Tire. While Green Tires are commercially available in the U.S., retail prices are nearly double the price of a standard non-silica tire. At this time, Green Tires are only sold as a premium product, to a luxury market.

TDA Research, Inc. (TDA) has developed a proprietary additive that could lead to an inexpensive alternative to silica that leads to tire components with lower rolling resistance. Our nanometer-sized additives are based on a high purity, low cost inorganic mineral (boehmite, AlOOH) whose surface can be easily modified to make it compatible with a wide range of polymers. We have previously shown that we can disperse our nanoparticles in several different rubber polymers including bromobutyl rubber (the rubber commonly used as an inner liner for tubeless automotive tires), chloroprene rubber, and now styrene-butadiene rubber as drop-in additives.

Nanoparticles – particles that measure less than $100\times10^{-9}$m – have been examined in the automotive industry as additives that can increase thermal stability and create stronger, more lightweight composite materials. These high surface area nanoparticles also must be surface modified so that they can be evenly distributed throughout a resin. They can then achieve a more intimate polymer interaction than traditional fillers. This project focused on the development of a new nano-scale additive that reduced the hysteresis losses in SB rubber. Our additive is a very cost-effective and competitive alternative to HD silicas. Our nanoparticles require less expensive surface modifying compounds and can be prepared in large quantities in water and alcohols. Our pre-modified nanoparticles were easily incorporated in current SB rubber formulations for tire tread caps without the additional "non-productive" mixing steps, changes in the tire formulation, or the introduction of new rubber processing equipment. The resulting composite of nanoparticles, SB rubber, and other additives that comprise a tire tread formulation is called a nanocomposite.

## Summary of Project Activities

The overall objective of this research was to develop a new additive for tire tread that led to low energy losses to hysteresis. More precisely, the goal was to transform ordinary tire rubber into a nanocomposite by adding specially designed nanoparticles. When appropriately prepared, the combination of a tire tread rubber and well-dispersed nanoparticles forms a nanocomposite – a new type of material with different bulk properties. Tires with our nanoparticle additives would save fuel by lowering the rolling resistance of tires, thus improving the fuel efficiency and decreasing carbon emissions.

We first prepared nanoparticles compatible with SB rubber. We then prepared a nanocomposite by mixing our nanoparticles into a general formulation for tire tread based on SB rubber, using a Brabender polymer mixer. The SB rubber nanocomposites were then tested with a variety of tests to assess our improvements in hysteresis and other physical properties. We analyzed those results and carried out a preliminary estimate to determine the feasibility of adding TDA's nanoparticles as a key ingredient in the manufacture of a fuel efficient tire.

To achieve those objectives the project was organized around several tasks, including:

1. Design and preparation of surface-modified nanoparticles compatible with SB rubber.
2. Incorporation of nanoparticles into SB rubber by melt processing (nanocomposite formation).
3. Testing of the nanocomposite for mechanical and physical properties, including hysteresis.
4. Conduct a performance evaluation and cost analysis

### *Task 1: Design and Preparation of Nanoparticles*

TDA's nanoparticle fillers are based on an inorganic mineral – boehmite [Al(O)OH]. These particles are hydrophilic and, as bare particles, are incompatible with hydrophobic hydrocarbon polymers like SB rubber. This is actually an extremely difficult issue to overcome – and is a significant barrier that we share with our competitors working with silica-based nanoparticles. Nanoparticle compatibility influences dispersion, which greatly affects the final properties (including appearance) of a nanocomposite. TDA's nanoparticles have a key advantage that the silicas lack: we can easily and inexpensively modify the inorganic boehmite nanoparticle surface with organic groups that give excellent dispersion in specific, targeted polymers like SB rubber. The resulting nanoparticles showed good overall compatibility SB rubber.

### *Task 2: Nanocomposite SB Rubber Formation*

During this project, we successfully prepared nanoparticles that were compatible with SB rubber, the most commonly used rubber for tire tread. Tires are a complex, highly engineered product that must perform at optimum levels under severe conditions. Many additives are therefore incorporated into the final SB rubber formulation for tire tread, each with necessary role during processing, curing, or in the final tire's performance. These include vulcanization agents and accelerators, reinforcing and mineral fillers, antioxidants, pigments, processing aids and plasticizers. During the first quarter of this project, we decided on a standard formulation for tire tread based on SB rubber. We came to this decision with help from our commercial contacts in the tire industry as well as from the open literature. A representative formulation for a SB rubber tire tread, supplied by Goodyear Chemical, is shown in Table 1.

Table 1. A representative SB rubber formulation for a tire tread (Courtesy Goodyear).

| Material | Relative Amount | Use |
|---|---|---|
| SB Rubber | 100 | Base SB rubber |
| Carbon black | 50 | Carbon black – Reinforcing filler |
| Naphthenic Oil | 15 | Plasticizer, processing aid |
| Stearic acid | 1 | Surfactant |
| Zinc Oxide | 3 | Pigment, curative accelerator, reinforcer |
| | | |
| Sulfur | 2 | Curative agent |
| TBBS | 1.75 | Vulcanization accelerator |

Our modified nanoparticles were mixed with the SB rubber formulation in our Brabender polymer mixer. The mixing occurred in two steps, similar to industrial compounding processes. In general we were able to easily mix our nanoparticles and the rubber ingredients together. The mixed rubber nanocomposite was then pressed into sheets and cured for testing. TDA has a Wabash press mold allowed melting of the masticated rubber and curing of the pressed sheets. We prepared several blank formulations of SB rubber tire tread without nanoparticles for use as comparison samples. We also prepared a variety of nanocomposites, using different nanoparticles as well as various nanoparticle concentrations. SB nanocomposites were prepared with 1 and 5% nanoparticle loadings, were pressed into thin films and cured at 160°C for 18.5 minutes.

This mixing process proceeded very well. We did not observe significant viscosity increases upon addition of our nanoparticles, and we were therefore able to prepare our nanocomposites quickly and easily. We prepared a variety of rubber nanocomposites with different nanoparticles at various concentrations. We also prepared several blank formulations without nanoparticles for use as comparison samples. All of our samples were pressed into thin films and cured at higher temperatures.

To compare our nanoparticle additives to the silica currently used to make low rolling resistant tires, we also prepared several samples with our equipment and a tire formulation that contained varying amounts of silica. We obtained samples of Ultrasil 7000GR silica and Si60 (silane coupling agent) from Degussa, and added those to a comparable tire tread recipe. We prepared samples in which Ultrasil 7000GR completely replaced carbon black (about 30% of the mixture). To achieve complete dispersion and thorough mixing, we had to add an additional mixing step to get all of the silica mixed into the rubber formulation – a step not required by our nanoparticles.

### *Task 3: Testing*

The thin films prepared in Task 2 were then subjected to testing. Our ultimate goal was to improve the rolling resistance of our nanocomposites, which can be tested by measuring the energy lost to hysteresis by a sample that has been stretched then relaxed. Up to 90% of the rolling resistance in a tire comes from hysteresis losses, so by measuring the energy lost to hysteresis we can approximate the ultimate rolling resistance of a tire made with a rubber sample. We measured hysteresis by two methods: directly by an Instron tensile tester and by an automated method on our dynamic mechanical analysis (DMA) tester. The Instron method is one accepted by industry, but contains several sources of error. The automated DMA method is not generally used by the tire industry, but has been used by the larger academic community to measure rubber dynamics. We operated the DMA in a static method, to best approximate the hysteresis cycle. We were able to carry out these specific DMA tests due to a software upgrade purchased for this project as a cost-share activity by TDA. In all cases, the two methods gave very good agreement.

We found that our nanocomposites could decrease energy losses to hysteresis by nearly 20% compared to a blank SBR sample (without nanoparticles). Depending upon the formulation, the energy losses to hysteresis by our nanocomposites ranged from 18.9 – 16.4 %, while the blank gave an average value of 20.5 % (the lower numbers are better, indicating less energy lost.) Representative hysteresis results are shown in Figure 2, which shows a smaller area inside the curve for our nanocomposites as compared to the blank formulation. These results were repeatable and are presented as an average of multiple samples. These samples were comprised of a model tire tread formulation (as recommended by contacts at Goodyear) with an additional 5% nanoparticles.

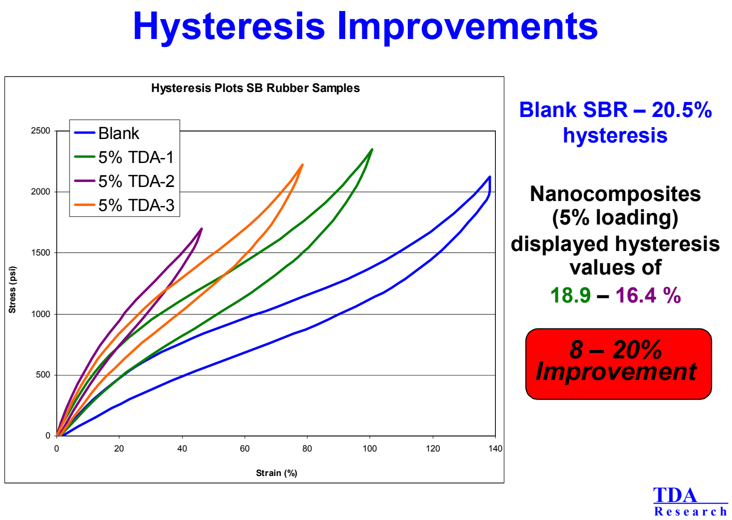


Figure 2. Hysteresis data for blank and nano-composite rubber samples.

Silica-containing tires were also tested for hysteresis. The full silica rubber sample (in which all of the carbon black was substituted with silica) gave a hysteresis drop of 16.4 % – the same as our best nanocomposite formulation (which was achieved with only a 5% addition of nanoparticles and a single mixing step) (Figure 3). A tire with silica instead of carbon black is not realistic due to both performance (full silica tires lack sufficient dry traction and durability) and cost. A sample containing a 5% added amount of silica (similar to our nanocomposites) gave a much greater hysteresis value of 24.6%. This greater number is not an appropriate measure of the performance of these silica nanoparticles, but rather a reflection of the greater difficulty in preparing the base materials.

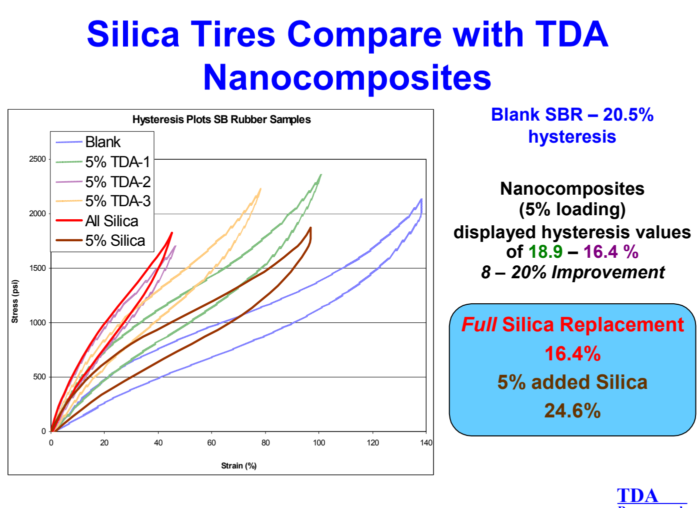


Figure 3. Hysteresis of silica samples compared with our nanocomposites. Low hysteresis numbers are better, indicating less energy lost.

A list of the samples prepared and tested is shown in Table 2.

Table 2. Hysteresis data for SB rubber nanocomposites.

| Surface Group | Nanoparticle Loading (%) | Hysteresis |
|---|---|---|
| Blank | 0 | 22.21 |
| Blank | 0 | 15.32 |
| TDA-1 | 1 | 26.20 |
| TDA-1 | 5 | 15.62 |
| TDA-1 | 5 | 18.95 |
| TDA-2 | 1 | 18.79 |
| TDA-2 | 5 | 15.99 |
| TDA-3 | 1 | 15.69 |
| TDA-3 | 5 | 16.39 |
| TDA-3 | 5 | 17.09 |
| | | |
| Full Silica | 30 | 16.51 |
| Partial Silica | 5 | 24.60 |

We also analyzed our data according to information from tire industry representatives met at the 2005 Tire Technology Expo Conference. While we collected hysteresis data by a static method on our dynamic mechanical analyzer (DMA), a simpler method (also on the DMA) can be used to screen samples for hysteresis results. A typical temperature scan on a DMA leads to storage and loss modulus information, and therefore to the tan δ curves. The peak of the tan δ curves indicate the point at which a material changes from being glassy to rubbery. However, the tan δ curve is also a measure of the energy loss in a system. This correlates with hysteresis, and can be used as a simple, brief test to measure similar samples that may have different hysteresis values. Specifically, tan δ curves in the region between ~30° and 80°C are used for hysteresis comparisons.

We analyzed the data from last quarter's report and inspected the region between 40 and 80°C. While the data did not correspond exactly with the range of values for hysteresis we collected in our previous method, the samples showed a similar trend. All of our nanocomposites displayed lower tan δ values than the blank sample, and the samples that showed the best improvements in hysteresis were also some of the lowest in the tan δ chart (Figure 4).

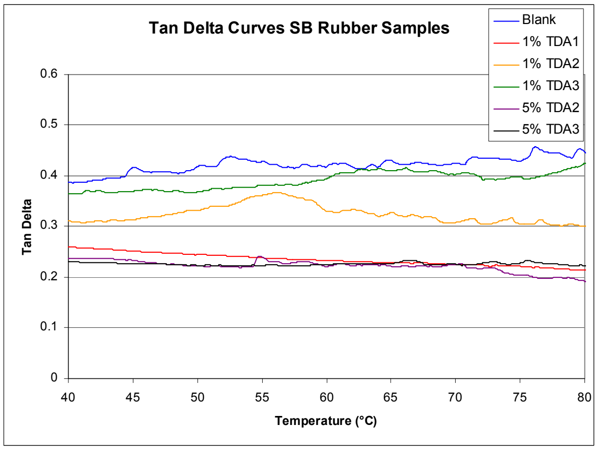


Figure 4. Tan delta curves in the temperature region that best approximates hysteresis or rolling resistance performance.

*Task 4: Performance Evaluation and Competitive Analysis*

The reduction in hysteresis due to our nanoparticles could lead to a significant energy savings by the formation of low rolling resistant tires. The conversion to low rolling resistant tires for passenger vehicles and trucks in the U.S. could yield significant energy savings for the nation. Presently, this conversion would only occur after a significant cost to vehicle owners due to the higher prices for Green Tires. A tire made with TDA's additives could compete on both price and performance with standard tires, and the fuel savings could justify the switch to a more energy-conscious tire. TDA's surface modification occurs *prior* to addition into a tire rubber mixture, making the blending of our nanoparticles faster (we don't have to rely on the rubber mixing process to modify our nanoparticles, thus reducing repetitive mixing steps) and easier (the nanoparticles are already compatible with the rubber host matrix, reducing the viscosity during mixing).

The largest volume commercial additive used to prepare Green Tires is high dispersible (HD) silica. Silica-containing tires can improve energy efficiency by up to 5%, resulting in a significant reduction in fuel consumption. Silicas are not without problems, however. To be active, the silicas used in rubber applications must have very high surface areas and are used as partial replacements of carbon black from 15 to 65%. The silane coupling agents are expensive and the silica additives and silanes must be mixed in separate steps to ensure effective coverage of the silica particles. These extra mixing and cooling steps are considered "non-productive" as they add to the standard mixing process of rubber formulation. The higher viscosities and different handling requirements encountered during silica/silane/rubber mixing also demands the capital investment of additional processing equipment – not merely an upgrade to existing equipment. The silica/silane system creates sensitivities in the order of addition of the various additives, participates in undesirable reactions with other functional groups, and accelerates scorching (Ciullo and Hewitt 1999, Joshi 2002). These complications all add to the cost of production, and increase the price of a green tire. Michelin currently sells energy efficient tires under their Energy MXV4 brand series, but the cost is nearly double the price of a traditional tire.

Europe has a higher percentage of passenger cars with green tires than the U.S., a reflection in part of higher fuel prices. Both countries offer room for market growth. According to Modern Tire Dealer, 193 million tires were sold in 2001 as replacement passenger tires with an additional 46 million for trucks (MTD Estimates 2002). At the current U.S. market share of 17%, green tires account for 33 million tires. For a tire weight of 20 lbs, a 5% loading of TDA's nanoparticles would correspond to 33 million pounds of nanoparticles for the current national green tire supply.

Development of an inexpensive additive that would improve tire performance through decreases in rolling resistance would result in a dramatic decrease in the fuel consumed by the driving public, by commercial traffic, and by the military. These tires would be more energy efficient, requiring less fuel. Energy losses to hysteresis contributes to 90% of the rolling resistance in a tire. Annually, a 20% reduction in rolling resistance (without any other unfavorable changes) could translate to a 4% fuel savings. (Dinkel, 1995) In 2001, over 113 billion gallons of fuel were used for household vehicles. By converting U.S. cars and trucks to these nanocomposite tires, we could see annual decreases of over 4.5 billion gallons of fuel consumed. This represents annual savings of over $5.58^{14}$ Btu, or 0.57 Quad of energy (assuming 124,000 Btu / gallon). (DOE EIA

2004)  With an average gasoline price of $2.78 (as of 9/19/05), this could represent the saving of over $12 billion.

This value is admittedly high and unlikely, but it represents an upper limit of what could be achieved by a minor change to an existing commodity product.  If we assume initial market penetrations of 5%, that would still translate into substantial annual energy savings.  Michelin sells a tire to the European market that offers a 30% decrease in rolling resistance and a consequent 5% reduction in fuel use. (Noordermeer 1997, 1998) Our Category I results showed a 20% decreases in hysteresis at only a 5% nanoparticle loading and without any changes to a standard rubber mixing procedure.  It is reasonable that we should be able to compete favorably on price and acceptability with the Michelin tires.

Lower fuel consumption will benefit transportation-related industries such as local and national trucking, shipping and airlines.  These industries spend large percentages of their budgets on fuel, and fuel-efficient tires would lead to lower operating costs.  Better fuel efficiencies and lower carbon emissions would benefit both the Federal and local governments by reducing fuel requirements for military and day-to-day operations.

Green tires also have significant environmental benefits.  By decreasing the amount of fuel consumed, we also decrease the amount of carbon- and nitrogen-based emissions produced.  An improvement in fuel savings of 4% would have a corresponding reduction in $CO_2$ emissions by 22 million tons.  Passenger cars and trucks produce more carbon dioxide emissions in the U.S. than any other single source, and recent activities suggest this trend will continue.  The current popularity of SUV's has introduced large numbers of fuel-inefficient automobiles, which use more fuel and produce more carbon emissions than regular passenger vehicles.

## Products Developed and Technology Transfer Activities

*Presentations*

During the Category I project, we worked with representatives from the Goodyear Tire and Rubber Company (formerly from Goodyear Chemical) to identify a model formulation for testing, to analyze our data, and to make a preliminary evaluation of our technology.  This led to an invitation by our partners at Goodyear to present our results at Tire Technology Expo 2005, an international conference in Cologne, Germany.  TDA was part of the first "Nanoscience and Nanotechnology" symposium at this annual meeting, where our presentation was well received by the symposium organizers and generated several discussions with our Goodyear contacts.  This project benefited from that conference technically through discussions with industrial contacts.  The conference identified several areas in which we could change the "language" and appearance of our data to be aligned with data reported in industry (instead of the academically correct, but slightly different ways we used previously) and several additional experiments to conduct to further explore the performance of our nanocomposites.  We were able to also meet with several scientists and management from Goodyear to discuss our project and ways to move forward.  The title of the talk was, "Rocks in the Road:  Nanoparticle Design for Improved Tire Performance," and is currently available for viewing on TDA's website. (http://www.tda.com/Library/library.htm).  This presentation contained work carried out under this project as well as a previous project funded by the U.S. Department of

Transportation (Contract # DTRS57-02-C-10018). The full reference for the presentation follows.

A. Myers*, R. Cook, C. Kreutzer, D. Galloway, J. Yu, M. Meiser, D. Stokowski "Rocks in the Road: Nanoparticle Design for Improved Tire Performance," Tire Technology Expo 2005; March 22-24; Cologne, Germany.

This presentation was also given in a seminar to the chemistry department at the Colorado School of Mines on October 14, 2005. Dr. Myers was an invited speaker for CSM's weekly departmental seminar series. A copy of that presentation is included with this report.

### *Collaborations*

This project led to collaboration and discussions with several technical members of Goodyear. While our results are still in the preliminary stage, by their estimation, our early results have been enough to keep their interest. They have offered to support continuing efforts in this area, and have provided contacts within Goodyear, to others in the tire industry, and to independent compounding and testing companies who evaluate products before passing them on to companies like Goodyear.

We also discussed this work with a contact at Noveon (formerly BF Goodrich). While Noveon is no longer in the tire business, he told us that a major barrier to the production of silica-containing, low rolling resistant tires in the U.S. was the need for additional capital equipment purchases. The silica formulations require more energy and steps for compounding with rubber formulations, thus requiring new equipment (as opposed to modification of existing equipment). This is an advantage to our technology, we believe, as we were able to add our nanoparticles to a tire tread formulation easily in our lab-scale Brabender polymer mixer.

### *Patent Inventions and Licensing Plans*

The key technical achievement in this project was the reduction in hysteresis in rubber nanocomposites prepared with our boehmite nanoparticles. We are in the process of preparing a patent on this invention. The decision on whether TDA manufactures or sells a license on a particular technology is based upon the resources required to produce, sell and market it. High-value products that require little capital investment are commercialized by TDA. For products and technologies that have lower margins but very large markets, and that require multi-million dollar investments, TDA's strategy is to license the technology to a company that is a leader in its field. Since most of our technologies involve new materials and processes or aerospace components, most of our activities revolve around licensing technology to Fortune 500 companies. Thus, TDA invests heavily in patenting its technology. TDA has 15 issued U.S. patents, 29 pending U.S. patents and 20 pending foreign patents. This strategy is succeeding. Last year research for government and private companies accounted for 80% of TDA's revenue, but 75% of our profits come from licensed technologies.

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