Final Scientific/Technical Report

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Project Title: Demonstration of improved vehicle fuel efficiency through innovative tire design, materials, and weight reduction technologies

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Executive Summary:

Cooper completed an investigation into new tire technology using a novel approach to develop and demonstrate a new class of fuel efficient tires using innovative materials technology and tire design concepts. The objective of this work was to develop a new class of fuel efficient tires, focused on the "replacement market" that would improve overall passenger vehicle fuel efficiency by 3% while lowering the overall tire weight by 20%. A further goal of this project was to accomplish the objectives while maintaining the traction and wear performance of the control tire.

This program was designed to build on what has already been accomplished in the tire industry for rolling resistance based on the knowledge and general principles developed over the past decades. Cooper's CS4 (Figure #1) premium broadline tire was chosen as the control tire for this program. For Cooper to achieve the goals of this project, the development of multiple technologies was necessary. Six technologies were chosen that are not currently being used in the tire industry at any significant level, but that showed excellent prospects in preliminary research. This development was divided into two phases. Phase I investigated six different technologies as individual components. Phase II then took a holistic approach by combining all the technologies that showed positive results during phase one development.

Figure #1

The six technologies investigated as a part of phase I were:

- Nano-fiber fillers
- Aramid bead bundles
- Aramid belt packages
- Ultra-Long wearing and low hysteresis tread compound
- Barrier film Innerliner
- Low rolling resistance tire profile from FEA modeling

1) Nano-fiber Filler Technology

<u>Phase I Development</u>

Multiple nano-fiber and macro-fiber fillers were explored during the DOE program. Each filler gave different performance characteristics for reinforcement and hysteresis as replacements for silica and carbon black. This development allowed Cooper to identify and characterize several different fiber filler materials and how these fillers could be used in tire compounds. Many of these fillers are produced from renewable sources which provide more sustainable alternatives to carbon black. Several of the fillers investigated would provide improved economics over silica and carbon black while several fillers are not economically feasible under current economic conditions. Two of the more promising fillers were built into tires and showed improved hysteresis at equivalent reinforcement. These two fillers also reduced the specific gravity of the compound which contributed to a lighter tire.

<u>Phase II Development</u>

Two fillers developed as part of this technology were used during the final tire build in Phase II and contributed to meeting the objectives of this project. Alternative fiber filler technology contributes to both a weight savings and a hysteresis improvement.

2) Aramid bead bundle

<u>Phase I Development</u>

Several materials were initially investigated to replace steel in the bead area but aramid was chosen as the only material that provided both the strength required as well as the desired weight savings. This investigation provided insight into the amount of aramid required to replace current steel reinforcement in the bead area. However, the aramid weight savings in the bead did not provide any improvement in the rolling resistance in the tire. The benefits provided by the aramid in the bead did not produce an economically feasible tire component. There were also some performance deficiencies observed that would need additional development before this technology would be ready for production products.

Phase II Development

Aramid beads were not used as a major part of the Phase II tire development. A few tires were built using this technology along with the other five technologies for very limited testing. This technology would only contribute to a small weight savings in the tire.

3) Aramid belt package

Phase I Development

Aramid was chosen as the material to replace steel in the belt package. It provides the strength needed along with a large weight savings. The weight savings in the belt package also contributes to a rolling resistance improvement. Aramid belts can provide a major contribution to a fuel efficiency improvement. There would be an increase cost associated with the use of aramid in the belts but the fuel savings over the life of the tire would more than pay for the increase in tire cost. This makes aramid belts economically feasible. There are still some performance issues with the use of aramid belts that need to be addressed. Further development is necessary to make aramid belts ready for production applications.

Phase II Development

Aramid belts were used as part of the final tire build in Phase II and contributed to meeting the objectives of this project. This technology contributes to both a weight savings and a rolling resistance improvement.

4) Ultra- long wearing and low hysteresis tread compound

Phase I Development

Tread compound development provided an opportunity to investigate some new materials that contributed to improved hysteresis or improved wear or improved traction or combinations of the three. The resulting studies yielded a compound that had 20% improved hysteresis and more than 30% improved wear while maintaining traction. Materials used to accomplish these performance characteristics contributed to a more expensive compound. However, the ability to use less tread compound along with the rolling resistance improvement would provide a savings for the consumer over the life of the tire. This makes this technology economically feasible.

Phase II Development

The ultra- long wearing and low hysteresis tread compound was used by all the features that were built in the phase II program and had a large contribution to meeting the objectives of this project. This technology contributed to both a weight savings and a rolling resistance improvement.

5) Barrier film innerliner

Phase I Development

Barrier film has potential to provide a significant weight savings but the fatigue performance did not meet the requirements necessary for tire usage. Because of the performance issues, the economic feasibility was never determined. Building processes were established that could make this a production viable material. Because of the low air permeability of the barrier film, the potential remains to reduce long term air loss in tires with barrier film compared to tires with conventional innerliner.

Phase II Development

Barrier film was not used as a major part of the Phase II tire development because of the unsatisfactory fatigue performance. A few tires were built using this technology along with the other five technologies for very limited testing. This technology would contribute to a significant weight savings in the tire.

6) Low RR tire profile

Phase I Development

A new FEA hysteresis model was developed and verified prior to using the model to optimize the tire profile for rolling resistance. Several different profiles were investigated in both the model and in actual tires. The low rolling resistance profile developed provided an improvement in both weight and rolling resistance. The tire builds confirmed that tire profile could be used to contribute to rolling resistance improvements. This development also allowed the investigation of how tread depth and tread void impacts hydroplaning and tread wear.

Phase II Development

The best profile for rolling resistance and weight that also met the other tire performance requirements was chosen for the Phase II development tire build and contributed to meeting the project objectives. The tire profile contributed to both a weight savings and a rolling resistance improvement.

7) Benefit of Development

Cooper is already using two of the DOE technologies in the development of new product lines for the US replacement tire market; the ultra-long wearing and low hysteresis tread compound and the low RR tire profile from FEA modeling. One aspect of the project work was the development and validation of an efficient rolling resistance analysis tool. While used extensively within the context of this project, it has been extended for general use and now implemented and included on all of our current tire analysis projects. Presently, there are several passenger tire programs in progress, that include rolling resistance reduction as one of the design conditions, which is facilitated by the analysis tool, but also enabled from the standpoint of introducing the aspects of the individual technologies developed within this project. Another aspect of the project work was the technology established from the development of the ultra-long wearing and low hysteresis tread. This technology is also currently being used in different ways for performance gains in various target specific applications within our new products.

In short, present tire development work is benefitting from the results of this project. Additionally, from the standpoint of Commercial Truck Tires, there is an increased focus on reducing rolling resistance / energy loss, and improving fuel economy from both a regulatory and Smart Way Certification standpoints. The new rolling resistance analysis tools and general new technology principles are also being applied on many current and new Commercial Truck Tire Products.

Proof of concept has been established during the DOE program for nano-fiber fillers, aramid belt packages and barrier film innerliner. Each of these technologies will require further development prior to using in a production product. The potential benefit to the consumer has been identified and proven as a result of the DOE program. Aramid bead is the only technology that Cooper does not plan any further development at this time, due to the limited benefit to the consumer and high development costs.

As the American consumer is educated on the benefits of fuel efficient tires the demand for energy efficient tires will grow. If the entire passenger replacement market, which is approximately 80% of the tire market, converted to fuel efficient tires with a 3% fuel savings, the US would save around 2 billion gallons of fuel per year (based on 2011 data). With lower fuel costs now in effect, this new class of fuel efficient tires will put 3 to 4 billion dollars back into the household budgets of American consumers every year. However, if the entire replacement market was able to reach the full 5% fuel efficiency improvement shown by this program, the savings would be closer to 3.3 billion gallons of gasoline.

Comparison of Project Goals and Objectives with Accomplishments:

The objective of this project is to design, develop, and demonstrate a new class of federal safety regulation compliant tires that will improve overall passenger vehicle fuel efficiency by at least 3% while lowering the overall tire weight by at least 20%. A further objective of this program was to not give up any of the tires traction or wear performance. This program will develop and demonstrate a new class of fuel efficient tires using innovative materials technology and tire design concepts. The goal by the end of the project is to have created and tested a prototype of a new fuel efficient tire and to have demonstrated the potential application of these technologies in a commercial product.

The control tire chosen for this project was a Cooper premium broadline CS4. All other performance characteristics were designated to be equivalent. Figure #2 shows the average fuel savings measured from both dynometer and vehicle on the road testing was between 5% and 6%. The vehicles used for fuel efficiency testing was a 2014 Nissan Altima. The weight savings of feature 1 with steel belts did not meet the goal of 20 percent. However, feature 2 with aramid belts did meet the goal of a 20% weight savings. Wear and traction for both features were equal or exceeded the control. The features did show a slight loss of snow and ice performance but still had very good winter performance. The tread pattern could be adjusted slightly to bring back the lost winter performance if desired.

DOE Fuel Efficient Tire Development					
	Ave. Fuel Savings Δ	RRc Δ	Weight Δ	Wear Δ	Traction
CS4	---	---	---	---	---
Feature #1	5%-6%	32%	13%	Improved	Equal
Feature #2	5%-6%	37%	23%	Improved	Equal

Figure #2

Summary of Project Activities:

Cooper completed an investigation into new tire technology using a novel approach to develop and demonstrate a new class of fuel efficient tires using innovative materials technology and tire design concepts. The objective of this work was to develop a new class of fuel efficient tires, focused on the "replacement market" that would improve overall passenger vehicle fuel efficiency by at least 3% while lowering the overall tire weight by a minimum of 20%.

In addition to the stated DOE program objective, the goal of this program included maintaining the traction and tread wear of the control tire. During normal tire development using standard materials and design, when one performance characteristic is improved, one or more performance characteristics are typically sacrificed as demonstrated in Figure #3.

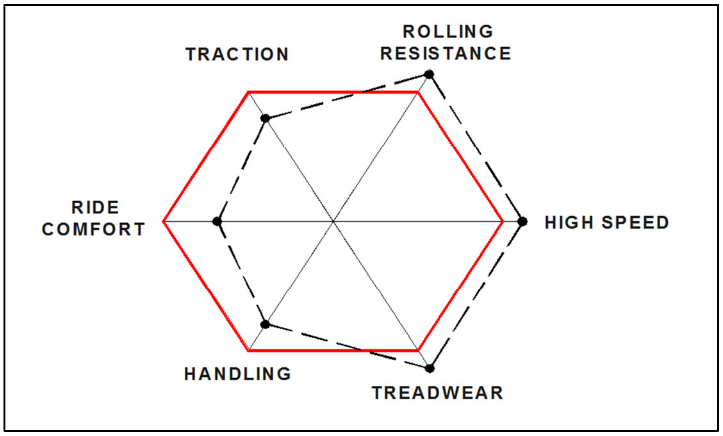


Figure #3

A typical tradeoff for a rolling resistance improvement is in the area of traction. A loss of traction will often also result in a loss in the area of handling. Only with the development of new materials and technologies can the overall performance be improved without any sacrifices as seen in Figure #4. This spider graph demonstrates what Cooper was able to accomplish during this DOE program. The overall design space was expanded as a result of the new technologies investigated.

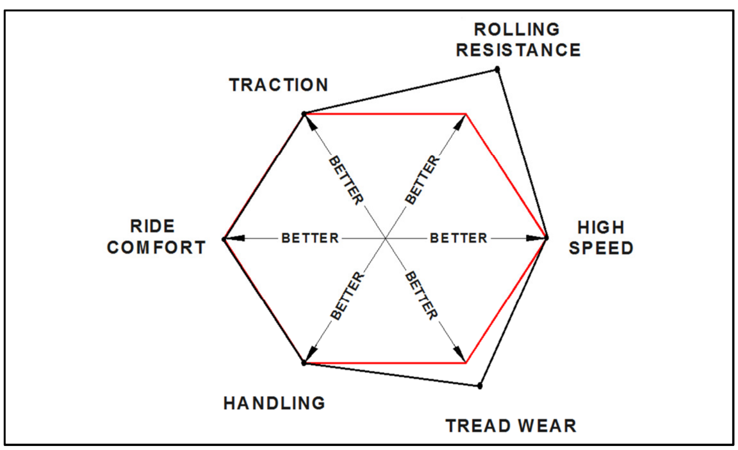


Figure #4

Cooper's innovative approach was to develop a "new energy efficient tire profile" in combination with an "ultra-light weight" tire construction. A rule of thumb is that a 10% reduction in rolling resistance provides a 1-2% improvement in fuel efficiency. Tire rolling resistance is the force required to make a loaded tire roll. When the tire deforms during rolling, a fraction of the deformation energy is stored elastically and will be recovered after the source of the deformation is removed. However, due to the visco-elastic nature of rubber, a significant fraction of the deformation energy is dissipated as heat. This hysteretic energy loss is the main source of rolling resistance of a rubber tire. The deformation of the tire is controlled by the (i) tire construction, (ii) materials used, (iii) its profile, and (iv) the load and inflation conditions of the tire. Therefore, less material usage, results in less material to be deformed, which results in less energy loss as hysteresis. Unfortunately, a significant reduction in tire weight with conventional materials affects the load bearing capacity of the tire. As a result, the only way to reduce tire weight substantially and solve the load bearing capacity issue is to use lighter weight materials that are super reinforcing and are less hysteretic than conventional materials currently being used.

Cooper was able achieve the goals of this project, through the development of multiple technologies. Six technologies were chosen that are not currently being used in the tire industry at any significant level, but that showed excellent prospects in preliminary research. This development was divided into two phases. Phase I investigated six different technologies as individual components. Phase II then took a holistic approach by combining all the technologies that showed positive results during phase one development.

The six technologies investigated as a part of phase I were:

- Nano-fiber fillers
- Aramid bead bundles
- Aramid belt packages
- Ultra-Long wearing and low hysteresis tread compound
- Barrier film innerliner
- Low RR tire profile from FEA modeling

With this approach, Cooper was successful in gaining insight in how to utilize these technologies to develop a new class of replacement tires that will improve passenger vehicle fuel efficiency by at least 3% while lowering the overall tire weight by 20%. It is important to point out that Cooper is interested in using these technologies in our current and future line of products, so we understand that this technology needs to be cost competitive in relation to current technology. Based on preliminary estimates, we believe this technology can be made cost effective due to:

(i) less conventional material being used (20%) in the tire,
(ii) a potential to significantly improve process & manufacturing efficiencies (examples: less mixing time, less material preparation, faster tire curing, etc.),
(iii) a reduction in capital equipment needs for future tire capacity growth requirements,
(iv) savings gained by the consumer in using a more fuel efficient product.

In the replacement market, improving rolling resistance technology has not been an important priority for the tire producers until recently. As consumers become more aware of tire fuel efficiency, it will be imperative for manufacturers of replacement tires to have competitive tire product offerings. Unlike new vehicle sales, it will be the consumers, not the automotive OEMs (Original Equipment Manufacturer), who are making the purchase decisions for replacement tires. Product offerings and marketing efforts need to keep the consumers' needs at the center of strategy and decisions. Tire manufacturers face pressures to produce more and more fuel efficient tires, and these pressures influence their decisions and behaviors. Tire rolling resistance is one factor that contributes to a vehicle's inefficiency.

Following is a summary the development process for each of the 6 technologies followed by a complete discussion of the Phase II process.

1) Nano-fiber Filler Technology

Phase I Development

The goal of this technology is to reduce the tire weight by reducing the specific gravity of tire compounds and to reduce the hysteresis of the tire by reducing the hysteresis of the tire compounds. Fiber technology that is being investigated will replace the current fillers, carbon black and silica, at a ratio of between 1:1 and 1:3 which results in a reduced specific gravity. The overall reduction in filler should also result in a reduction in hysteresis. Ideally, the properties of the compound with experimental fillers would match the properties of the standard compound such that no performance would be sacrificed.

The initial strategy was to develop a masterbatch using nano-fiber. At the beginning of this development, the masterbatch produced contained only 5-10 phr of nano-fiber. After further trials, the masterbatch produced contained over 20 phr of nano-fiber. This concept showed promising compound properties but would be very expensive to bring to the production trial phase. Because the properties were not exact and the cost for a plant trial was so high, additional strategies were also explored.

Macro-fibers were then investigated in non masterbatch applications using conventional mix strategies but the dispersion and compound properties would not meet requirements. Research was then started to find coupling or compatiblizing agents for the nano-fiber material. Coupling agents would provide improved compound properties by bonding the filler to the polymer. As of the close of this program, a suitable coupling or compatiblizing agent had not been found. This is an area that many institutions and many companies are working to develop. Raw materials are relatively inexpensive and renewable.

As a result of the issues involved with the first nano-fiber development, additional macro/nano-fibers and bio fillers were investigated in both masterbatch and non masterbatch strategies. From this development, alternative fillers were found that could provide acceptable compound properties and be added to the compounds using conventional mixing. These compounds lowered specific gravity and reduced hysteresis which contributed to both program goals.

Development of this technology focused on development in three areas, one of which was tread compounds and two of which were non-tread compounds. Using these macro/nano-fillers, however, always resulted in reduced tread wear. Tread wear was reduced enough that tread was dropped from the research process and the focus was placed on two non-tread compounds. Phase I research resulted in the development of two alternative fillers being used as carbon black replacements in these two non-tread compounds. Figure #5 shows the hysteresis reduction accomplished in each of the two compounds using the two new experimental fillers. Tire testing would then be used to see what impact lower compound hysteresis would have on the tire rolling resistance.

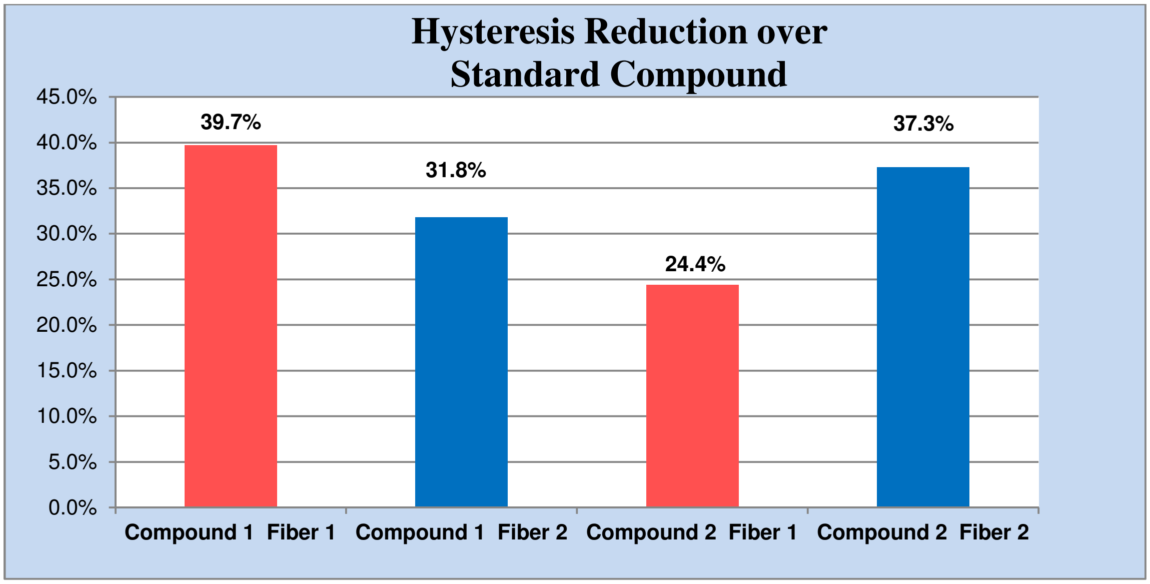


Figure #5

Tire projects were successfully completed where both fillers were investigated in both compounds. Figure #6 shows the results from a tire program where one project looked at alternate filler 1 in both compounds and the other project investigated alternate filler 2 in both compounds. These tire projects verified that if hysteresis was lowered in these compounds then the overall tire rolling resistance would be improved. The lowest hysteresis compound for each non-tread application was chosen for use in Phase II.

Tire Weight and Rolling Resistance Results				
	Tire Wt	Tire RRc	Δ Wt	Δ RRc
Tire w/Standard Compounds	23.33	9.34		
Tire w/Filler 1 Compounds	22.77	8.68	2.4%	7.0%
Tire w/Filler 2 Compounds	22.87	8.81	2.0%	5.6%

Figure #6

Phase II Development

The two alternate fillers developed in Phase I were used during the final Phase II tire build. Two compounds were used, one with each alternate filler. This provided the lowest hysteresis for each compound. These compounds were used in all the features that were built in Phase II. Alternative filler technology contributed to both a weight savings and an improved tire rolling resistance. (See section 7 Phase II Summary for results) Because experimental compound properties matched the standard compound properties, no other performance was sacrificed in the tire.

2) Aramid bead bundle

Phase I Development

The goal of this technology is to reduce the weight of the tire by reducing the weight of the bead material. Current technology uses steel for the bead material while this project investigated aramid which has high strength but a lower specific gravity. The bead plays a very important role in the design of the tire; it is what holds the tire on the rim. There are established government standards that must be met to ensure that the tire is safe. Aramid at equal strength to steel has a much lower weight and would provide a weight savings without reducing the strength of the bead. Two aramid bead strategies were investigated as part of this development.

The first strategy investigated a bead that was manufactured outside Cooper. The aramid bead was then painted with a rubber cement so the bead filler could be applied. Once the bead filler was applied, it was built into a tire the same as a standard steel bead. Initial testing was conducted to verify the strength of the bead was equivalent to the steel bead. Hydro burst testing was used to verify the bead strength which is a test where the tire is pressurized with water until the tire fails. Both the aramid bead and the steel bead testing resulted in a tire failure in the crown area of the tire. Neither bead broke which confirmed the strength of the aramid bead.

The second strategy investigated a stiff aramid cord that was processed through normal steel bead forming equipment. During this process, the cord is coated with rubber which allows the direct application of the bead filler. Once the bead filler was applied, it was built into tires using the normal tire building process. The first trial with this approach resulted in a failed hydro burst test. A second trial was conducted where the cord strength was increased and the number of wraps in the bead was increased. The second trial passed the hydro burst test which confirmed the strength of the aramid bead from this process.

Once the beads where shown to have the necessary strength, additional tires were built for further testing. All wheel testing showed acceptable performance including lower sidewall endurance testing. Track testing resulted in a slight drop in handling performance but overall results were very close to that with steel beads. The biggest issue experienced was with bead push off testing (Figure #7). This has a DOT requirement which is tested at 26 psi inflation pressure and was not acceptable. The bead unseat testing was also conducted at other inflation pressures for comparison. At each inflation pressure, the aramid bead was pushed off the rim at a lower pressure than the steel bead. At this point, development on aramid beads was halted. Rim slip was also a concern and testing provided mixed results. Bead circumference may be able to be adjusted to eliminate this issue.

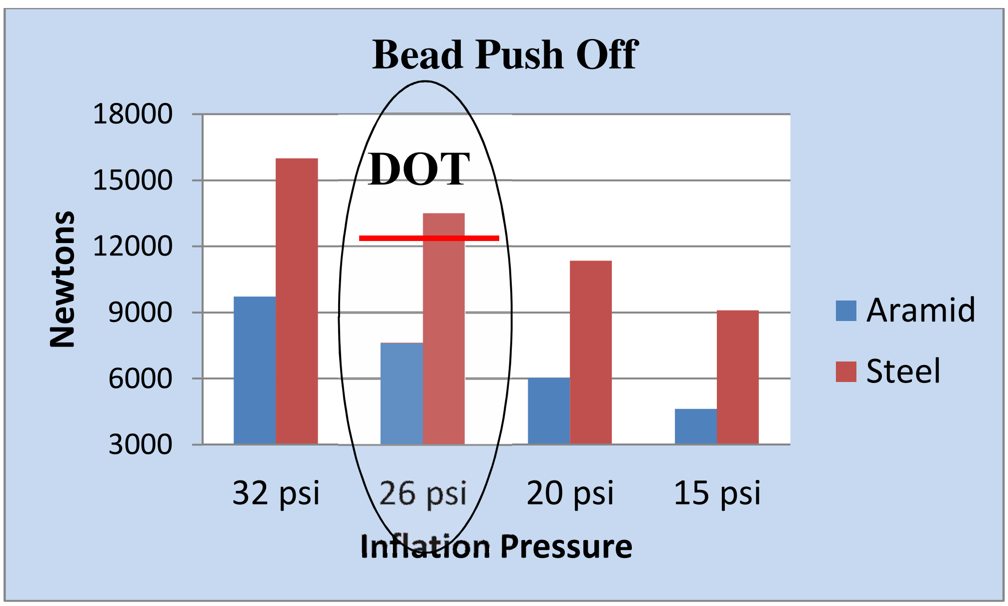


Figure #7

Tire testing showed no benefit in rolling resistance and only a moderate weight savings (Figure #8). This technology was not chosen to be a major part of Phase II development. It was determined that only a few tires would be built for rolling resistance testing and weight measurement.

Feature	Weight Reduction	RR Reduction
Aramid Bead	2% - 4%	Minimal

Figure #8

Another observation from the development work, unmounted tires with aramid beads are very flimsy in the bead area while tires with steel beads are very rigid in the bead area. If this technology was developed to the point of introducing it into the market place, the dealers and consumers would have to be educated on the difference to the feel of the tire. There might be a negative perception of tires with very little sidewall stiffness in an unmounted tire.

Phase II Development

Several tires were built with aramid beads combined with all the other technologies. These tires were then tested for rolling resistance and measured for weight. No other testing was performed. (See section 7 Phase II Summary for results)

3) Aramid belt package

Phase I Development

The goal of this technology is to reduce the rolling resistance and weight of the tire by reducing the weight of the belts. Current technology uses steel for the belts while this project developed aramid as the belt material which has a lower specific gravity than steel. The belt package is responsible for serving as a support structure for the tread, but also to guard against puncture from road hazards. There are established government standards that must be passed. Aramid at equal strength to steel has a much lower weight and provides a weight savings without reducing the strength of the belt. Several aramid programs were completed to try and optimize the performance. There are still some performance characteristics that need to be improved prior to using in a production product.

The first program investigated the performance of the aramid in a belt application. There was some thought that the aramid would cause a rounded tire profile in the crown of the tire. This was not an issue for this test program. The tire profile with aramid belts was actually less rounded than the steel belt profile. Vehicle handling was equivalent or better when compared to the steel belts. Limited testing was completed on tire from this program. All the aramid belt projects passed DOT requirements for high speed but were still below the high speed results for the steel belted tires. Testing also showed about a 9% improvement in weight and about a 6% improvement in rolling resistance.

The second program investigated varying the rubber gauge between the belts. These changes were investigated to increase the high speed results. All the aramid belt projects passed DOT requirements for high speed but were still below the high speed results for the steel belted tires. Testing also showed about an 8% improvement in weight and about a 5% improvement in rolling resistance. Vehicle handling testing showed slight differences in performance. Extreme handling tests showed a slight decrease in performance for the aramid belt tires while the soft handling tests showed equivalent performance.

The third test program investigated a change in belt angle to improve high speed and a change in over wrap construction to improve rolling resistance. This program included the full range of tests that would be needed to approve a change in the belt area. All the aramid belt projects, once again, passed DOT requirements. However, high speed was still lower for the aramid belts compared to the steel belts. The over wrap change did not improve the rolling resistance. While aramid belts show promise, there are still gaps between aramid belt performance and steel belt performance in this program. Vehicle handling was equivalent or slightly down depending on the test.

The average advantage in weight and rolling resistance observed in the first three programs was just over an 8% weight savings and almost a 6% improvement in rolling resistance (Figure #9). Because all DOT requirements were passed and because an improvement in both weight and rolling resistance was obtained, aramid belts were used in two of the three phase II projects.

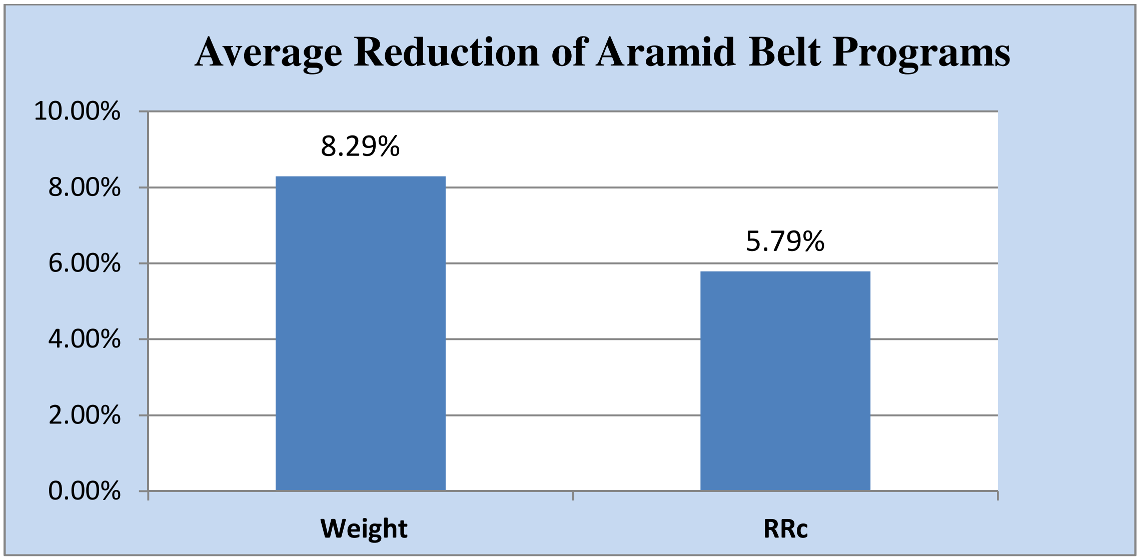


Figure #9

The fourth and final aramid belt program was conducted after the Phase II program. This program was completed to try and further optimize all areas that still showed test results lower than steel belts. A major part of this program was the development of a new belt coat compound. The new belt coat compound was used on five out of the seven projects built. This compound attempted to improve the fatigue properties without changing the other properties. Other features included several belt angles and additional design changes. One of the new angles and one of the design changes surpassed the high speed results of the steel belts. Vehicle handling was equivalent for most of the projects.

Further optimization is still needed to provide aramid belts that match all the performance characteristics of the steel belts. Vehicle handling was very close to what is experienced with steel belts. Wear testing showed equivalent wear or better than the steel belts.

<u>Phase II Development</u>

Aramid belt developed helped meet the goal of a 20% weight reduction in the Phase II program. Tires containing aramid belts in Phase II passed all DOT requirements. Future development will be necessary prior to using aramid belts in a production product. (See section 7 Phase II Summary for results)

4) Ultra- long wearing and low hysteresis tread compound

<u>Phase I Development</u>

The goal of ultra- long wearing and low hysteresis tread compound is to reduce the rolling resistance of the tire by reducing the hysteresis of the tread compound and to reduce the rolling resistance and tread weight by reducing the tread depth. (Figure #10) Tread compound strategies targeted a lower hysteresis by 20% to 30% along with the 25% reduction in tread depth. In order to maintain tread wear, the tread compound also needs to have its tread wear capabilities increased by 25-30%. A common trade-off made when attempting to improve tread-life and rolling resistance is in the area of traction. The tread is a major contributor to the tire traction and handling performance. This program will also attempt to maintain all traction performance that is seen in the control tire.

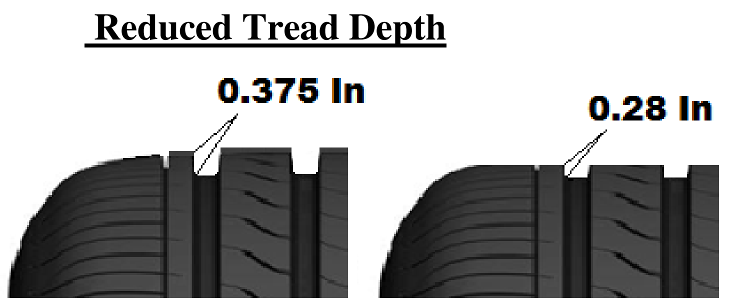


Figure #10

The first program for improved tread compound investigated new silane technology and new polymer strategy to improve tread wear. Tire wear testing revealed a 16% improvement in tread wear with the new silane and a 37% improvement in tread wear with the new polymer strategy. (Figure # 11) This testing was completed using a typical tread compound as the control. Vehicle braking results were equivalent or better for the experimental compounds while vehicle handling results were slightly lower.

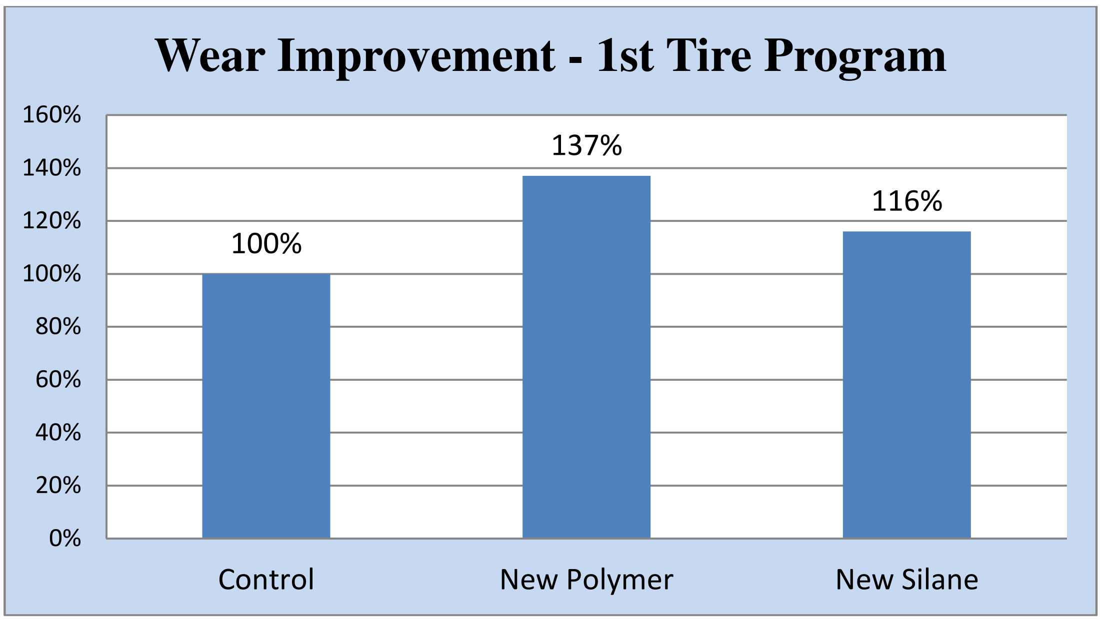


Figure #11

The second program for improved tread compound investigated a new tread compound that would reduce hysteresis by 20% and increase wear by 25%. Also investigated as part of this program was a new functionalized polymer that should have resulted in improved wear and/or improved hysteresis, neither improvement was observed. Tire testing of these experimental tread compounds showed a rolling resistance improvement of 16% and a tread wear improvement of 25-35%. (Figure #12) This program reached the tread wear improvement but missed the rolling resistance target. Winter testing showed the new tread compound was equivalent for snow and ice traction. Track testing resulted in mixed results for wet traction.

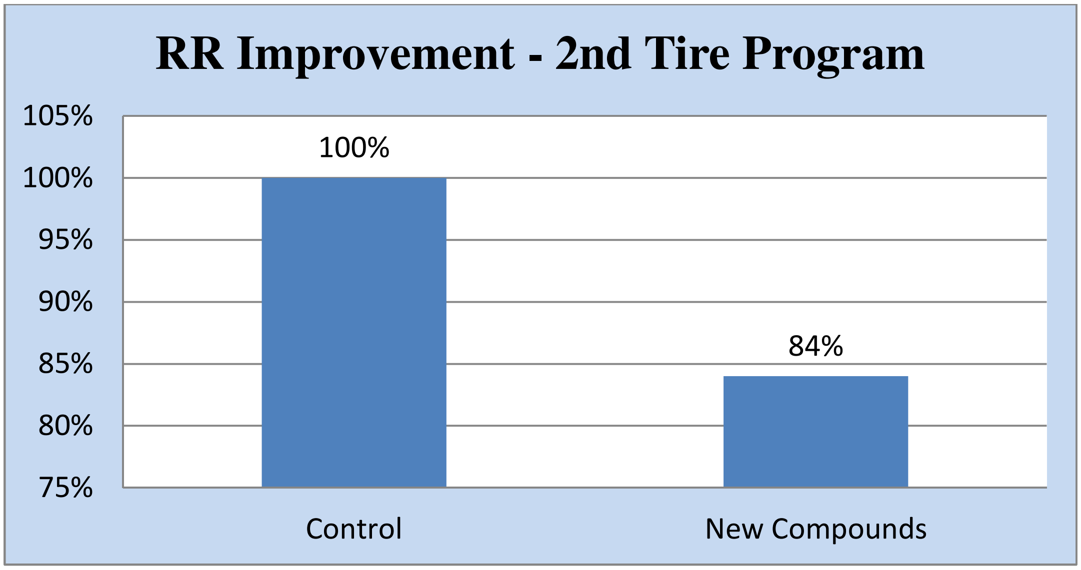


Figure #12

The third tire test program investigated optimizing the tread compounds from the first two programs. Each of the experimental tread compounds was tested in a new low nonskid mold. As part of this program, the new silane from program one was used but did not result in any wear improvement compared to standard silane. However, a slight improvement in rolling resistance was observed with the new silane (Ex#2). Also investigated was another polymer strategy (Ex #3) which resulted in poor wear and much improved wet traction. Experimental feature 2 (EX #2) was chosen as the compound to use in the final Phase II tire build. (Figure #13) Even with the reduced tread depth (9/32") the experimental compound provided tread wear slightly higher than the control (12/32"). All other performance characteristics matched the control tire.

Compound Evaluation - 3rd Tire Program					
Mold Profile	**Compound**	**RR**	**Wet Traction**	**Snow Traction**	**Wear**
CS4 - 12/32"	Control				
New Profile - 9/32"	Ex #1	16%	2.5%	-4.8%	7.3%
New Profile - 9/32"	Ex #2	20%	2.5%	4.0%	5.3%
New Profile - 9/32"	Ex #3	19%	4.0%	2.0%	-6.8%
New Profile - 9/32"	Ex #4	16%	3.0%	-9.5%	0.0%

Figure #13

Phase II Development

The ultra- long wearing and low hysteresis tread compound (Ex #2) was used in all the features investigated in Phase II. Experimental tread compound Ex #2 met all the goals targeted for the tread compound. When this technology is combined with the lower nonskid mold, it helps contribute to both a weight savings and a rolling resistance improvement. (See section 7 Phase II Summary for results)

5) Barrier film innerliner

Phase I Development

The goal of this technology is to reduce the weight of the tire by reducing the amount of material used to maintain air pressure in the tire. Historically, the air pressure in a tire is maintained using a layer of compound where the polymer system consists of Halobutyl or a blend of Halobutyl and NR. The current development is focused on a new material where the liner gauge could be reduced dramatically. The gauge reduction would result in a significant weight reduction. Once this technology was developed, there could be the ability to reduce air permeation through the tire to almost zero. The gauge would have to be increased but it would still be substantially thinner than conventional innerliner.

Initial tire trials were completed using version one of the barrier film which reduced the gauge of the air perm layer by 95%. Tires tested from this program showed a reduced weight by 8%. However, the barrier film increased the rolling resistance by about 10%. In order to overcome the increased rolling resistance caused by the barrier film, the hysteresis of the barrier film needs to be substantially reduced. Unfortunately, the barrier film cracked in the shoulder area during endurance testing from fatigue failure. Additional versions were tested in other tire test programs. Endurance testing for each version showed fatigue crack issues in the shoulder area of the tire. (Figure #14) Version 2 finished the endurance test but when the tires were inspected they also showed fatigue cracking in the shoulder. Version 2 was improved over version 1 but version 3 regressed and was poorer than version 2.

Barrier Film Summary			
	Endurance Test	**Liner Cracking**	**Weight (lbs)**
Rubber Liner	100%	None	2.1
Version 1	53%	Severe	0.6
Version 2	100%	Moderate	0.6
Version 3	74%	Severe	0.6

Figure #14

One of the issues that would have to be considered if this technology was adopted is how to repair a tire that used barrier film if it obtained a puncture. Current tire patches are designed to adhere to the halobutyl innerliner. This technology was not chosen to be a major part of Phase II development. It was determined that only a few tires would be built for rolling resistance testing and weight measurement.

Phase II Development

Several tires were built with barrier film along with all the other technologies combined. These tires were then tested for rolling resistance and measured for weight. The Phase II tire build was completed with a 4th version of the barrier film which also failed the endurance test for fatigue cracking. (See section 7 Phase II Summary for results)

6) Low RR tire profile

Phase I Development

The goal of this technology is to use FEA modeling to evaluate and develop a profile designed to provide the lowest rolling resistance while maintaining tire performance and reducing tire weight. The FEA modeling will also be used to evaluate design and compound modifications to further reduce weight and rolling resistance.

It is well known and understood that rubbery material experiences hysteresis losses in deformation cycles, as a result of its viscoelastic nature. Minimization of the adverse deformation cycles reduces hysteresis loss. In the tire construction, deformation cycle reduction is accomplished through extensive computational analysis methods. This involves the use of substantial computing resources.

The heaviest single component of a tire is its tread as verified with FEA modeling, and this component alone accounts for roughly 50% of a tire's hysteretic losses. The FEA model shows that utilizing reduced hysteresis tread that also improves wear resistance will allow a significant reduction in overall non-skid depth which results in an overall tread mass reduction. This will result in lower tire weight with the remaining tread mass having lower volumetric hysteresis, yielding a synergistic effect in reducing the tire's overall rolling resistance.

When the program began, the level of finite element analysis capability required for this project exceeded Cooper's in house resources. Cooper established a working relationship with the National Renewable Energy Laboratory (NREL), and began collaboration with NREL where they would support Cooper on this project. This collaboration leveraged the analytical and computational resources of NREL, as well as provides access to the Red Mesa computing facility at Sandia National Laboratory. Red Mesa is one of the country's major computing installations with over 180 Teraflops of computing capacity.

Over the course of the first year, Cooper increased our resources to the point that we no longer needed the collaboration with NREL to complete the FEA analysis. Cooper soon had the ability to complete computational analysis on the proposed projects for construction characteristics for the fuel efficient tire and to also optimize the design of the profile for optimum fuel efficiency.

Step one of the process involved developing a new model and then validating that model through tire testing. This was completed prior to moving on to step two which was completing a design of experiments on seven different tire design parameters. These parameters were then optimized for weight and rolling resistance and a new profile was identified.

Prior to identifying an optimized profile, engineering judgment was used to develop a low rolling resistant profile which was then turned into a new best geometry mold ("BG" mold). This mold was used as part of the second tread development program and yielded a 9% rolling resistance (Figure #15) improvement and an 8% reduction in weight.

Rolling Resistance/Weight Results			
Mold Profile	**Compound**	**RR % Improvement**	**Wt. % Improvement**
CS4 - 12/32"	Control	---	---
"BG" Profile - 9/32"	Control	9%	8%

Figure #15

After the first tire program was completed with the "BG" mold and the FEA design of experiments was completed, a new mold profile was identified and two new molds were produced. One new mold (profile 7) used a 9/32 inches tread depth and the second mold (profile 8) used an 8/32 inches tread depth. Mold profile 8 at 8/32 inches also had the void volume increase in the circumferential grooves of the tread pattern to maintain water evacuation. "BG" profile and profile 7 had similar wear results but profile 8 resulted in about 30% lower wear (Figure #16) due to the increased void volume. Hydroplaning results were similar for all three profiles indicating that the void volume increase was sufficient to maintain water evacuation.

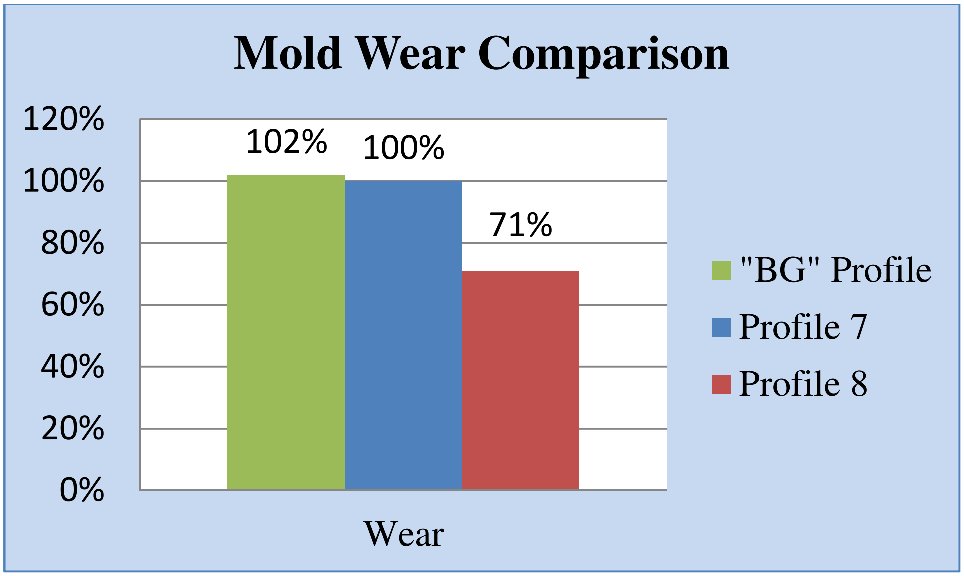


Figure #16

Weight results were similar between "BG" profile and profile 7 while the reduced tread depth used in profile 8 resulted in almost a 6% additional weight reduction (Figure #17). Rolling resistance results showed that the "BG" profile was about 2.5% better than profile 7 while profile 8 was the lowest by 3%. Profile 8 had the lowest weight and rolling resistance but it also had the poorest wear. Overall, the performance shown by the "BG" profile was the most balanced and was chosen for the Phase II tire build. Handling and traction for these molds was adjusted with experimental tread compounds.

Rolling Resistance/Weight Results			
Mold Profile	**Tread Compound**	**RR% Improvement**	**Wt. % Improvement**
CS4 - 12/32"	Control	---	---
"BG" Profile - 9/32"	Control	11.5%	9.4%
Profile 7 - 9/32"	Control	9.0%	9.4%
Profile 8 - 8/32"	Control	14.50%	14.0%

Figure #17

<u>Phase II Development</u>

The BG profile was used in all the features investigated in Phase I and provided the best balance of rolling resistance, weight, traction and wear. When this technology is combined with the new tread compound it helps contribute to both a weight savings and a rolling resistance improvement without sacrificing any other performance. (See section 7 Phase II Summary for results)

7) Phase II Summary.

Once Phase I testing was completed, all six technologies had been investigated. All of the tire components have direct and indirect influences on each other, and as a result, it is necessary to consider the tire assembly as a whole, and not just a collection of local interactions. Phase I development allowed for the establishment of the underlying properties for the six technologies through the use of multiple tire programs. Phase II then used this information to determine the optimal fashion in which to assemble the tire components, in order to achieve the stated objectives. Phase II was broken down into three features (Figure #18), where each additional feature built on the previous feature. The first feature (purple) investigated three of the technologies, the second feature (purple and gray) investigated the three technologies from the first project along with an additional technology and the final feature (purple, gray and orange) investigated all six technologies. The first two features experienced extensive testing and the final feature experienced only limited testing.

	Phase II Design & Projected Results						
	RRC*	Weight Reduction	Tire Weight	Δ WT %	Δ RR % *	Commercial Risk	Performance Risk
Control CS4	10.8		26.0				
Mold Profile/Tread Compound	7.85 *	2.5	23.5	9.62%	27.31%	Low	Low
Fiber Reinforced Compounds	7.35 *	0.5	23.0	11.54%	31.48%	Low	Low
Aramid/Monoply	6.90 *	3.2	19.8	23.85%	34.26%	Med	Low
Barrier Film	7.25 *	1.5	18.3	29.62%	32.87%	High	High
Aramid Bead	7.25 *	0.4	17.9	31.15%	32.87%	High	High
* Estimated Results							

Figure #18

Once the Phase II program was built, extensive testing was conducted to evaluate the overall performance of the technologies when used in combination with each other. Figure #19 shows the estimated results that are expected when building multiple technologies together. The rolling resistance goal was expected to be met by all three features while the weight goal was expected to be met by the second and third features. Final testing (Figure #18) showed the estimated rolling resistance and weight results were close to actual test data.

DOE Fuel Efficient Phase II Tire Development					
	RRc Δ Estimated	**RRc Δ Actual**	**Weight Δ Estimated**	**Weight Δ Actual**	**Fuel Improvement**
CS4	---	---	---	---	---
Feature #1	31.50%	31%	11.50%	13%	5 % - 6%
Feature #2	34.30%	36%	23.90%	24%	5 % - 6%
Feature #3	32.90%	34.50%	31.20%	37%	N/A

Figure #19

As part of the final program testing, fuel economy testing was completed at an independent lab (Transportation Research Center or TRC). Test procedures SAE J2263 and SAE J2263 were completed to establish the test conditions for dynamometer fuel economy testing. Both city and highway test procedures were evaluated for fuel economy on the indoor dynamometer. The city test procedure showed 3.8% improvement for feature #1 and 3.2% improvement for feature #2. These results were opposite of what was expected because it showed feature #1 was better than feature #2. This could be explained by the curve fitting TRC used to set up the dynamometer. The coast down curve used by TRC for feature #2 did not appear to represent the overall coast down data. It was established using TRC curve fitting software. All of our testing showed feature #2 was better than feature #1. The highway test procedure resulted in a fuel savings of 7.1% for feature #1 and 5.6% for feature #2. Once again the results indicated that feature #1 was better than feature #2.

Cooper also completed highway fuel economy testing using actual vehicle road testing. This test procedure was developed to try and maintain environmental conditions as close as possible for the two test vehicles. Tires were rotated between vehicles to try and remove vehicle differences. This actual road testing indicated that feature #1 would be slightly better than feature #2 with both having an average fuel efficiency improvement of between 5 and 6 percent.

Phase II testing resulted in two features that exceeded the passenger vehicle fuel efficiency improvement target of 3% and one feature that exceeded the weight reduction target of 20%. This testing showed that Cooper was able to meet and exceed the overall goals for this program.

Products Developed:

Conference papers:

Presentations presented by Teijin that included DOE work on Aramid Belts and Beads:

Future Tire Conference, in Brussels, Belgium 4 & 5 June 2013 – **"Future tires with Twaron: A raw material's perspective on the tire industry's trends and developments"**
The Future of Tire Technology, Charlotte, NC 28 & 30 October 2013 – **"Future Tires with Twaron p-aramid: A raw material's perspective"**

Presentations presented by Cooper that included DOE work:

SAE 2015 Government/ Industry Meeting, Future Vehicles: Integrating Safety, Environment and the Technology, January 21-23, 2015 – **"Developing and Introducing Fuel Efficient Tire Technology in the Replacement Market – A Manufacturer's Perspective"**

There are no Web sites or internet sites that reflect results from this Program.

Collaborations fostered:
NREL
Teijin

Inventions/Patent Applications:
Applied for Aramid Bead application patent.

Modeling:

Introduction:

To produce the "best" result for this project, the evaluation of many dimensions and combinations of the design variable space is required. Historic, traditional methods of build and test are very time consuming and expensive, and would not have been tractable within the time constraint of this project.

Therefore, computational analysis methods, in this case non-linear FEA, were used in this project to sort through all of these variations. This enabled Cooper to narrow the field of consideration from several hundred at the very beginning, to about 3 or 4 final shapes/constructions, in a fairly short amount of time and cost effective manner.

It should be noted that the modeling employed for this project, was not modeling associated with the development of statistical, phenomenological, correlation based, or other types of generalized mathematical modeling requiring extensive research, and subsequent validation. The mathematical modeling for this work was based on the well-developed science, math and physics of finite element analysis principles. A few comments relative to approximations and assumptions will be made for background purposes.

Project Objective(s) with respect to Modeling:

The primary objectives of the project were to develop a tire which was light weight and improved vehicle fuel economy by a specific percentage. One assumption involved at the outset was, from "conventional wisdom", there is a generally accepted rule of thumb relationship that states that for every 1% change in fuel economy, about 10% change in energy loss from rolling resistance is required to achieve that result. This is somewhat arbitrary, and does not define a consistent basis from which percentages are measured. However for the present work, the baselines for each were established, with respect to a specific baseline tire, and subsequently a baseline vehicle for fuel economy measurement.

Other objectives required that other general measures of tire performance, e.g. handling, traction, wear, etc, for the new tire design would be equal to or better than the selected baseline.

Modeling Background:

FEA Theory and Application:

With most all types of mathematical analysis, assumptions and approximations, along with the mathematical representations of the specific sciences are invoked along the way, to affect final solutions. In this particular case, the physics of solid mechanics and fundamental principles such as potential energy and minimization of potential energy leads to the underlying mathematics of the finite element method. The solution of the equilibrium equations are the necessary and sufficient conditions to guarantee a minimum potential energy solution.

Within the context of the "continuous" mathematics definitions, approximations are made to convert the continuous domain to a discretized domain of many small pieces, in a piecewise continuous fashion, generally called elements. In turn the solution variables within the element domains are approximated using various orthogonal interpolation function classes, i.e. Hilbert Space Methods.
This generally leads to a system of algebraic equations, (non-linear in this case), with displacements as the primary solution variable, of the force / displacement equilibrium equations. This final system of equations is an appropriate assembly of all of the element systems, which have also now included equations for material constitutive relationships and appropriate derivatives of the interpolation functions of the independent displacement degrees of freedom to get stress and strain information within each element.

The above incorporates a number of approximations and assumptions that are an integral, and well understood part of the FEA system.

From a different perspective, the solution of the force / displacement equilibrium equations is the minimization of the error of the approximating functions of the independent variable interpolation functions as operated on by the functional requirements of the minimizing principle. Thus, while displacements are generally the independent solution variable, stress, strain (appropriate derivatives of displacements) and strain energy within each element which is required to satisfy the minimum potential energy criteria.

The above theory and process is long established in advanced literature and journals, and embodied in many different commercial and public domain FEA Codes.

FEA Codes - ABAQUS - Commercial FEA:

The code used by Cooper for this purpose is ABAQUS, which is a proprietary commercial FEA program, from Dassault Systemes. Complete user, theory, validation, etc, documents are available from Dassault Systemes Simulia Corp. ABAQUS has many different classes of analysis. The class of analysis used for this project was standard, implicit, static, geometric non-linear analysis. The justification for using this approach is outlined in the following discussions.

FEA Tire Models – Generic:

The above discussion addressed the general characteristics of the assumptions and approximation built into the fundamental method of analysis. Additionally, there are assumptions of the application of the above to the general subject of tire analysis, as well as the assumptions used to quickly characterize and sort the tire constructions / models for the present project.

From a general perspective, the finite element process permits the modeling of a substantial amount of detail relative to tires. This ranges from the details of the external, for example a fully treaded tire, to specific details of reinforcement / compound interaction. The challenge is to determine the balance between deep computational detail and practical sufficiency.

Recognizing that the purpose of this project, as defined earlier, requires primarily a good tool that is sufficiently sensitive to differentiate between the design variable space, in terms of weight and rolling resistance estimates, for the design space in consideration, this enabled a number of modeling simplifications of idealized constructions, such as working with ribbed tires as opposed to fully treaded tire details; working with statically inflated and loaded tires as opposed to at speed rolling tire analysis; making use of reinforcement model constructs built into ABAQUS, as opposed to detailed models of reinforcing component / compound interaction.

With the simplifications outlined, in the general case, the models that were used for this project involved on the order of millions of degrees of freedom that required a non-linear solution procedure.

Rolling Resistance Theory:

Within the context of the project objectives and general computational requirements of the modeling aspects of the present work, a key piece of work for this project required the development of a new rolling resistance theory. This theory had the requirements of being stand alone, physics based, sensitive to the variations to be introduced in the model, and computationally highly efficient, such that it could be used as a fast grading / ranking tool for the entire scope of the design variable space involving shape, construction, materials, and more.

The underlying key assumptions involved working entirely in a path integrated cyclic energy variation and energy loss space, as opposed to classical methods derived from specific stress and strain cycle path integrals. The details of the theory and development are outlined in a following section.

The performance criteria for the model, was, that all taken together, the variation from experimental measurements should be "consistent" and tracking the rolling resistance experimental data within about 10% variation, in order to establish sufficient confidence to be able to use the tool for the intended purpose.

RR Theory Formal Validation:

The rolling resistance theory, outlined the next section, was validated informally on different tires, where experimental data existed, for both passenger and truck tires. Additionally, a project was run to formally validate the theory for use in this project. The validation project included several passenger tires, of varying diameters, widths, aspect ratios and compounds. Specifically, the diameter range was from 14 to 18 in diameter, the aspect ratio range was 45 to 65 series tires, the widths ranged from 185 to 275 mm, and one tire included was the GFE, current Cooper fuel economy tire.

Standard production tires were tested using the current rolling resistance test protocol. Independently, the set of tire constructions were modeled using the standard modeling methods at Cooper which correspond to the nominal / idealized, as designed tire. Since the objective was to compare to experimental data, it is always important to construct the model and test conditions that are as close to what was actually tested as possible. The reason for this is to remove the effects of assumptions that may be implied, if only nominal / idealized, as designed tires are used for the models. That procedure was done for this project. That is, some of the tested tires were subsequently cut in order to produce models whose tire section gauges corresponded to the cut tire sections, for all of the tire sizes included in this project. Both set of models were run through the analysis and rolling resistance calculations and subsequently, independently compared to the experimental data.

The rolling resistance theory, as developed, is sufficiently sensitive to identify proper correlations to changes in loading conditions such as pressure, load, rim, flat/drum surface, etc. Additionally, the theory is sufficiently sensitive to correctly identify changes in the model, construction, material properties, etc. The "as designed" and "as manufactured" models did exhibit differences, as expected. Further, the comparisons to the respective experimental data results were very good. The correlation can be seen in Figure #20. This provided sufficient validation to proceed using this theory for the rest of the project. As a side note, this theory has been implemented as a standard tool for rolling resistance computational calculation from FEA results.

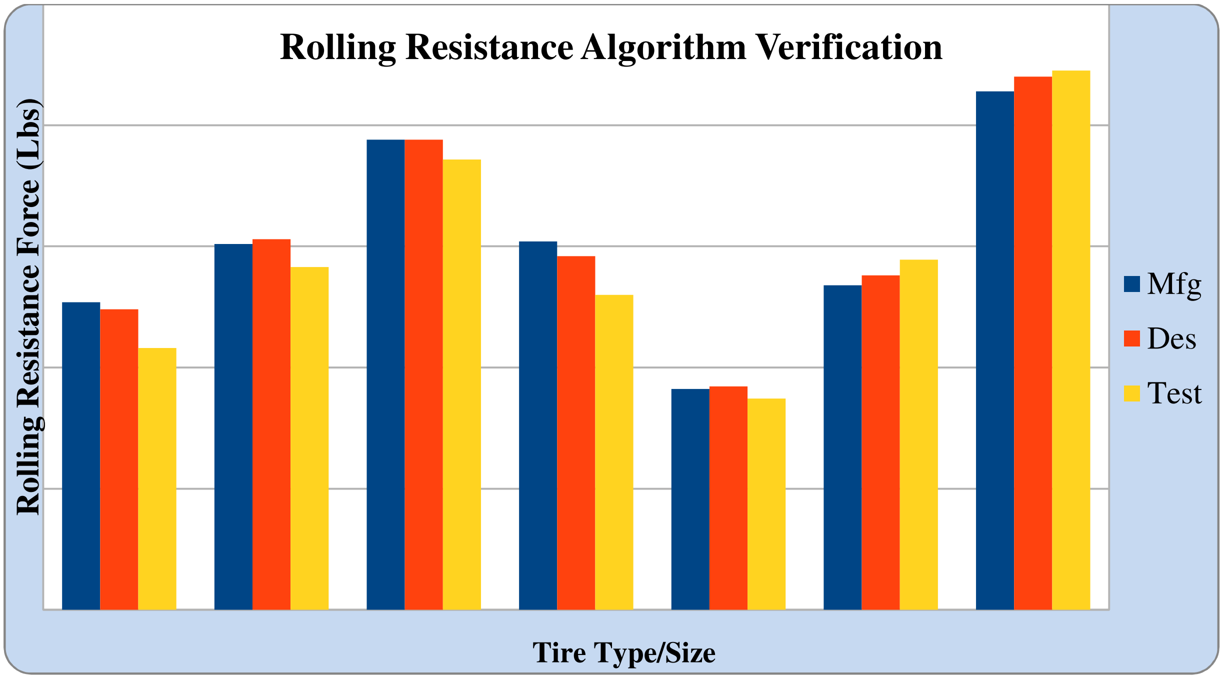


Figure #20 - FEA Rolling Resistance Theory Validation Project Result

RR Theory Development:

There are a number of ways to develop the theory of rolling resistance for tires. One method involves the tracking of the actual strain tensor component through its history and proceeds to develop a stress / strain history and graph through which losses are determined. In the most rigorous form, this requires the introduction of material properties and analysis classes that can account for loading and unloading behavior with associated energy loss. For example, one approach would require a full time accurate transient rolling tire model with visco based materials that can exhibit energy dissipation, and that dissipation would need to be accumulated over the rolling cycle. This is generally done in the context of an explicit, time integrated analysis. One short coming of this approach is that it is difficult to separate frame invariance, from the specific tracking of strain and stress history components. Therefore, an alternate formulation was developed, that is both highly efficient relative to the analysis required to characterize rolling resistance, and is frame invariant, by definition.

The present approach developed for this DOE project involved applying a spatial integration over the loading cycle of a tire using a static inflated and deflected solution using non-linear elastic material properties, rather than a temporal integration. Further, it was developed using strain energy and strain energy density as the primary field variable, which is frame invariant by definition. One of the underlying approximations, was, that what is observed for energy loss in tires generally runs in a specific frequency range, e.g. highway speeds, which is fairly consistent and reasonably independent of frequency. One indication that hysteresis can be observed without high frequency viscous effects is that when stress / strain loading cycle tests are conducted at even a low rate, hysteresis is exhibited. Therefore, if frequency is not a large contribution, this work can be transformed to a spatial integration over a static inflated and deflected solution, as an approximation, and subsequently be sufficient for a quick relative ranking tool. What is necessary is that the proper field variable quantities of interest be integrated, which in this case was strain energy, and strain energy density as noted.

The fundamental underlying principle of this approach is that in the consideration of a typical rubber compound going through a loading / unloading cycle of specific magnitudes, the "stress / strain" curve exhibits very definite characteristics for loading and unloading. By definition, the integrated area under the curve for the loading cycle can be considered as the loading energy. Similarly, the integrated area under the curve for the unloading curve can be considered the unloading energy, or the recovered energy. The difference between the two areas is directly lost energy, or hysteresis. The manner in which this translated to extracting and summarizing information from the tire solutions was as follows:

1. Integrate the element strain energy density over the volume of the "ring of elements" in the circumferential direction, and subsequently, determine a volume weighted mean strain energy density (VWMSED).

2. Use the VWMSED quantity to subtract from the element strain energy densities of the same ring and integrate the absolute value over the volume of the ring to produce a volume weighted variance of the strain energy. Abaqus was used in this case with non-linear elastic material properties, so this quantity represents an elastic energy variation for each element ring of the tire cross section.

3. At this point, the appropriate energy loss characteristics for each compound is incorporated to determine the energy loss associated with the given elastic energy cycle variation for the rolling direction cycle.

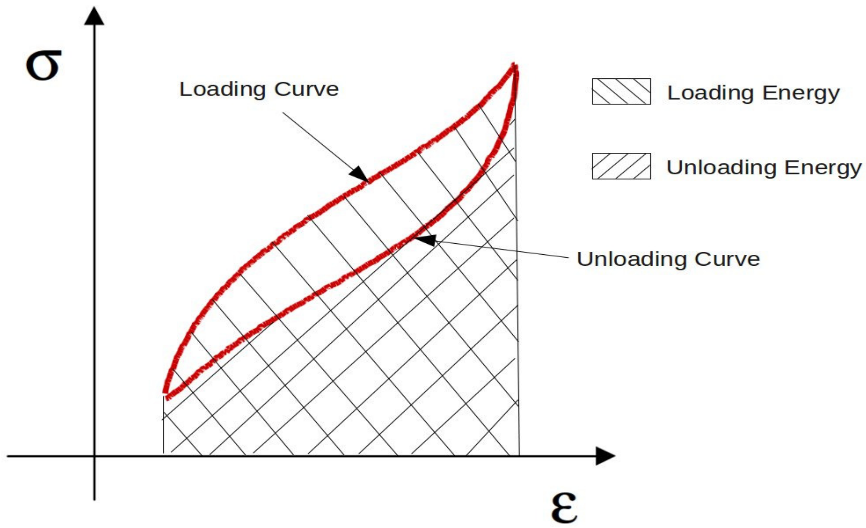
4. This information is summed up over the components of the tire cross section for the entire tire model, and directly related to the test conditions to determine a rolling resistance force, that relates to force data that is derived from the standard tests.

Since this approach is highly dependent on strain energy information, it is imperative that the discretizations of the FEA models are sufficiently refined to capture important strain gradients in the cross section as well as around the circumference. The motivation for this was outlined in the section regarding general theory and approximations in the finite element method.

This application and development of the theory is cognizant of the levels of approximation, or limitations, that are included. For example, presently the theory only is applied in the context of a static inflated and deflected tire. Additional effects such as at speed rolling with the associated strain energy stiffening from centrifugal loading and thermal / heat transfer effects relative to material / hysteresis properties represent direct extensions to the present theory, and can be introduced at appropriate times, as warranted. The initial development was consistent with the level of approximation required for the exercise of the present project.

As noted above, The Fundamental Rolling Resistance Theory has been developed on an energy variable basis. It considers the total strain energy cycle and variation from the mean Elastic energy cycle for each circumferential ring of elements on the tire cross section. The variation from the mean represents the variation of the strain energy cycle as integrated for each ring of elements.

Consider that for “rubber compounds” in general, the stress-strain curve for a specific loading and unloading cycle generically appears as follows:



Hysteresis = Loading Energy – Unloading Energy

This indicates that from a general perspective, the hysteresis / energy loss is directly determined by the difference between the area under the loading curve, and the area under the unloading curve.

From a mathematical perspective, the basic principles of the newly developed Rolling Resistance Theory can be summarized in the following:

Element Elastic energy cycle:

$\text{Total Strain Energy}_{\text{element ring}} = \text{TSE}_{\text{element ring}} = \int_{\text{circ}} \int_{\text{elem vol}} (\text{SED})\, dv$

$\text{Vol}_{\text{element ring}} = \int_{\text{circ}} \int_{\text{elem vol}} dv$

Volume Weighted Mean of Total Elastic Strain Energy per element ring

$\text{VWMSED}_{\text{element ring}} = \text{TSE}_{\text{element ring}} / \text{Vol}_{\text{element ring}}$

Variation of Elastic energy cycle:

Cycle of Total Elastic Strain Energy Variation per element ring

$\text{VTSE}_{\text{element ring}} = \left(\int_{\text{circ}} \int_{\text{elem vol}} (\text{SED - VWMSED})^2\, dv\right)^{1/2}$

Energy Loss:

Hysteresis = f(material loss prop, VTSE)

The above is integrated over all of the components in the tire, and summed to arrive at the total cyclic energy variance in the tire, for the non-linear elastic materials. Taken together with the material hysteresis properties, directly yields the energy loss for the tire. The value is then re-cast in terms of the test rig structure, which measures a force at a distance from the center of rotation, from which we arrive at a force which produces a torque, which relates to the energy loss in the tire with respect to the finite element model and the loading conditions.

The theory and mathematics were informally, internally, reviewed and discussed with colleagues, but not formally and/or externally peer reviewed. The approach outlined the levels of approximation available and what level of approximation was necessary and included / required in the context of the project, and how the present theory is directly extended to accommodate additional physics.

The theory was further supported by the results of the formal validation project, thus providing the confidence to proceed for the present DOE Project.

There are a variety of computational platforms that can accomplish the necessary computing to various levels. The system available within Cooper that was used for this project was an HP DL585 cluster, with 4 compute nodes each of which contained QUAD AMD Magny-Cours (12 cores) processors for a total of 48 cores, and 256 GB memory per node. The cluster was configured with an internal Infiniband network for parallel MPI process communications, and an internal Gigabit network for general network traffic within the cluster.

Documentation for the finite element software, ABAQUS, can be obtained via Dassault Systemes Simulia Corp.

Specific Project Approach:

While not specifically addressed in the requirements outline, this section discusses what, how, when the computational technologies were applied within the scope of the overall project.

The overriding principle here was to develop and validate a technology that could then be used as a sorting tool for tire variation studies, and then proceed to work on the various aspects of the project as required. The following section discussions represent the different phases of the various technologies, and what / how the subject was studied using the computational tools.

Low RR Mold Shape Study:

One premise of the DOE Project Proposal was that the rolling resistance could be influenced by modifying only various parameters of the mold shape only. After a detailed review, the number of parameters of the design space along with the interactions lead to a consideration of approximately 35 different theoretical mold shapes. In this case, the tire construction details / materials were held constant. The results indicated that there was a non-trivial difference in rolling resistance with respect to variations in the mold shapes. The results for the initial study were not in terms of continuous variables, such that an optimal solution could be inferred or interpolated from a response surface of the design space. This information allowed the field to be narrowed to about 5 basic shapes which translated to a final set of 3 mold shape variations for which molds were made to begin physical testing and validation of this aspect of the work.

It should be noted that the tires produced from this process were tested for rolling resistance, and the results agreed very well with the "predictions" made, before tires were built.

Material Parameter Sensitivity Study:

One characteristic of the rolling resistance analysis is that it can report, on a component basis, where rolling resistance is concentrated. Given that information, a study was made to postulate the effects of different combinations of stiffness and hysteresis parameters for the "more important" components. For this work the components varied were the tread, sidewall, and rim cushion. The result of this work pointed to work that needed to be done with these compounds. The physical studies and physical compound development was a subject for a different phase of the project.

Tire Construction Variation Study:

Once the mold shape parameters were known, along with the weight and rolling resistance considerations, additional work was done to study selected carcass, specific compound, and reinforcing material variation studies. Subjects included mono-ply, multi-ply, ply configurations, ply endings, belt widths, belt angles, belt materials, i.e. steel vs. aramid, etc, where the objectives now include, a measure of endurance, handling, etc. Cooper's standard FEA analysis tools were applied for this purpose. These tools are used only for the purpose of making directional design decisions rather than for ultimate product qualification. The end result of the study was that the mono-ply with particular ending locations, along with aramid belts, with widths, separations, and angles chosen to satisfy the multiple objectives. The end product is then qualified by rigorous testing to DOE and internal Cooper standards for product release.

Final Validation / Correlation / Actual Materials / final design data:

With "final" selections made for mold shape, construction, actual as manufactured material gauges, reinforcing, along with material properties for the actual new compounds were determined from experimental characterizations. The computational result using actual tire construction and material characterizations agreed within 5% of the experimental data. This is yet a final test and yet another validation of the overall computational rolling resistance model.