

# **Energy Efficiency in Heavy Vehicle Tires, Drivetrains, and Braking Systems**

A Multi-Year Program Plan for  
Lower Running Resistance and Improved Braking Systems

Prepared for

Sidney Diamond  
Program Manager  
Office of Heavy Vehicle Technologies  
United States Department of Energy

by

Peter J. Blau  
Metals and Ceramics Division  
Oak Ridge National Laboratory

April 26, 2000

---

## Table of Contents

---

|            |  |           |
|------------|--|-----------|
| <b>1.0</b> | <b>Introduction .....</b>                          | <b>3</b>  |
| <b>2.0</b> | <b>Purpose of this Planning Document .....</b>     | <b>3</b>  |
| <b>3.0</b> | <b>Information Resources .....</b>                 | <b>4</b>  |
| <b>4.0</b> | <b>Discussion .....</b>                            | <b>4</b>  |
| 4.1        | Lower Rolling Resistance of Truck Tires .....      | 5         |
| 4.2        | Reducing Parasitic Losses in the Drive Train ..... | 7         |
| 4.3        | Safe and Energy-Efficient Braking Systems .....    | 8         |
| <b>5.0</b> | <b>Proposed Project Areas .....</b>                | <b>9</b>  |
| 5.1        | Materials Research and Characterization .....      | 10        |
| 5.2        | Sensors, Instrumentation and Controls .....        | 10        |
| 5.3        | Systems Integration and Design .....               | 10        |
| <b>6.0</b> | <b>Estimated Funding Requirements .....</b>        | <b>11</b> |

# Energy Efficiency in Heavy Vehicle Tires, Drivetrains, and Braking Systems – A Multi Year Program Plan

## 1.0 Introduction

This document was prepared to support the primary goals of the Department of Energy, Office of Heavy Vehicle Technologies. These were recently stated\* as follows:

“Develop by 2004 the enabling technologies for a class 7-8 truck with a fuel efficiency of 10 mpg (at 65 mph) which will meet prevailing emission standards.

For Class 3-6 trucks operating on an urban driving cycle, develop by 2004 commercially viable vehicles that achieve at least double the fuel economy of comparable current vehicles (1999), and as a research goal, reduce criteria pollutants to 30% below EPA standards.

Develop by 2004 the diesel engine enabling technologies to support large-scale industry dieselization of Class 1 & 2 trucks, achieving a 35 % fuel efficiency improvement over comparable gasoline-fueled trucks, while meeting applicable emissions standards.”

---

\*Ref: DOE, *OHVT Technology Roadmap*, DOE/OSTI-11690/R1, February 2000.

The enabling technologies for improving the fuel efficiency of trucks, include not only engine technologies but also technologies involved with lowering the rolling resistance of tires, reducing vehicle aerodynamic drag, improving thermal management, and

reducing parasitic frictional losses in drive train components. Opportunities also exist for making better use of the energy that might ordinarily be dissipated during vehicle braking. Braking systems must be included in this evaluation since safety in truck operations is vital, and braking requirements are greater for vehicles having lowered resistance to rolling.

The Office of Heavy Vehicle Technologies has initiated a program to improve the aerodynamics of heavy vehicles through wind tunnel testing, computational modeling, and on-road evaluations. That activity is described in a separate multi-year plan; therefore, emphasis in this document will be on tires, drive trains, and braking systems. Recent, dramatic fluctuations in diesel fuel prices have emphasized the importance of effecting savings in truck fuel economy by implementing new component designs and materials.

## 2.0 Purpose of this Planning Document

The purpose of this document is to describe a multi-year, R&D program plan (MYPP) aimed at improving the energy efficiency of heavy vehicles, in particular Class 8 on-highway trucks, through lowering the rolling resistance of tires, reducing parasitic energy losses in drivetrains, and improving the performance of braking systems.

A further purpose for this document is to delineate, where possible, the appropriate participants and technical resources for

addressing these R&D needs. A number of industry-proprietary issues and regulatory concerns surfaced while assembling this report. Since industry participation is encouraged in all phases of this program, proprietary concerns will need to be addressed as R&D partnerships form.

*Note:* The initial draft of this report was dated January 27, 2000 and posted on the internet at:

<http://www.ms.ornl.gov/cerss/mypp.htm>

The current, revised document differs in several key areas, and it addresses suggestions and comments received from both industry research managers and government laboratory staff members.

### 3.0 Information Resources

The following resources were used to develop the information presented here:

- ◆ Private discussions with representatives of trucking companies, trade organizations, and truck and trailer manufacturers and suppliers
- ◆ Articles and trade publications, including those on the Internet
- ◆ Information collected during the American Trucking Associations, The Maintenance Council, annual meeting in Nashville, Tennessee (March 1999).
- ◆ Feedback from a meeting with trucking company managers conducted in Fort Smith, Arkansas (July 1999).
- ◆ The findings of a DOE/ORNL workshop held in Knoxville, Tennessee (August 18-19, 1999).\*
- ◆ Comments on the previous draft of

this draft MYPP.

---

\* A workshop report available to DOE, ORNL, DOE contractors and U.S. trucking industry participants: "Workshop on Opportunities for Heavy Vehicle Energy Efficiency Gains Through Running Resistance and Braking Systems R&D- Final Report," P. J. Blau and A. E. Pasto, Oak Ridge National Laboratory, Internal Report, September 1999.

---

**4.0 Discussion.** Future R&D needs and opportunities in heavy vehicle running resistance and braking systems can be subdivided into three general categories:

#### **Lower Rolling Resistance of Truck Tires**

#### **Reducing Parasitic Losses in the Drivetrain**

#### **Safe and Energy-Efficient Braking Systems**

R&D efforts in each area do not offer equal potential benefits in terms of energy savings, and therefore, a prioritizing process that accounts for this can be instituted in charting the directions of future programs.

Fuel economy savings for tires, axles, and brake technologies are difficult to estimate because a great deal depends on how the vehicle is operated and its type of service (local delivery versus long-haul).

For example, potential tire rolling resistance improvements of up to 15-18% have been proposed. However, compared to aerodynamic drag, tire rolling resistance rises to a significant percentage of the total vehicle running resistance only as speeds drop below about 45-50 mi/hr [ref.: *A Multi-Year Program Plan for the Aerodynamic Design of Heavy Vehicles*, R. McCallen et

al, UCRL-PROP-127753, Lawrence Livermore National Laboratory, February 1998]. Therefore, the magnitude of the energy efficiency gains achievable through various running resistance reduction technologies will depend on the conditions of vehicle use.

It has been estimated that only about 3.0 % energy efficiency gains are possible through axle and drive train improvements [ref: R. Cuenca, Argonne National Laboratory, analysis of heavy vehicle energy losses]. This is less than 1/3 of what might be achieved through tire rolling resistance reductions.

The energy savings associated with regenerative braking cannot be adequately estimated without engineering studies on detailed designs for such systems, but they could be particularly significant for short-haul, or local delivery trucks and buses where the brakes are used more frequently.

In the face of limited resources and the potential impact of certain new technologies relative to others, a priority list for new R&D projects must be established. This document is intended to provide information to that end.

#### **4.1 Lower Rolling Resistance of Truck Tires**

Tires transmit forces from the vehicle propulsion system to the ground or road surface. Any slippage or loss of traction in the tire/road interface can dissipate energy that would otherwise be available to propel the vehicle forward. Additional energy is lost in deforming the tires as they roll. It has been estimated that a heavy truck fuel

savings of up to about 15-18% can be realized through reduced tire rolling resistance.

The main factors that affect the rolling resistance of truck and automotive tires are:

- a. Tread design
- b. Casing design
- c. Materials of construction
- d. Inflation pressure
- e. Tire alignment
- f. Conditions of use (speed, temperature, road surface condition)

Tire technology has been greatly advanced by considerable investment in corporate research and development programs. Tire material compositions are scientifically developed to optimize performance under a variety of road conditions. Industry-developed models for tread and casing designs continue to be refined and used in new product development. Advanced tire designs and sensor technologies are under commercial development. For example, a major tire manufacturer recently announced new bead and clamp designs that prevent tires from coming off the wheel. The same tires also contain built-in air pressure sensors and the capability to monitor 'run-flat' conditions. Since rolling resistance is a competitive selling point for truck tires, the industry tends to protect this technology.

a,b. *Tread and casing designs* of individual companies are proprietary, as are the computational and experimental methods used to develop them. However, scientific and technical expertise in the national laboratories, not-for-profit research corporations, and universities could still be used to benefit these facets of tire

technology. For example, high-performance computing could be used in certain aspects of tire modeling. Likewise, techniques like state-of-the-art thermal imaging could be applied to analyze characteristics of tire/pavement interactions and make that information available for use in validating proprietary models.

c. *The formulation of elastomeric materials* also involves proprietary issues. The most promising opportunities for projects in this area, therefore, lie in the development of new mathematical tools to enable improved modeling of tire material behavior. Such a project could draw upon the strengths of both national laboratories and academia to respond to industry needs. In addition, effective test methods to validate the predictions of these materials models would be needed.

d. *Inflation pressure* can affect tire fuel economy. This fact suggests a need to develop advanced methods to sense the gas pressure in vehicle tires, in real time, and to warn the driver of the need to adjust it. As noted earlier, the tire industry has already invested heavily in condition monitoring and embedded tagging and sensor systems for tires. Therefore, no additional government funded R&D is suggested for this particular area.

e. *Tire alignment*, both for the tractor and for tractor-trailer combination, is known to significantly affect rolling resistance. Static alignment methods for trucks may not satisfactorily reflect the alignment of the vehicle when it is in motion. Dynamic alignment detection systems could greatly enhance tire life, reduce costs, and also improve fuel economy. This R&D area

offers an opportunity for significant contributions, and is considered by at least one tire maker to be pre-competitive and worthy of government-industry cooperation.

f. *Conditions of use* can strongly affect rolling resistance and energy efficiency. Tire traction varies with surface speed, temperature, the angle of the tire to the direction of travel, tread wear, and the nature of the road surface (type of road surface and weather conditions). It is difficult to control the conditions of use, so tires with the capability to exhibit energy-efficient characteristics over a wide range of conditions are required. This conclusion implies optimizing factors a-e, above .

*Conclusions.* The rolling resistance of tires can have a significant effect on the cost of truck operation and fuel economy, particularly at lower travel speeds. Therefore, rolling resistance has become a important issue among tire manufacturers. Projects that enable optimization of tire materials and improve tire test methods represent an opportunity for investment. The best opportunities for DOE participation in rolling resistance R&D seem to be as follows:

4.1.1 Develop better mathematical models for predicting tire material behavior under a range of conditions. In particular, make effective use of the high-performance computing capabilities and materials modeling expertise of universities and national laboratories.

4.1.2 Develop improved test methods to validate the performance of analytical models for materials behavior. In order to test advanced tire materials and

validate new constitutive models for the behavior of those materials, improved test methods will be needed.

4.1.3. Develop new, real-time tire alignment sensor systems for moving vehicles. This technology development and demonstration project has a high potential to impact tire performance, durability and vehicle fuel economy.

4.1.4 Develop new approaches to thermal management in the wheel well, which can integrate braking responses and aerodynamic flows as well. Heat is generated both by braking and by hysteresis losses in the rolling tires. The use of channeled air flows and diversions to improve wheel well heat flow characteristics will involve modeling and proof-of-concept research.

## **4.2. Reducing Parasitic Losses in the Drivetrain**

The drivetrain consists of the hardware that follows the engine: transmission, drive axles, differential, etc. Parasitic energy losses can occur in gears. According to a study by Argonne National Laboratory staff, about 2.7-3.3% energy savings are achievable from improvements to the gear train. This figure does not account for the possible benefits of innovative technology such as regenerative braking, but does suggest that only a small relative benefit can be gained in energy efficiency by enhancing current axles and gear trains.

A potential area for improving truck energy efficiency is through drivetrain weight reduction, but according to the participants in the August 1999 workshop (including

calculations of potential energy savings), weight savings in the drive train components was not felt to offer a significant benefit to fuel economy in heavy trucks.

One of the main sources of parasitic energy losses in current transmissions is viscous drag losses in the lubricating fluids. Improved designs seem to offer one solution, and truck industry suppliers have introduced new design concepts to help reduce viscous drag.

One promising opportunity to improve fuel efficiency in the drive train area lies with the use of regenerative retarders. Regenerative retarders generate extra electricity by electro-magnetically coupling to rotating drive axles while they augment vehicle braking at the same time. That extra energy could help to supply power for running accessories, for example.

*Conclusions.* With the possible exception of developing regenerative retarders, there are no significant energy efficiency gains possible in the drive train area. Incremental improvements are expected from optimizing the engineering designs of drivetrain components specifically suited to a particular vehicle platform. Therefore, the main R&D opportunity for government participation in this area seems to be:

4.2.1 Support the design and validation testing of regenerative retarder systems. This multi-partner, design and proof-of-concept program must involve the heavy truck industry. The energy-efficiency gains could be significant, and the initial part of any new project in this area should be focused on establishing a target for the possible fuel savings of regenerative

retarders under different vehicle operating conditions.

### **4.3. Safe and Energy-Efficient Braking Systems**

Braking is both an energy-efficiency and a safety issue. Most heavy, long-haul trucks in the United States use drum brakes that use friction between drums and pads to convert kinetic energy to heat, dissipate that energy, and thus slow the vehicle. Disc brakes, involving rotors and flat pads, are more commonly employed in European trucks and busses, but their use in the US heavy trucking industry is seriously being discussed. Previous problems in implementing disc brakes on US heavy trucks has soured some in the trucking industry on transitioning to this configuration; however, others in the brakes industry believe that a future conversion to disc brakes is 'inevitable.' DOE can play a role in clarifying the costs and benefits of drum versus disc brakes in heavy vehicles.

There are over 2000 additives used today in brake materials around the world [M. Weintraub, automotive brakes consultant, private communication (1998)], and it is typical for a single brake pad material to contain more than 15 additives. Clarifying the fundamental scientific bases for complex brake additive interactions, as they affect friction and wear, represents a rich, multi-disciplinary research challenge.

Industrial testing of brake materials tends to rely on either inertial dynamometers or road tests. Dynamometer testing protocols are in a continual state of review by the industry. The Society of Automotive Engineers has been active in developing brake materials test

procedures that involve multi-stage, complex protocols. Qualification testing is made more difficult owing to the wide range of braking habits of individual drivers.

Similarly to tires and drivetrains, brakes issues involve design, materials, and condition-sensing. To some extent, feedback controlled braking systems, like ABS, can optimize braking system response and thereby compensate for friction material variability. However, even if advanced braking controls can compensate for the response of different friction materials during braking, brake wear is still a major issue. One company espouses a goal of 'million-mile brakes.'

*Conclusions.* Several R&D opportunities were highlighted at the August 1999 workshop held in Knoxville, Tennessee. These form the basis for the following brakes-related projects:

4.3.1. Develop new, improved friction materials. Work with brake testing laboratories, national laboratories, and truck companies to investigate the application of new materials for high-energy-dissipation brakes that work over a wide temperature range. Investigate the effects of both high temperature and cold weather conditions on the friction characteristics and wear of these materials.

4.3.2. Obtain a better scientific understanding of the properties of interfacial shear films. Thin films that form on brake drums and rotors during use have been observed to play an important role in the control and stability and of brake friction. A materials



science-oriented project in this area would constitute a fundamentals-oriented companion project to the development of advanced brake materials described in 4.3.1.

4.3.3 Low-cost, reliable brake condition sensors. This instrumentation-oriented program could be performed by a consortium of trucking industry suppliers, academia, and national laboratories. It could also involve organizations that instrument vehicles to analyze their performance. The potential for widespread synergy and leveraging during sensor development is high.

4.3.4 Develop strategies for active thermal management. This project could leverage some of the work going on in aerodynamic drag and may lend itself to modeling and design challenges that integrate the thermal behavior of tire and brake systems in the wheel well environment. (See also 4.1.4)

## **5.0 Proposed Project Areas**

The foregoing issues in tires and braking systems seem to fall naturally into three technical areas, as follows:

### Materials Research and Characterization

### Sensors, Instrumentation, and Controls

### System Integration and Design

It therefore makes sense to divide a multi-year program plan for reducing running resistance and improving braking systems into these three interdisciplinary areas.

The three project areas comprise a spectrum of opportunities for DOE support. These involve: (1) developing better methods to obtain materials properties data for use in existing models; (2) developing a better scientific understanding of both tire and brake materials behavior through improved, highly-instrumented testing facilities; and (3) developing analytical modeling tools, sensor system concepts, and innovative drivetrain design concepts than could be implemented by industry to suit specific product needs. Pre-competitive opportunities involve developing engineering tools and applying new technology from other fields to brakes and tires.

While industry participation is key to this effort, national laboratories can also play a significant role, provided that the appropriate technical guidance for their efforts is obtained from industry. For example, in the brakes area, the establishment of a highly-instrumented research facility has been included as a tangible expression of DOE's commitment to advancing the science of safer, more energy-efficient brakes. Also, high-performance computing capabilities at several national laboratories could be teamed with industry partners to model materials, heat flows, and control system responses.

A three-pronged, four-year plan is proposed. Projects concern materials modeling and development, instrumentation and controls, and the design and analysis of systems. Numbers in parentheses ( ) indicate estimated project lengths in years. Industry will be expected to play an integral part in these projects, either in an advisory role or as a participating partner. Some of the proposed project funds could be invested in cooperative research and development

agreements (CRADAs) in which industry provides in-kind support. More fundamental projects would be fully-funded by DOE, and broad-based projects would be funded by a partnership of two or more federal agencies to leverage their resources.

### 5.1 Materials Research and Characterization

5.1.1 Develop better mathematical models applicable to the behavior of elastomeric **tire materials**. (3)

5.1.2 Acquire an improved understanding of the **formation and micro-mechanics of friction-induced films** on heavy vehicle brake surfaces. (3)

5.1.3 Develop advanced **brake materials** that have stable frictional behavior over a wide range of temperatures. (4)

5.1.4 Design, construct, and equip a **DOE advanced brake materials research facility** with advanced analytical capabilities. This facility would be a key resource for U.S. industry, national laboratories, and universities to conduct leading edge research in an environment similar to the existing High Temperature Materials Laboratory (HTML) User Program. (4)

### 5.2 Sensors, Instrumentation, and Control

5.2.1 Design and demonstrate robust instrumentation systems for real-time, vehicle-in-motion, **tire alignment sensing**. (4)

5.2.2 Design and demonstrate low-cost, reliable **brake condition sensors**.

Specifically, the reliability of electrical connectors is a barrier to implementing road-rugged sensor systems. (4)

5.2.3 **Develop ‘smart’ brake materials** with embedded heat and pressure sensors. This would complement 5.2.2 and may be integrated in feed-back control braking systems. (3)

5.2.4 **Develop ‘smart’ tire materials** with embedded heat and pressure sensors. (3)

5.2.5 **Develop wireless brake condition monitoring systems** to avoid the problems associated with hard-wired electronic systems. Adopt advanced telemetry concepts from other fields. (4)

### 5.3 Systems Integration and Design

5.3.1 Design and demonstrate **regenerative retarder systems**. This broad effort would involve energy efficiency modeling, design, and technology demonstration. (4)

5.3.2 Develop analytical models and integrated aerodynamic design strategies for **wheel well thermal management**. These would integrate heat generation and dissipation requirements for tires and brakes into a single approach. (3)

5.3.3 Conduct an **energy savings impact analysis of new developments in rolling resistance**. Base the analysis on emerging rolling resistance technology for city, suburban, and highway driving scenarios, and for truck classes 6-8. (2)

**5.3.4 Impact of heavy vehicle conversion to air disk brakes.** Conduct an economic impact analysis of the effects on operating cost and reliability of the conversion of heavy truck fleets from predominantly drum brakes to predominantly air disc brakes. Compare and contrast the impact of such conversions in Europe's trucking industry. (1)

## **6.0 Estimated Funding Requirements**

A summary of the estimated funding requirements, by year and by project, has been prepared. There are no proposed projects involving gearing and axles because the predicted energy benefit associated with these components is predicted to be comparatively small.

The higher-budget projects are those

involving component development or testing systems design because they are likely to require both construction and validation testing of hardware.

Significant in-kind contributions from industry to the hardware design-concept oriented projects are needed for successful technology transfer to commercial heavy vehicle systems. Therefore, funding has been included to enable overall technical and administrative coordination as well as to support an external, trucking industry advisory committee that will periodically review progress and recommend changes in program directions, as needed. Funding to enable this continuing industry participation has been included in the last line item in the estimated budget table that follows.

## Estimated Resource Requirements for Running Resistance and Braking Systems\*

Estimated Resource Requirements, \$000

| <b>Project</b>  | <b>FY<br/>2001</b> | <b>FY<br/>2002</b> | <b>FY<br/>2003</b> | <b>FY<br/>2004</b> | <b>Line<br/>Total</b> |
|---|--------------------|--------------------|--------------------|--------------------|-----------------------|
| 5.1.1 Develop mathematical models for elastomeric materials behavior                                  | 250                | 400                | 525                | 375                | 1550                  |
| 5.1.2 Improved basic understanding of friction-induced film formation and dynamics related to braking | 300                | 475                | 475                | 375                | 1625                  |
| 5.1.3 Develop advanced brake materials  | 350                | 650                | 675                | 550                | 2225                  |
| 5.1.4 Develop DOE advanced brakes research facility   | 175                | 550                | 475                | 425                | 1625                  |
| 5.1.5 Evaluation of impact of using light-weight braking systems on energy efficiency                 | 125                | 160                | 0                  | 0                  | 285                   |
| 5.1.6 Development of light-weight braking systems   | 0                  | 0                  | 450                | 450                | 900                   |
| 5.2.1 Instrumentation systems for real-time alignment sensing   | 180                | 400                | 450                | 325                | 1355                  |
| 5.2.2 Low-cost, reliable brake condition sensors  | 260                | 425                | 550                | 320                | 1555                  |
| 5.2.3 Development of 'Smart' brake materials  | 0                  | 325                | 525                | 500                | 1350                  |
| 5.2.4 Development of 'Smart' tire materials   | 0                  | 325                | 325                | 275                | 925                   |
| 5.2.5 Wireless brake condition monitoring   | 80                 | 325                | 360                | 450                | 1215                  |
| 5.3.1 Design and demonstrate regenerative retarder systems  | 425                | 575                | 630                | 625                | 2255                  |
| 5.3.2 Models and designs for improved wheel well thermal management                                   | 0                  | 350                | 500                | 450                | 1300                  |
| 5.3.3 Energy efficiency analysis of rolling resistance improvements                                   | 0                  | 160                | 180                | 0                  | 340                   |
| 5.3.4 Economic analysis of US trucking industry conversion from drum to disc brakes                   | 300                | 0                  | 0                  | 0                  | 300                   |
| Project coordination, program reviews, advisory panel meetings, and technical administration          | 125                | 215                | 215                | 225                | 780                   |
| <b>Column totals</b>  | <b>2570</b>        | <b>5335</b>        | <b>6335</b>        | <b>5345</b>        | <b>19585</b>          |

\* Dollar amounts are estimated government funds and do not include the value of in-kind contributions received from industry R&D partners.

Revised 4/27/2000

(pages 13,14 are blank)

