Multiyear Program Plan:

Reducing Friction and Wear in Heavy Vehicles

December 13, 1999

U.S. Department of Energy
Energy Efficiency and Renewable Energy
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I. EXECUTIVE SUMMARY

Reducing friction and wear in engines and drivetrains is one of several approaches that will enable the Office of Heavy Vehicle Technologies (OHVT) within the Office of Transportation Technologies (OTT) of the U.S. Department of Energy (DOE) to meet its goal of fostering the development of fuel-flexible, energy-efficient, heavy-duty U.S. diesel engine technology.

Implementation of the planned friction-reducing technologies, along with complementary approaches such as improving truck aerodynamics and reducing running resistance, will reduce petroleum consumption of Class 1-8 trucks by more than 1.8 million barrels of oil per day by 2030. In addition, there will be 7 to 30% reductions in PM10 emissions, CO_2 greenhouse gases, NO_x, nonmethane hydrocarbons (NMHCs), and CO. Economic benefits will include an increase of 15,000 jobs and $24 billion in GDP.

Proper attention to friction and wear could save the U.S. economy as much as $120 billion per year. In the transportation sector alone, land-based vehicles consume gasoline and diesel fuel equivalent to about 3.4 billion barrels of crude oil per year, of which 650 to 830 million barrels are lost to friction. At the current price of crude oil, that amounts to $12 to $15 billion per year.

This document outlines a research program that was recommended by representatives from all sectors of the ground transportation industry, including fleet operators, truck and automobile manufacturers, diesel-engine manufacturers, component manufacturers, lubricant suppliers, railroad operators, and locomotive manufacturers. Their input was obtained through personal interviews and a plenary workshop that was held at Argonne National Laboratory on March 22-23, 1999, under the auspices of DOE's Heavy Vehicle Systems Technologies (HVST) program within OHVT.

The primary benefits to be derived from implementing the technologies in this planned program are energy savings and reduced operating costs for heavy-duty fleet operators and individual owner operators. However, reducing fuel consumption also will have a directly proportional benefit on reducing emissions from vehicles. In addition, new technologies for reducing friction and wear also are needed to enable the trucking industry to meet forthcoming standards for diesel exhaust emissions. Still other benefits include reduced downtime, lower costs for repair and replacement of worn parts, and improved safety.

Friction, wear, and lubrication are important considerations in virtually every approach to reducing energy consumption and emissions, as described in the OHVT Technology roadmap. Following are some examples:

- To develop enabling technologies for Class 7 & 8 trucks to achieve a fuel efficiency of 10 mpg without sacrificing air quality will require the following:

    - To develop a 55% efficient engine, an efficiency increase of 1% or greater is expected from reductions in engine mechanical friction, and increased cylinder pressures will require improved friction control and piston/ring lubrication.

  - To reduce mechanical losses in transmissions and axles and parasitic losses in shaft-driven auxiliaries by 25%, new cost-effective coatings, materials, or designs will be required.

  - To meet federal and state emission requirements, soot and acid loading from EGR will require improved lubricants or coatings, and lubricant formulations without sulfur and phosphorus will be required to prevent contamination of catalysts for exhaust after-treatment.

  - To develop engines that can run on alternative liquid or gaseous fuels, lubricious coatings or fuel additives will be needed to compensate for the lower lubricity of the alternative fuels.

- To encourage significant dieselization of Class 1 & 2 trucks (pickups, SUVs), thereby achieving at least a 35% fuel efficiency improvement over gasoline-fueled engines, while at the same time meeting emission requirements.

  - New coatings, lubricants, or designs will be needed to minimize friction losses at part loads.

Major research areas that received a strong endorsement by industry include developing:

- A quantitative understanding of failure mechanisms such as wear, scuffing, and fatigue. This will be important for developing both improved computational design codes and bench-top tests to accurately and reliably predict full-scale component behavior.

- Bench-top tests that are predictive of full-scale behavior. Rapidly changing emission standards require frequent changes in lubricant formulations and component designs. Current laboratory tests to evaluate or qualify those changes do not correlate well with full-scale behavior, but full-scale engine tests are prohibitively expensive.

- A variety of affordable surface-modification technologies that would be suitable for various components in various fuels or lubricants under various operating conditions. New emission-reduction technologies and the move to higher power densities are placing demands on surfaces in terms of wear and fatigue that can no longer be met by conventional bulk materials. To satisfy the variety of needs that are emerging, several different surface-modification technologies will be needed. These may include various coating systems, thermal treatments, and texturing or smoothing.

- Develop a better understanding of the chemistry of lubricants and how additives affect their interactions with rubbing surfaces. This will provide a foundation for developing new lubricants that will be longer-lasting, environmentally friendly, capable of handling increased soot and acid loading from EGR, and compatible with catalysts and/or new, lightweight nonferrous materials.

- Advanced computer codes that model friction, wear, distribution of lubricants, lubricant interactions with surfaces, and lubricant aging/degradation phenomena. A comprehensive general model is needed in addition to specific models for splash/mist lubrication and vapor-phase lubrication.

- Affordable high-performance steels to withstand the higher stresses resulting from increasing power density and fuel pressure.
- Improved rotary-seal systems for longer life.
- Improved brake systems to compensate for heavier loads and reduced aerodynamic drag.

Although each sector of the ground transportation industry has different needs and objectives, the recommended research areas address all of those needs and objectives because friction and wear affect fuel efficiency, emissions, reliability, durability, safety, and profitability. The current status, goals, and barriers related to the highest-priority research areas are summarized in Table 1.

Most of the research projects probably should be conducted by teams of some or all of the following:

- A national laboratory and/or university, to conduct early-stage research and material evaluations.
- A component manufacturer, to make prototype parts.
- A lubricant and/or additive supplier.
- A vehicle or engine manufacturer, to provide overall guidance and test the final parts.

Table 1. Summary of Technical Targets and Barriers for Reducing Friction and Wear

Challenge	Current Practice	Technical Target	Barriers
Cost of validation testing	Engine tests costing approximately $60,000 each	Inexpensive, predictive bench-top tests for cylinder-liner and piston-ring materials, bearings, and valve-train components	Lack of quantitative understanding of failure modes. Lack of understanding of time-dependent in-situ contamination and degradation of lubricants. Lack of model to predict performance based on material properties and design features.
Cost-effective surface-modification technologies	Limit performance based on bulk-material properties	Coatings or other surface treatments to allow fuel injectors, pistons, cylinder liners, and valve-train components to tolerate higher stresses, lower lubricity, and higher corrosivity resulting from new emission-reduction technologies	High cost of current coatings and surface-modification technologies. Limited wear resistance, durability, and adhesion.
Lubricant and additive chemistry	Trial-and-error approach to lubricant formulation	Develop environmentally friendly lubricant that is compatible with new emission-reduction technologies	Need model to predict long-term performance of lubricants based on properties of base oil and additives. Need for sulfur and phosphorus for high-pressure applications, but deleterious effect of sulfur and phosphorus on catalysts. Disposal or biodegradability.
Comprehensive computer codes	Fragmented codes unable to handle lubricated parts in relative motion	General-purpose friction/wear/lubrication codes that include splash and mist lubrication for designing low-friction, low-emission lubricated components and systems	Extremely complex system. Lack of quantitative understanding of friction and wear as a function of basic material properties and loading conditions.

Each team should have expertise in materials, coatings, lubricants, design, and service life evaluation because all five factors are interrelated and need to be considered to achieve an optimal solution for most friction and wear problems.

The recommended budget for the first year is $2 million, rapidly increasing to $7 to $10 million per year for four to five years, supplemented by appropriate industry matching funds. It is estimated that this level of financial resource will be required to solve these high-priority, high-payoff problems.

The recommended funding schedule for the highest-priority research areas is summarized in Table 2.

Table 2. Resource Requirements (in millions of dollars) for Top-Priority Projects on Reducing Friction and Wear

R&D Area	**FY 01**	**FY 02**	**FY 03**	**FY 04**	**FY 05**	**Total**
Surface-Modification Technologies	0.7	1.1	1.6	1.6	1.0	6.0
Chemistry of Lubes & Additives	0.7	1.1	1.6	1.6	1.0	6.0
Failure Mechanisms	0.5	0.7	1.0	0.8	0.2	3.2
Advanced Computer Codes	-	0.9	1.6	1.6	1.0	5.1
Predictive Bench-Top Tests	-	0.5	1.0	1.0	0.3	2.8
Other	0.1	0.1	0.5	0.7	0.5	1.9
TOTAL	2.0	4.4	7.3	7.3	4.0	25.0

II. INTRODUCTION

As described in its multiyear program plan for 1998-2000, the Office of Heavy Vehicle Technologies (OHVT) envisions the development of a fuel-flexible, energy-efficient, near-zero-emissions, heavy-duty U.S. diesel engine technology devolving into all truck classes as a real and viable strategy for reducing energy requirements for commercial transport services and the rapidly growing multipurpose vehicle market (pickups, vans, and sport utility vehicles).

Implementation of the OHVT program plan will have significant national benefits in energy savings, cleaner air, more jobs, and increased gross domestic product (GDP). Successful implementation will reduce the petroleum consumption of Class 1-8 trucks by 1.4 million barrels of oil per day by 2020 and over 1.8 million by 2030, amounting to a reduction in highway petroleum consumption of 13.2% and 18.6%, respectively. All types of regulated emissions will be reduced, that is, 20% drop in PM10 emissions (41,000 metric tons per year) by 2030, 17% reduction in CO_2 greenhouse gases (205 million metric tons per year), 7% reduction in NO_x, 20% reduction in NMHC, and 30% reduction in CO. An increase of 15,000 jobs by 2020 is expected, as is an increase of $24 billion in GDP.

The strategy of OHVT is to focus primarily on the diesel engine since it has numerous advantages. It has the highest efficiency of any engine today, 45% versus 30% for production gasoline engines; and it can be made more efficient at least to 55% and possibly up to 63%. It is the engine of choice for heavy vehicles (trucks), because it offers power, efficiency, durability, and reliability and is used extensively in rail, marine, and off-road applications. Its emission can be ultra-low to near zero, and the production infrastructure is already in place.

The primary goals of OHVT are as follows:

- Develop by 2002 the diesel-engine enabling technologies to support large-scale industry dieselization of light trucks, achieving a 35% fuel efficiency improvement over equivalent gasoline-fueled trucks.

- Develop by 2004 the enabling technology for a Class 7-8 truck with a fuel efficiency of 10 mpg (at 65 mph) that will meet prevailing emission standards, using either diesel or a liquid alternative fuel.

- Develop by 2006 diesel engines with fuel flexibility and a thermal efficiency of 55% with liquid alternative fuels, and a thermal efficiency of 55% with dedicated gaseous fuels.

- Develop a methodology for analyzing and evaluating the operation of a heavy vehicle as an integrated system, considering such factors as engine efficiency; emissions; rolling resistance; aerodynamic drag; friction, wear, and lubrication effects; auxiliary power units; material substitutions for reducing weight; and other sources of parasitic energy losses. Overarching these considerations is the need to preserve system functionality, cost, competitiveness, reliability, durability, and safety.

The above fuel-efficiency goals were established before issuance of the consent decree between the engine manufacturers and the U.S. Environmental Protection Agency (EPA), which will require accelerated reduction of emissions. Those goals will now be even more challenging because methods to reduce emissions probably will cause a 5 to 10% decrease in fuel efficiency by 2007.

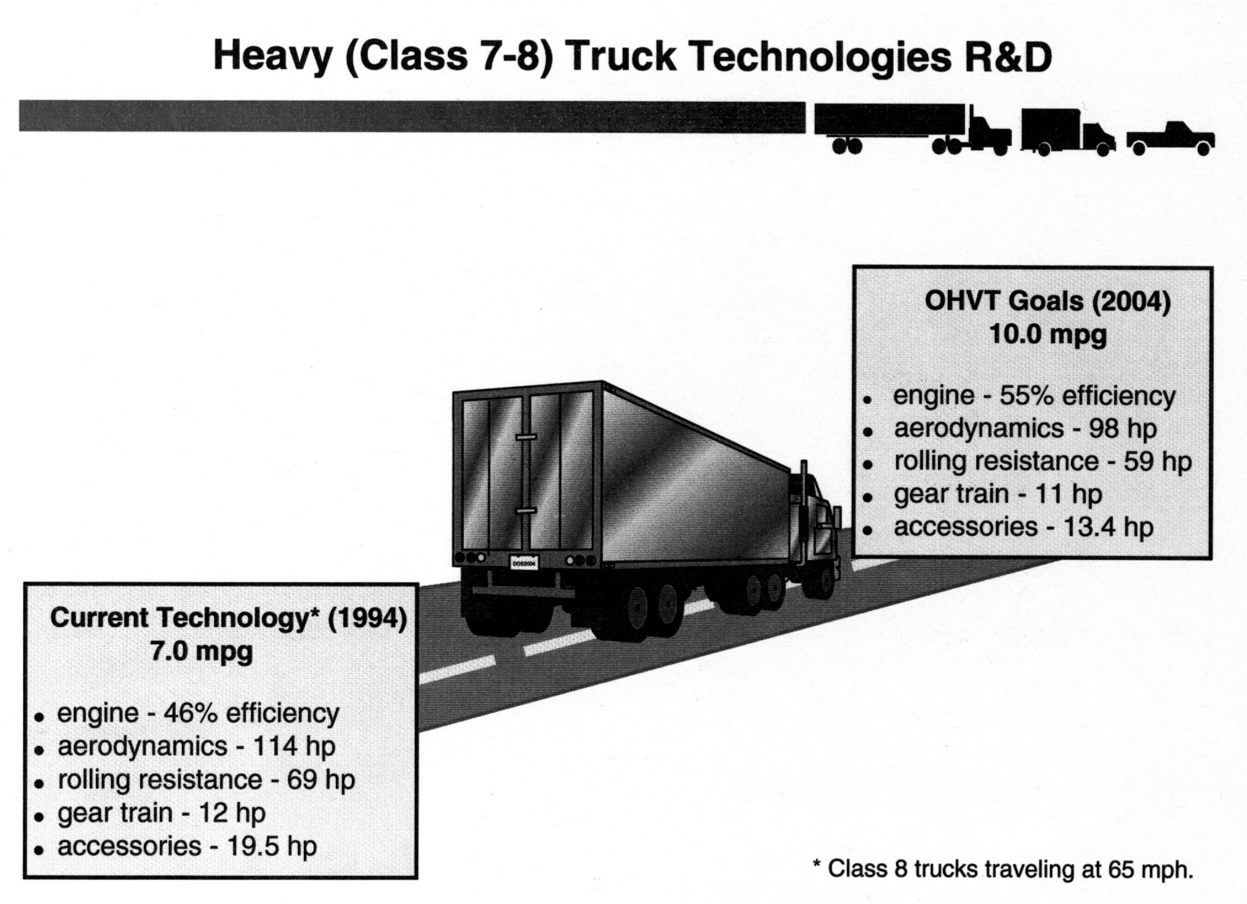


Figure 1. Goals for Class 7 and 8 Trucks

The OHVT Advanced Heavy Vehicle Technologies R&D program has the following two-pronged approach:

(1) A partnership with the domestic transportation industry, energy-supply industry, other federal agencies, and research and development organizations to develop high-efficiency engine technologies and alternative-fuel utilization technologies for trucks and to promote their acceptance. The technologies that were determined to have the greatest market applications and thus fuel savings are

- Diesel for light trucks and sport utility vehicles.
- Advanced diesel for Class 3-8 trucks with enhanced fuel flexibility.
- Improved near-term natural gas engine for buses and trucks.
- Advanced natural gas engine with diesel-equivalent efficiency.

(2) Continuing development of key enabling technologies to ensure market success:

- Exhaust aftertreatment.
- Materials.
- Fuels.
- Combustion.
- Natural gas storage.
- Environmental effects.

These enabling technologies are coordinated through a diesel cross-cut team that has linked DOE diesel R&D in the OHVT and Partnership for a New Generation of Vehicles (PNGV) in the office of Advanced Automotive Technologies. Many of the advances in these technologies will be applicable to spark-ignition engines as well as to diesel engines. Thus, the benefits of the R&D will be enjoyed by the entire transportation industry, including the automotive sector.

For several years, participation and input from OHVT's customers has been solicited through a series of customer-focus workshops to identify the critical R&D needs and define the R&D thrusts, financial resources, and schedules to meet those needs. Two general workshops covering a broad range of needs and technologies were held in April and October of 1996. Subsequently, more targeted workshops were held with industry stakeholders to provide input to the program plan in areas such as alternative fuels, natural gas engines, fuels and engine policies and directions, truck aerodynamics, and diesel-engine emission reduction.

This document is based on a workshop on Research Needs for Reducing Friction and Wear in Transportation, which was held at the Argonne National Laboratory on March 22-23, 1999. Participation was solicited from all parts of the transportation industry that might be concerned about friction and wear, including fleet operators, truck and automobile manufacturers, diesel-engine manufacturers, component manufacturers, lubricant suppliers, railroad operators, and railroad engine manufacturers. Personal visits were made to many of the industrial participants before the workshop to explore key issues in depth. In addition to the industrial participants, representatives also were invited from the national laboratories, other federal laboratories, contract research organizations, and universities.

The workshop was divided into six segments:

- Introductory talks by representatives of DOE to describe how this subject area fits into their overall plan.
- Keynote talks on the effect of friction on fuel economy and the effect of emission-related efforts on new challenges related to friction and wear.
- A series of presentations by representatives of the various affected industrial segments on their needs related to reducing friction and wear and what kinds of technological developments would be useful.
- Five state-of-the-art talks on recent technological developments that might be useful for solving problems related to friction and wear.
- Breakout sessions to prioritize research needs in four areas: materials, coatings, lubricants, and design methods.
- Reports from the breakout sessions and discussions thereof.

An agenda for the workshop is provided in Appendix B.

The purpose of this document is to present an industry-relevant Multiyear Program Plan (MYPP) for research directed toward reducing friction and wear in heavy-duty vehicles. The bulk of the document will summarize the results of the workshop and of the preliminary meetings with industry, upon which the plan is based. Ultimately, this and other specific MYPPs will be combined into an umbrella MYPP for the OHVT.

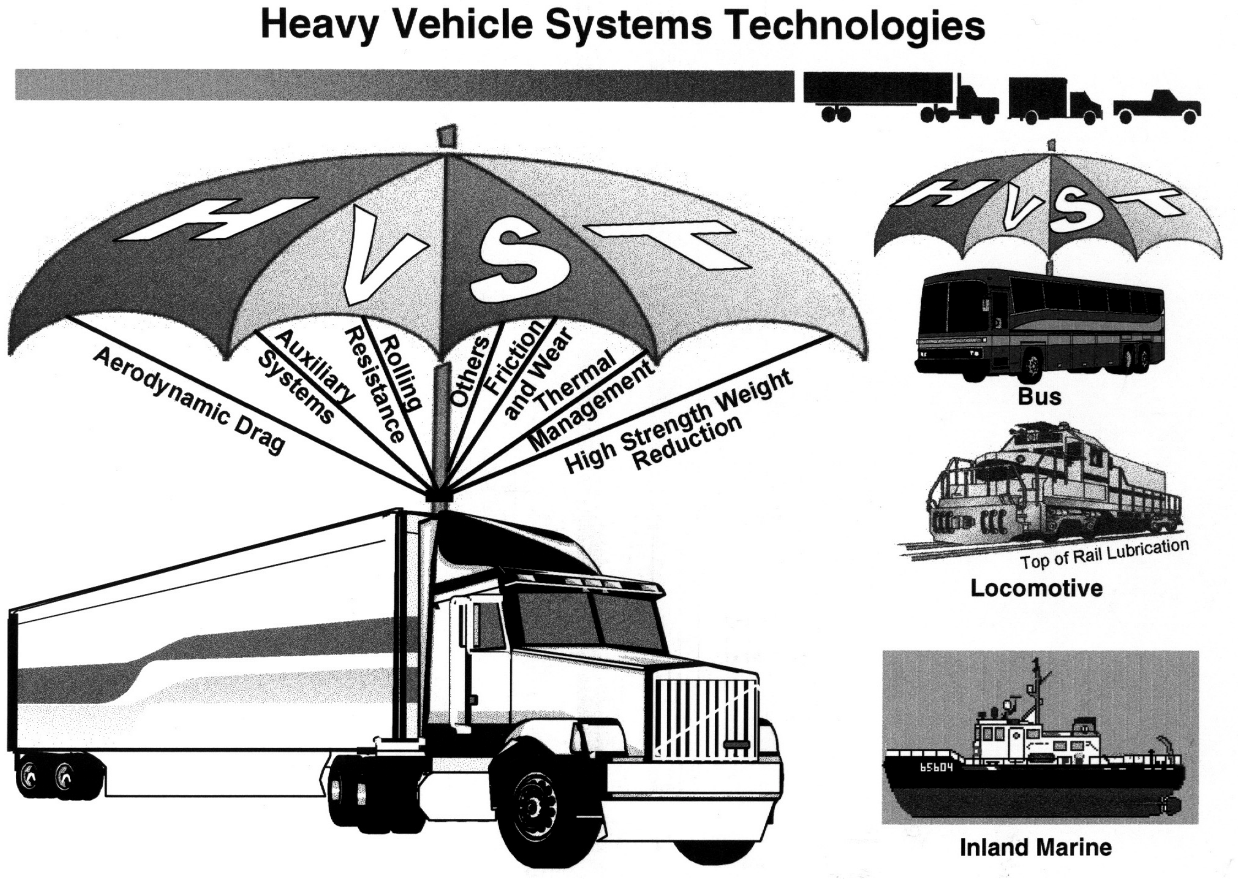


Figure 2. Approaches to Fuel Savings in OHVT Program

Management of the Friction and Wear R&D Program is the responsibility of the Team Leader for Vehicle System Technologies, who reports to the Director of the Office of Heavy Vehicle Technologies within the DOE Office of Transportation Technologies.
Project selection will be based on priorities as established by this plan, advice from industry, and available budget. Planning and R&D implementation will be closely coordinated with related activities within DOE and other agencies that sponsor work in Heavy Vehicle Technologies. R&D projects will be placed through procurement and nonprocurement mechanisms with industry, academia, independent researchers, and national laboratories.

The Heavy Vehicle Technologies Program supports the R&D of advanced technologies directly with engine and vehicle manufacturers and with fuel developers and producers to ensure that the technologies are transferred to appropriate customers who are ultimately responsible for commercializing the end products.

Wide dissemination of results from DOE-sponsored R&D is also accomplished through licensing of patented technologies, publications in technical and trade journals, presentations at technical society meetings, workshops, and contractor coordination meetings. These reviews are held with program managers, principal investigators and research teams to determine technical progress, identify and address problems, and generally maintain project focus. Periodic scheduled program review meetings provide a particularly effective means of exchanging information within the program. These forums allow direct interaction between the federal laboratory and industry researchers, facilitate the building of collaborative relationships, and promote technology transfer.

Progress with respect to this MYPP will be reviewed in a 1-day meeting after two to three years and in a 1.5-day workshop after five years.

III. EFFECT OF FRICTION ON FUEL EFFICIENCY

Friction and wear create a major cost to the U.S. economy. It is generally believed[1,2] that proper attention to friction and wear could save each developed country between 1.3 and 1.6% of its gross national product. For the U.S., this amounts to as much as $120 billion per year.

In the transportation sector, friction causes a significant decrease in the fuel efficiency of automobiles, trucks, buses, locomotives, and other vehicles. In a typical automobile, almost 25% of fuel energy is dissipated in frictional losses of one form or another.[3] As is shown in Tables 3 and 4, land-based vehicles in 1995 consumed gasoline and diesel fuel equivalent to 3.36 billion barrels (or almost 20 quadrillion Btu) of crude oil,[4] of which it has been estimated that 650[5] to 830[3] million barrels were lost to friction. At the current price of about $18 per barrel, that amounts to $12 to $15 billion per year.

Table 3. Total Annual Fuel Consumption (Data for 1995[4,5])

	Diesel Fuel, Million bbl/year	Gasoline, Million bbl/year	Total Fuel, Million bbl/year	Total Fuel, Quads
Heavy-Duty Trucks	574	100	674	3.91
Buses	29	7	36	0.21
Off-Highway	98	26	124	0.72
Rail	86	0	86	0.50
Total Heavy Duty (HD)	788	133	921	5.34
Light Trucks (LT)	36	933	969	5.62
Total HD + LT	824	1065	1890	10.96
Automobiles	19	1453	1472	8.54
Total Vehicles	843	2519	3362	19.50

Table 4. Energy Lost to Friction in Vehicles (Data for 1995[4,5])

	Diesel Fuel, Million bbl/year	Gasoline, Million bbl/year	Total Fuel, Million bbl/year	Total Fuel, Quads
Heavy-Duty Trucks	98	20	118	0.68
Buses	5	1	6	0.04
Off-Highway	17	5	22	0.13
Rail	15	0	15	0.09
Total Heavy Duty (HD)	134	27	160	0.93
Light Trucks (LT)	6	187	193	1.12
Total HD + LT	140	213	353	2.05
Automobiles	3	291	294	1.70
Total Vehicle	143	504	647	3.75

Most heavy-duty vehicles (trucks, buses, off-highway vehicles, and locomotives) are diesel-powered. Frictional losses in those vehicles amount to the equivalent of 160 million barrels per year. Light trucks (vans, SUVs, pickups) represent the fastest growing segment of trucks. Currently, most operate on gasoline engines, and their contribution to frictional losses is about

190 million barrels per year. Automobiles also are predominantly gasoline-powered, and they account for almost 200 million barrels equivalent per year. While total elimination of friction and wear obviously is impossible, eliminating even a small fraction would have tremendous benefits, and a significant reduction certainly appears to be achievable.

As shown in Figure 3, the largest sources of frictional losses are pistons, rings, and connecting rods. For heavy-duty vehicles, these components account for 40 million barrels per year; for light trucks, about 60 million barrels per year; and for automobiles, over 90 million barrels per year (see Table 5).

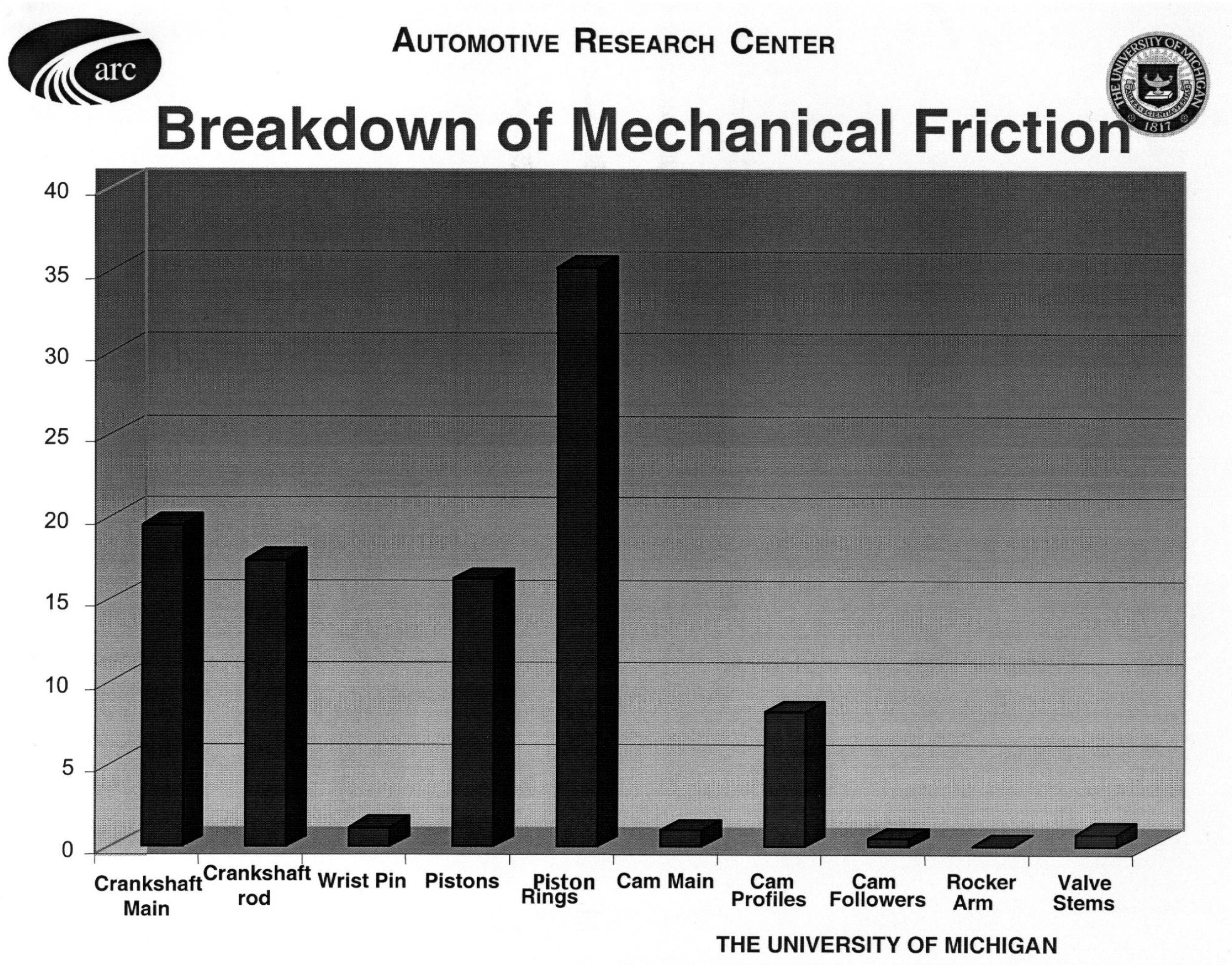


Figure 3. Percentage Energy Losses in Various Engine[3]

Table 5. Energy Lost to Friction in Pistons, Rings, and Connecting Rods (Data for 1995)

	Diesel Fuel, Million bbl/year	Gasoline, Million bbl/year	Total Fuel, Million bbl/year	Total Fuel, Quads
Heavy-Duty Trucks	23	6	29	0.17
Buses	1	0	2	0.01
Off-Highway	4	2	6	0.03
Rail	3	0	3	0.02
Total Heavy Duty (HD)	31	8	40	0.23
Light Trucks (LT)	1	60	61	0.35
Total HD + LT	33	68	101	0.58
Automobiles	1	93	93	0.54
Total Vehicles	33	161	194	1.13

Even without considering the costs of replacing worn parts, downtime on commercial vehicles, and safety implications, the impact of friction on fuel efficiency offers an attractive target for R&D related to new materials, better coatings and surface conditioning, improved lubricants, and advanced design methods.

IV. IMPORTANCE OF REDUCING FRICTION AND WEAR

Because friction has a significant effect on fuel efficiency, reducing friction will be important to all concerned about reducing fuel consumption. This encompasses a wide range of stakeholders, including fleet operators, individual owner operators, vehicle and engine manufacturers, component manufacturers, lubricant suppliers, and, in fact, the general public. In addition to being concerned about fuel efficiency, each group of stakeholders has a number of other related concerns that also are incentives for developing new technologies. Some of those concerns are summarized in Figure 4.

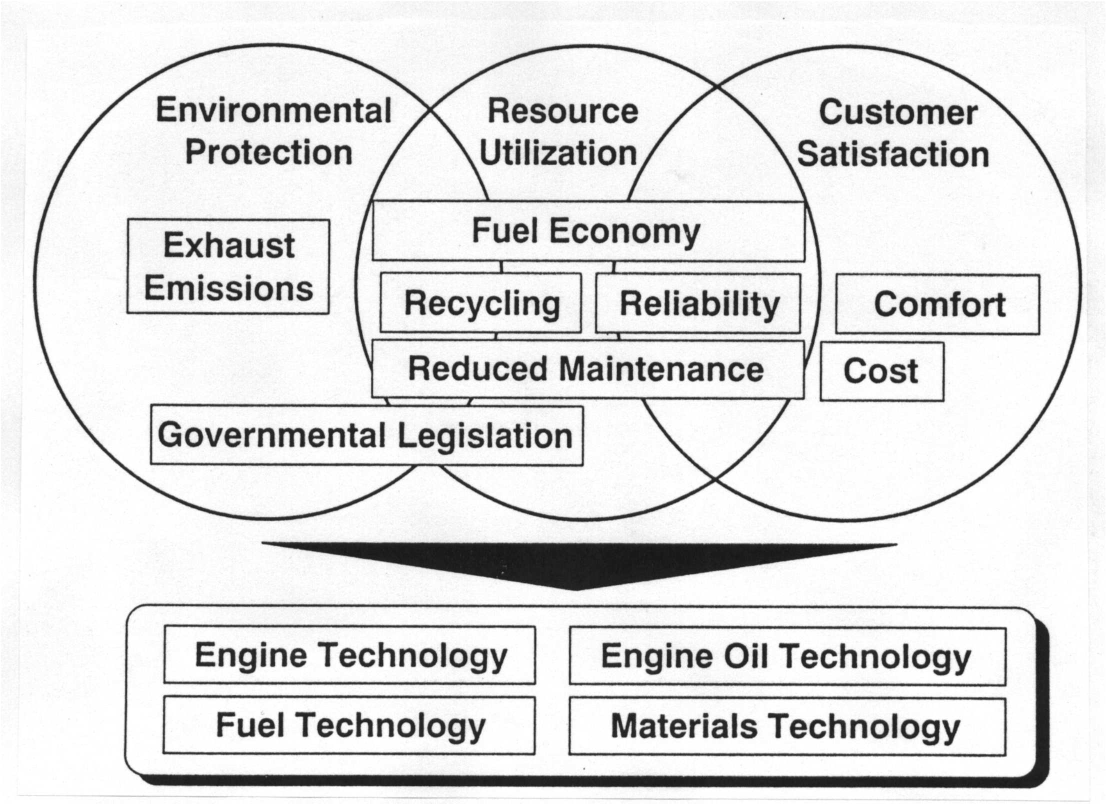


Figure 4. Drivers of Future Technology Developments in Transportation Industries

The remainder of this section discusses the views of each group of stakeholders separately. An attempt has been made to present a combined view of several companies within each group, based upon their presentations at the workshop plus discussions with them during the preworkshop site visits. Some industrial contributors expressed a desire that their comments not be attributed to them or to their companies. Therefore, to encourage open and frank discussions, it was agreed that all comments would be kept anonymous. Apologies are offered to any of the contributors who would have preferred to be identified.

A. General Public

Societal pressures for reducing energy consumption are well known. The transportation sector is the largest user of petroleum in the United States, accounting for two-thirds of the nation's oil demand, and the demand continues to rise. Most of the increase is attributed to trucks, which by 2010 are expected to use as much energy as automobiles. As a result of the increasing number of vehicles and miles driven, oil import demands continue to rise, as does global demand for oil. Meanwhile, worldwide oil reserves are becoming concentrated in a smaller number of countries, many of which may be politically unstable and hostile to the U.S. Therefore, we grow ever more vulnerable to serious potential adverse economic impacts of disruptions in the oil supply. In addition, the large and growing oil imports are a major contributor ($49 billion in 1995) to the nation's negative balance of payments.

Consumption of petroleum inevitably results in the production of air pollutants and greenhouse gases, which also are already a major national and international concern. Any reduction in fuel consumption will cause a proportionate reduction in pollutants from the vehicles.

B. Fleet Operators

Fleet operators and independent truckers are extremely sensitive to cost because of their very low profit margin. Typically, of the $1.20 to $1.60 per mile gross revenue, the net income is only $0.01 to $0.02 per mile at best, or only 0.5 to 1.5%. Therefore, anything that reduces cost, such as improving fuel efficiency through lower friction, would be welcome, but anything that increases cost could be an economic disaster for them. Another deleterious aspect of cost increases is the necessity of industry to pass those costs on to its customers and eventually to the general consumer.

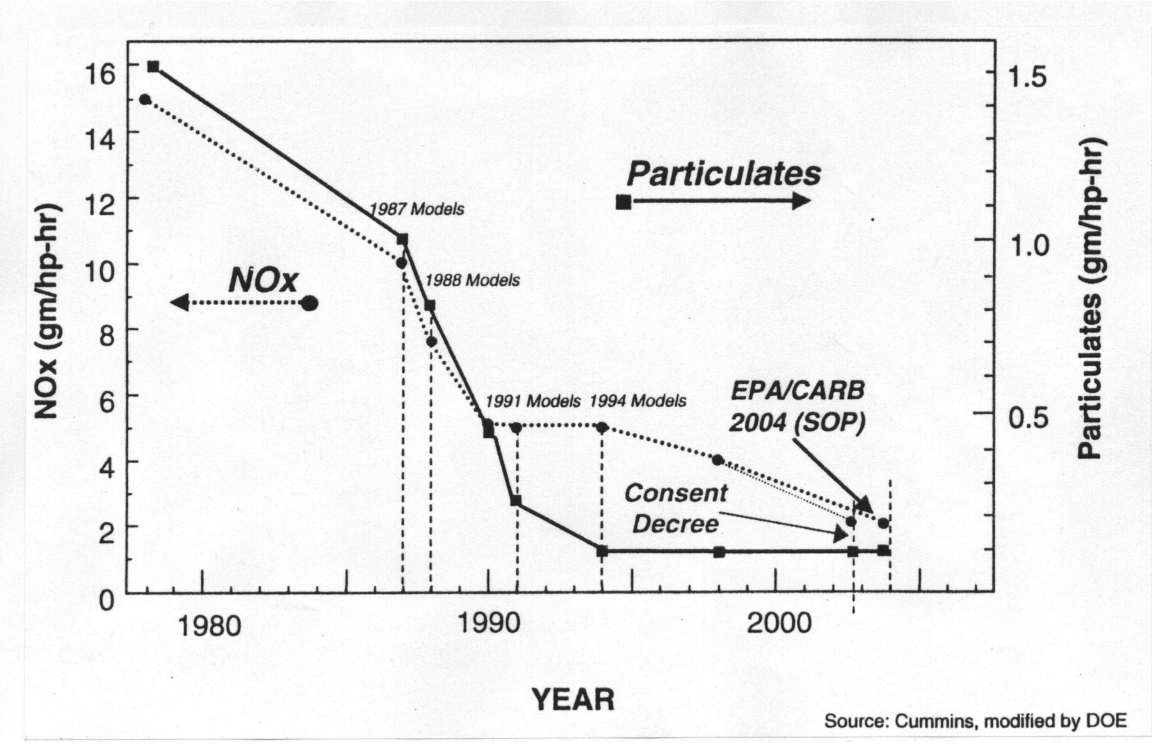
The interval between oil changes also is a major concern, not only because of the cost of the oil and shop labor, but also because of the cost of downtime in terms of lost revenue and driver pay. Oil-change intervals have gradually increased. An interval of 25,000 miles is fairly common, and 50,000 miles is possible with premium lubricants and proper scheduling. However forthcoming antipollution measures, such as exhaust-gas recirculaton (EGR), are threatening to accelerate degradation of the oil and reduce intervals between changes. Therefore, there is a need to develop better lubricants or better ways to remove contaminants from lubricants to extend oil-change intervals as much as possible.

C. Truck Manufacturers

Truck manufacturers depend primarily upon their suppliers for R&D, and they feel that it would be appropriate for DOE to work with the suppliers, especially the diesel engine manufacturers. The truck manufacturers also are extremely sensitive to their customers, the fleet operators and independent drivers. Thus, they are in favor of anything that would improve the cost-effectiveness of trucks.

The emission requirements to become effective in 2002 (see Figure 5) will place much greater demands on engine oils, because of increased levels of contaminants, such as soot from EGR, and to higher temperatures. It is estimated that the new antipollution technologies may cause a

40 to 60% increase in cooling requirements. Improved lubricants will be needed to tolerate the resulting higher temperatures.



Source: Cummins, modified by DOE

Figure 5. Diesel Engine Emissions

Higher-temperature lubricants could have other advantages as well. For example, a higher-temperature cooling fluid would increase the efficiency of the radiator by increasing the delta T. That would enable better aerodynamic design, which would improve fuel efficiency.

The efficiency of the drivetrain – transmission and axles – also is of interest because 5% of total engine horsepower typically is lost in the drivetrain as heat. Furthermore, the required cooling components add weight and cost.

D. Off-Road Vehicles

Off-road vehicles include equipment for construction, mining, agriculture, forestry, paving, and waste-hauling. Because the fuel consumption of off-road vehicles is only about 18% of that of heavy-duty trucks, one might argue that it would be difficult to justify R&D directed toward increasing fuel efficiency of off-road vehicles. However, the issues related to off-road vehicles are virtually identical to those for heavy-duty trucks, so any R&D directed toward diesel-powered trucks would be equally applicable to off-road vehicles.

The main issues facing operators of off-road vehicles are up time (including reliability and durability), owning and operating costs, and environmental compliance (see Figure 6). In addition, there is an economic incentive to use ever-larger vehicles. This places increasing demands on the materials of construction because the weight of the vehicle increases with the third power of the dimensions, whereas the load-carrying capability increases only with the square of the dimensions. This translates into a strong need for higher power density.

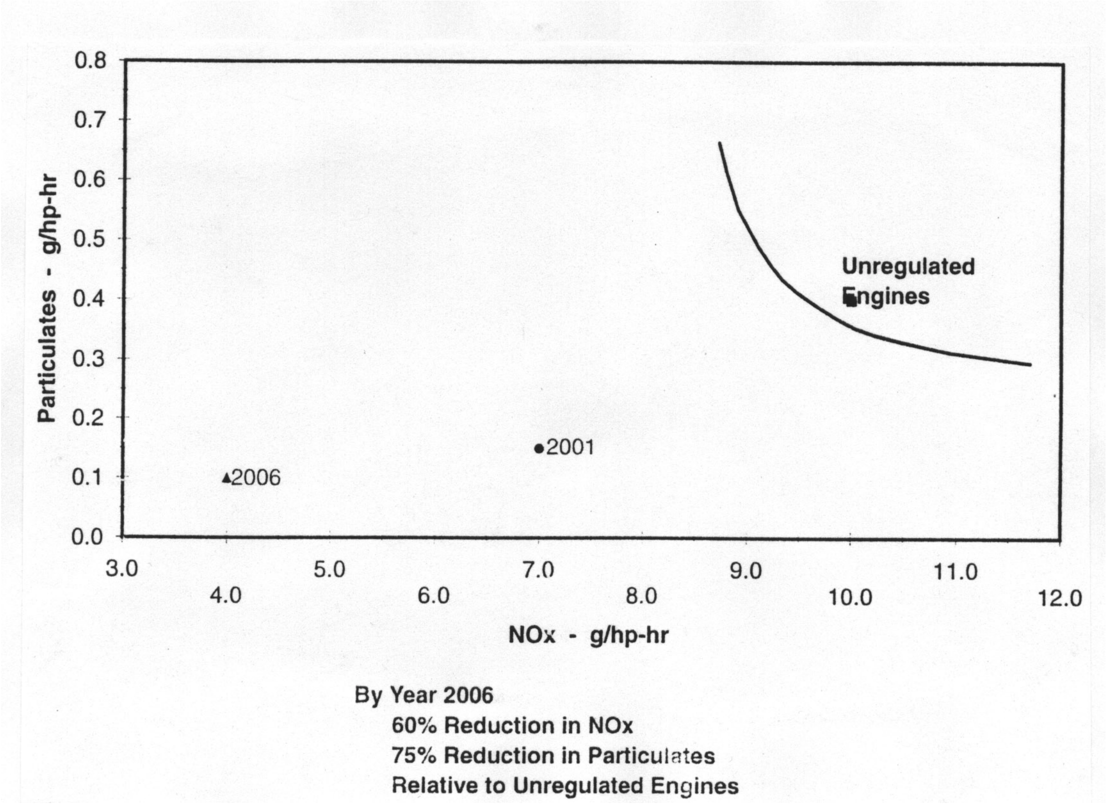


Figure 6. EPA Off-Road Emission Standards

Manufacturers of off-road vehicles are faced with the conflict between the societal need to reduce noise and emissions and the market need to reduce owning and operating costs. Specific development needs include

- Higher-load-carrying articulating joints.
- Higher-energy-capacity friction materials.
- Higher-power-density gears and bearings.
- Biodegradable or recyclable fluids.
- Fill-for-life systems capability.

To achieve the fill-for-life goals, technology advancements will be needed in the following areas:

- Methods to control contamination.
- Durable coatings, materials, and seals.
- Engineered surfaces.
- Techniques for monitoring oil quality.
- Prediction of performance and life.
- Long-life-lubrication technologies.

A fundamental research program to provide a basis for those technology advancements should include investigations into the following subjects:

- Break-in phenomena.
- Boundary-lubrication phenomena.
- Pitting-fatigue effects related to lubricant chemistry.
- Failure/life-prediction methods.
- Surface-texture design.
- Alternative lubrication approaches.

E. Diesel Engine Manufacturers

When designing new engines, the diesel engine manufacturers are driven by the following needs:

- Lower emissions.
- Better fuel economy.
- Extended durability.
- Higher power output.
- Competitive cost.

Faced with severe reductions in allowable emissions by 2002, and even more drastic reductions in subsequent years, the diesel engine manufacturers are now almost totally consumed with lowering emissions. Although specific details of how the emission requirements will be met are kept proprietary by each manufacturer, it is generally agreed that three of the most likely approaches include exhaust gas recirculation (EGR), higher injection pressures, and exhaust aftertreatment. However, these approaches also result in decreased fuel efficiency. Depending upon the specific approaches taken, methods to reduce emissions probably will cause a 5 to 10% decrease in fuel efficiency by 2007. This provides further incentive to offset this decrease by methods such as reducing friction.

Each of the potential methods for reducing emissions also raises new concerns about friction and wear.

It is clear that all of the engine manufacturers are giving serious consideration to EGR, but this technology raises two serious concerns: soot loading of the oil, which is expected to increase the wear rate of engine parts; and higher oil acidity, which is expected to cause corrosion of rings, bores, and valves. In the long term, both of those deterioration mechanisms could decrease the engine emission performance and increase maintenance costs. Therefore, there is a strong need for better materials, coatings, and surface conditioning technologies to protect the engine components, and for new lubricant formulations that are compatible with the higher level of contaminants.

Higher injection pressures not only place higher stresses on certain engine components, but they also require much closer dimensional tolerances, which makes lubrication more critical but also more difficult. Improved materials and low-friction, wear-resistant coatings will be needed.

Aftertreatment requires one or more catalysts, and current catalysts are poisoned by sulfur and phosphorus, both of which are present in, and critical to the performance of, current lubricants at levels that are too high to allow practical catalyst life. Incidentally, the use of catalysts also may require very low limits on the sulfur content of fuels.

In spite of the heavy emphasis on emissions, better fuel economy is not being ignored, especially in view of the fuel penalty associated with the emission technologies. The highest potential for fuel savings in the engine is the cylinder kit (piston rings and liners), but the potential from overhead components (cam rollers and rocker-arm bushings) and main bearings is not insignificant. Just from the cylinder kit and bearings, the potential fuel savings are estimated to be about 5 gallons per vehicle per day. In 1996, there were approximately 1.7 million Class 8 trucks on the road. Reducing fuel consumption for that fleet by 5 gallons per day would result in an annual reduction of 0.4 quads, or 69 million barrels of oil equivalent.

Extended durability could be achieved with better (less-empirical) design methods for hydrodynamic lubrication conditions and advanced bearing concepts for mixed lubrication conditions.

A significant barrier to increasing power output is the temperature capability of in-cylinder components. Improved materials, coating, and surface treatments are needed, along with improvements in combustion and cooling technologies.

Solving the engine-related problems will require an integrated engine/system approach, including development of

- Novel experimental methods.
- Predictive models.
- New designs, materials, and coatings.
- Innovative lubricant formulations and concepts.

Novel experimental methods should include

- Development of accelerated bench tests that correlate well with long-term, full-scale behavior.
- Development of sensors to monitor engine performance and lubricant condition.
- Basic investigations into the fundamental nature of friction and wear.
- Development of sophisticated characterization techniques.

Those developments would be appropriate for national laboratories and universities, which would coordinate with the engine manufacturers, who would identify needs, down-select technical approaches, and conduct fixture and engine tests.

The mathematical bases for new predictive models probably should be developed at national laboratories or universities, with engine consulting companies developing the commercial codes. The engine manufacturers would identify needs, provide phenomenological descriptions and data for validation, and apply the results to new designs.

The role of national laboratories and universities in developing new designs and materials would be to develop new coatings and new manufacturing methods, and to conduct friction and wear tests. The component suppliers would determine manufacturing feasibility and provide samples to the engine manufacturers, who would develop specifications, oversee development, and conduct engine tests.

Lubrication R&D should be directed toward the following objectives:

- Enhanced maintenance by extending drain intervals and reducing the environmental impact of oil disposal.
- Reduced oil consumption through improved liner topography, ring geometry, and interface details, along with consideration of metered delivery.
- New formulation of base stocks and additives, including minimizing sulfur and phosphorus contents.
- Vapor-phase lubrication.
- Other advanced concepts.

Fundamental investigations and precompetitive R&D might be done under the guidance of a horizontally integrated committee of engine companies, but product-development efforts would more appropriately involve a vertically integrated team of an engine company, its customers and suppliers, and an appropriate national laboratory and/or university. In all areas of fundamental research, significant programmatic participation by DOE’s Office of Scientific Research would be essential and enthusiastically welcomed by OTT and its industry partners.

F. Automobile Manufacturers

Automobile manufacturers have long been concerned about fuel efficiency because of the need to meet stringent CAFE requirements. The success of their efforts to date is reflected in the fact that total annual energy consumption by automobiles in the late 1990s is slightly lower than at the time of the 1973 oil embargo, despite a significant and continuous increase in the numbers of vehicles on the road, drivers, and miles driven per vehicle. This is even more remarkable in view of the American consumers’ low level of sensitivity toward fuel efficiency, as is evident from the explosive growth in sales of SUVs. In 1995, Class 1 and 2 trucks (pickups, vans, and SUVs) consumed about 75% as much fuel as did automobiles and about 50% more than Class 3 through 8 trucks. It is estimated that by 2000 energy use by Class 1 and 2 trucks will exceed that of automobiles and be nearly double that of Class 3-8 trucks.

Almost all of the SUVs in this country have spark-ignition gasoline engines. Consumers are unlikely to switch to the much more efficient diesel engine solely to achieve fuel efficiency without further incentives, because the initial cost of the diesel engine is much higher and the public retains outdated and unfavorable notions about diesel engines. Although light trucks and SUVs may eventually be powered by diesel or hybrid power plants, in the immediate future, automotive companies must continue to make spark-ignited engines more efficient. Fortunately, much of the R&D directed toward reducing friction and wear in diesel engines (e.g., coating developments, lubricant developments, and fundamental mechanistic studies of friction and wear) should be equally useful and effective in automotive applications.

Many challenges, in addition to fuel efficiency, that the automotive industry faces also will require technological advances related to friction, wear, and lubrication. Increasing power density will lead to higher temperatures, which will require high-temperature coatings and lubricants. High-power-density gears and journal bearings will require lower-friction surfaces. Increasing durability will require wear-resistant components, control of oil quality, improved antiwear additives, and long-drain oils. Using lightweight and advanced materials will require new lubricants designed specifically for those materials. Reducing emissions will require clean-burning lubricants and better oil control in the ring/liner area. Pollution control measures will require new fluids for air-conditioning systems, biodegradable lubricants, and improved sealing. Reducing manufacturing costs will depend upon improved metal-working lubricants.

Alternative fuels also are receiving considerable attention. Each fuel will introduce its own unique problems related to friction and wear. For example, dimethyl ether, which produces very low emissions and has good fuel economy for diesel engines, has much lower lubricity than do conventional diesel fuels. Therefore, its use will probably require low-friction coatings in critical engine parts such as fuel injectors. For vehicles powered by fuel cells, friction in the air compressor is a serious problem that must be solved.

When faced with reducing friction and wear in spark-ignited engines, the automobile manufacturers have very similar development needs to those of the diesel engine manufacturers:

- New, preferably lightweight, materials that are compatible with alternative fuels and higher operating temperatures and stresses.
- Low-friction, wear-resistant coatings that are compatible with new lubricants and can withstand increasingly severe operating conditions in engines and drivetrains.
- Lubricants that can extend drain intervals, are biodegradable, and are compatible with new materials and coatings.
- Sensors to monitor oil quality.
- Modeling capability for splash- and starved-lubrication conditions and for predicting scuffing, wear, and seizure, including the effect of surface finish.
- Bench-scale tests to reliably predict full-scale behavior and validate design calculations.

With the trend for industrial research to focus on shorter time frames and low- to medium-risk technologies, there is a growing need for the national laboratories and universities to pursue and evaluate emerging high-risk technologies.

G. Component Manufacturers

Pistons, Rings, Connecting Rods, and Crankshafts

As mentioned previously, the cylinder kit and associated bearings account for the largest fraction of energy loss due to friction in the engine. In addition, manufacturers of those components are under considerable pressure to improve their durability because of expanding warranty periods. Industry goals are at least million miles for heavy-duty vehicles and 150,000 to 200,000 miles for automobiles. Thus, both wear and friction are critical issues with these manufacturers. Furthermore, as engines become smaller, bearings become smaller, and operating stresses increase for a given load.

For these components, coatings and surface finish are extremely important. Making surfaces smoother has provided significant benefits, but costs increase exponentially with increasing surface quality. Information is needed on adequate smoothness. There is a need to develop affordable, lead-free coatings for crankshaft bearings and durable, wear-resistant coatings for rings and cylinder liners.

Fuel Injectors

It is anticipated that in order to meet stringent diesel engine emission requirements, fuel injection pressures will increase significantly, and flexible fuel metering/controlling devices will be needed. At the same time, the million-mile warranty goal will require improved system component and material durability. Higher fuel pressures will require new developments to prevent abrasive "jet" wear, eliminate seizure and galling of plungers, and increase the fatigue strength of components.

Fruitful areas for research include:

- Advanced low-friction, wear-resistant coatings for plungers and valve seats.
- Hydraulic modeling for fluid cavitation and fuel spray pattern.
- Faster actuators.
- Affordable high-fatigue-strength materials.

Bearings

Increasing power density is the current primary concern of bearing manufacturers. As with any component, transmitting more power through a smaller package results in higher stresses, which can lead to fatigue failures.

In recent years, significant improvements in power density, without sacrificing fatigue life, have been made with the following three approaches:

- Improving the materials, primarily cleanliness of steels.
- Improving machining to produce more accurate motion geometries.
- Improving the surface texture by making surfaces much smoother.

It is felt that those techniques have been taken as far as possible, and any further increase in load-bearing capacity will require special surface treatments – probably coatings – to prevent surface failures. Designing a coating system for a bearing is not simple. In addition to overcoming the significant problems of adhesion, wear resistance, and cost, it may be necessary to have different coatings on different parts of the bearing depending upon whether the relative motion is rolling, sliding, or a combination of both.

There also are opportunities to improve bearing performance by optimizing the lubrication system through improved base fluids and additives. Modifying the lubricant also can be complicated. In one instance, a special additive to reduce wear resulted in a 50% decrease in fatigue life. In other words, all aspects of bearing performance must be considered when choosing and developing a lubricant.

Seals

Seals represent another important source of energy loss due to friction. In a 100-car freight train traveling at 60 mph, an estimated 50% of the energy consumed arises from overcoming friction in seals, of which there are 16 per car. In an automobile, there are dozens of seals in the engine, transmission, driveline, suspension, steering system, air conditioner, and fuel tank.

The design of a seal (see Figure 7) must consider the entire system, including the fluid and the surface of the rotating shaft. An incompatible fluid could chemically attack the elastomers, resulting in reversion, hardening, or softening and swelling. Other potential problems include oil carbonization from excessively high temperatures, high friction from excessive viscosity at low temperatures, or leakage from low-viscosity synthetic oils.

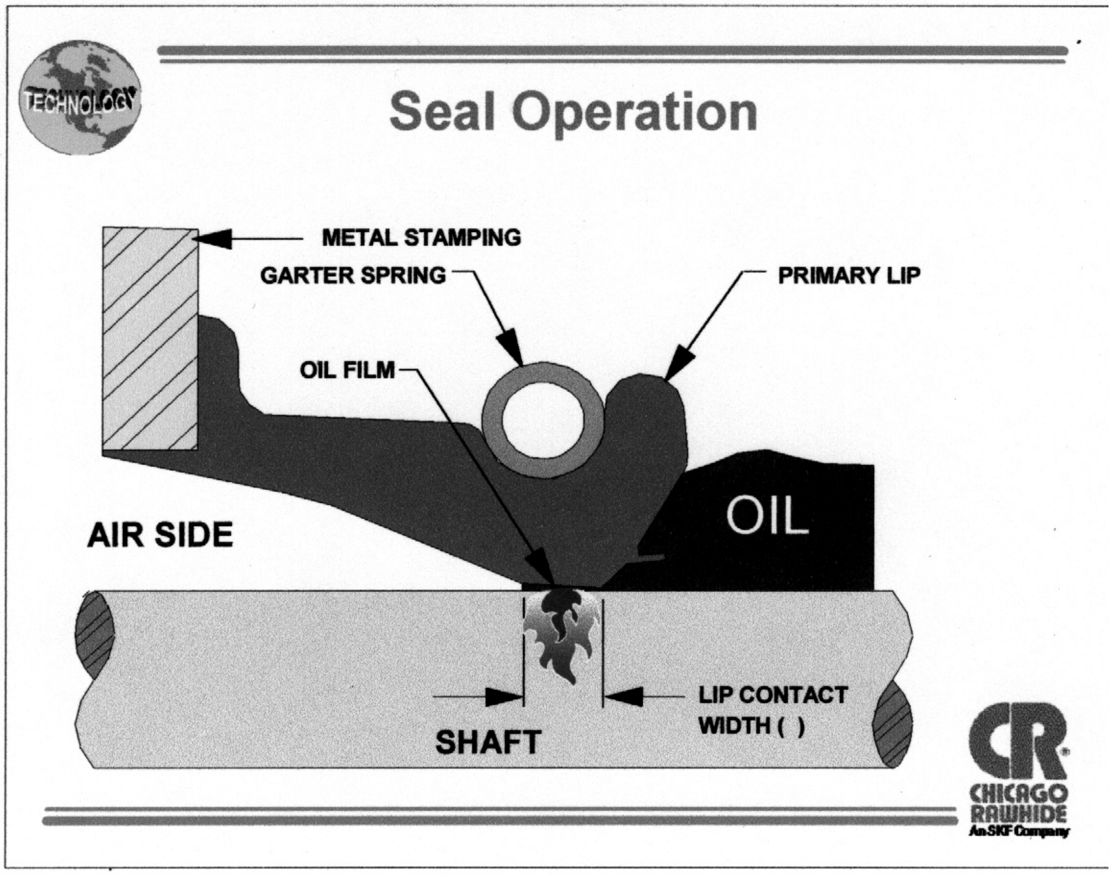


Figure 7. Elements of a Rotary Seal

The optimal finish of the shaft will depend on whether it undergoes high-speed rotation or lower-speed oscillation, and on the pressure of the fluid. In addition, any wear-resistant coating on the shaft will affect the seal design.

Future challenges faced by seal manufacturers include:

- Improved reliability and robustness.
- Longer life.
- Higher pressures, up to 2000 psi.
- Higher operating temperatures, up to 150^0C.
- Low-temperature materials for synthetic fluids.
- Improved lubricant compatibility.
- Lower friction, by as much as 20%.
- Contaminant-exclusion designs.
- Higher speeds, up to 8000 rpm.
- Compact designs.

Manual Transmissions

Manufacturers of manual transmissions for large trucks are faced with essentially the same challenges as are bearing manufacturers – power density and durability. Although the product envelope has not changed in size since the 1960s, power requirements have increased from 300 to 800 horsepower, and warranty periods are at 750,000 miles and moving to 1,000,000 miles. The increasing power density causes surface fatigue (pitting and wear) on the gears, which results in noisy gears, tooth breakage, and lower efficiency.

Methods to solve those problems include use of premium steels, improved lubrication, and surface treatments such as smoothing and coatings. Affordability has been a key concern with these approaches.

Continued improvements in engineered surface would allow improved fuel efficiencies through friction reduction, enhanced gear life through increased resistance to pitting and wear, lower operating temperatures, and cost savings in steel consumption and cutting tools.

Automatic Transmissions

An important factor affecting the efficiency of an automatic transmission is the amount of oil that it contains. Increases of efficiency between 1 and 5% could be obtained by reducing oil flow, and up to 10% if the transmission could run totally dry. While these approaches are theoretically possible, heat dissipation becomes a problem at low oil flow rates, and new friction materials also might be needed. A systematic approach to transmission design will be required to solve these problems. The approach should include:

- Generic studies of the factors that affect torque capacity.
- Generic studies on efficient heat dissipation at low oil flow.
- Generic studies of factors that affect drag losses in friction systems.
- Analyses to optimize the above phenomena.

The studies should be based on an experimental and practical approach supported by theoretical analyses of the friction interface and the surrounding environment. The entire system of friction material, automatic-transmission fluid, and separator plates should be considered in an integrated systems approach.

H. Lubricant Suppliers

Standards for lubricants are set by the automotive, truck, and engine companies. Not surprisingly, the lubricant industry, which consists of the oil companies and the additive suppliers, is dealing with the same issues that their customers face. The oil companies produce the base stock – a mineral or synthetic oil – that essentially determines the fluidity of the lubricant. As shown in Table 6, additive suppliers must deal with a wide range of properties, including temperature effects on fluidity, contaminant control, rust protection, cleanliness, acid neutralization, wear control, oxidation protection, friction reduction, and foam control. Additive chemistry is extremely complicated and still largely empirical. The effect of any given additive might be strongly influenced by other additives in the lubricant formulation.

Table 6. Functions of a Lubricant

Lubricant Marketer	**Formula Component**	**Possible Elements**
Fluidity	Mineral or synthetic oil	H, C, O
Additive Supplier		
Multigrade	Viscosity modifier	
Low-temperature flow	Pour-point depressant	
Suspend contaminants	Ashless dispersant	N, B
Rust protection Cleanliness Acid neutralization	Detergent	Ca, Mg, Na
Wear control Oxidation protection	Zinc dithiophosphate Ashless antioxidants	Zn, P, S N
Friction reduction	Friction modifier	Mo, S
Foam control	Antifoam	Si

For the heavy-duty vehicle market, oil and additive suppliers are focusing on supporting efforts to reduce emissions. Sulfur in the lubricating oil may contribute more sulfur compounds to the exhaust than will future ultra-low-sulfur fuels[6] (see Figure 8), and in some operating modes, the lubricant can account for up to 60% of particulate emissions. As stated previously, EGR will introduce much higher levels of soot into the lubricant, requiring new properties to prevent wear. Virtually all lubricants contain sulfur and phosphorus in the form of zinc dithiophosphate, which is needed in areas of very high contact pressures, such as the valve train. Both sulfur and phosphorus are serious poisons for catalysts in exhaust gas aftertreatment devices, but, to date, no effective substitute for zinc dithiophosphate is available.

The cost of conducting a single engine test is approximately $60,000. To fully qualify a lubricant, a number of engine tests and development feedback loops are often required. Such costs are becoming prohibitive. With increasingly rapid changes in standards, particularly with respect to emissions, it is becoming more important to develop reliable cost-effective bench-scale laboratory tests that are predictive of full-scale engine performance.

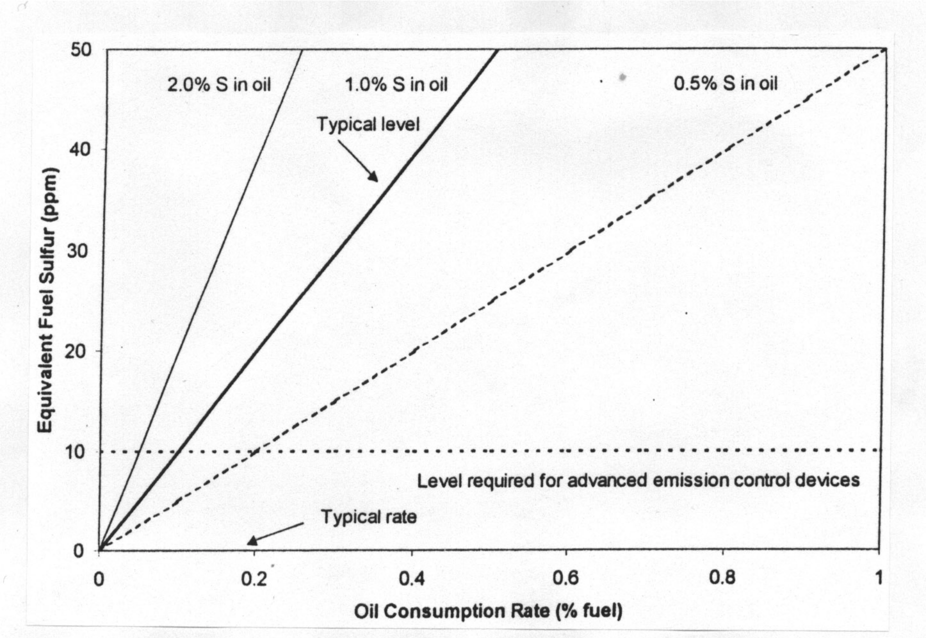


Figure 8. Sulfur Compounds from Oil

Extending lubricant life is important both for economic and environmental reasons, since downtime for oil changes is costly for truckers and lubricating oil is the single worst liquid contaminant in landfills. Approaches to achieve lubricant life extension could include the development of oil-quality sensors, which could be used to prevent premature oil changes, and development of improved biodegradable lubricants. Current vegetable oils have good friction and wear properties but low oxidation stability and poor low-temperature behavior.

Looking farther into the future, a number of alternative lubricant concepts are being considered, including the following:

- A consumable lubricant, which would burn with the fuel and thus not need to be drained; new oil would just be added as needed.
- Partitioning the engine so that an optimal lubricant could be developed for each specific area.
- Conversely, developing a universal lubricant that could be used in transmissions and axles as well as in the engine.
- Developing new lubricants that are compatible with advanced materials and coatings or, conversely, developing advanced materials and coatings that do not require liquid lubricants.

An interesting compatibility problem has retarded past developments of lubricants. This has occurred because any new lubricant has been required to be compatible with old hardware, and new hardware developments have been limited by compatibility with current or old lubricants. Most rapid progress could be made if the lubricant were considered as a design variable simultaneously with the materials and mechanical design.

I. Railroad Operators

The single greatest problem of friction and wear in railroads occurs at the interface between the wheels and the rails where the wheel flange contacts the rail, particularly in curves. It has been estimated that the industry could save about $250 million annually from an effective program to reduce flange/rail friction by lubrication or other means. About 1/3 of the savings would come from increased fuel efficiency, 1/3 from reduced rail wear, and 1/3 from lower wheel wear. The magnitude of savings could vary considerably from place to place depending upon grades, curves, maximum speeds, and types of trains. Research with full-scale trains has shown that effective spray lubrication of the rail can result in fuel savings of up to 25% on highly curved track and about 5% on relatively straight track.

Flange lubrication also is expected to improve the safety of freight trains by lowering the chance for derailment by reducing the forces that cause the wheel to climb the rail.

Although spray lubrication systems have been demonstrated successfully under controlled conditions, practical problems have seriously limited their use. These problems include poor durability of the spraying mechanism, difficulty in maintaining the system, and lack of acceptance by train crews who fear loss of braking power or traction.

Another approach to rail lubrication uses wayside lubricators, which are permanently located along curves in the tracks. Initial results with this system have been very promising, but additional field trials are needed.

As concerns about the environment continue to increase, the development of affordable biodegradable lubricants for rails grows in importance.

A second source of friction in freight cars occurs between the wheel tread and the top of the rail. A system for top-of-rail lubrication has been developed recently, and it has been able to achieve additional fuel savings of about 50% of those possible with flange lubrication. Current concerns about top-of-rail lubrication include the high cost of the lubricant and possible adverse interactions with the flange lubricant.

Another approach to reducing flange resistance is the use of radial or steerable trucks. This approach usually is used only on new car fleets because of the large capital investment that would be required for installed fleets.

While low friction is desired between the rail and the wheels on freight cars and between the rails and the flanges on locomotives, high friction is needed between the tread of the locomotive wheels and the rails. The recent introduction of locomotives with 4300- to 6000-hp engines and AC asynchronous motors has produced a quantum increase in the power produced and available at the railhead, but, at lower speeds (less than 20 mph), locomotives are limited to less than full power because of low adhesion between the wheel and the rail. Translated into productivity, an increase in adhesion from 35 to 40%, for example, could result in a 14% improvement in potential trailing tonnage for a train ascending a 1% grade at 10 mph.

Possible approaches to improving adhesion include:

- Alter the profile of the wheel or its mechanical properties, but only if it can be done without compromising car wheel life and wear or fatigue of the railhead. There are about 500 times more freight cars in North America than AC-traction locomotives. In addition, replacing rails incurs huge capital costs and expensive service delays.
- Apply chemicals that increase the coefficient of friction between the wheel and the rail.
- Improve computer controls of locomotive engines.
- Clean the railhead to remove water and organics.

Concerns about diesel engines in locomotives are similar to those for heavy-duty trucks. Reliability and durability are of paramount importance because road failures can be extremely expensive in terms of loss of revenue. Research objectives related to reliability and durability include improved additive packages for engine oils, improved filtration or treatment schemes for engine oils, and improved wear resistance of parts.

J. Locomotive Manufacturers

Locomotive manufacturers view fuel efficiency and emissions as issues with national impact. Although the number of locomotives produced per year is too low to independently bear the cost of a large R&D program, the problems faced by locomotive manufacturers are virtually the same as those faced by truck and diesel-engine manufacturers. A DOE program with industrial consortia could have huge benefits, not only for heavy-duty vehicles and trains, but for a broad cross section of U.S. industry for which friction and wear cost billions of dollars every year. Other nations, such as Japan, have taken up these issues as national projects, and we are in danger of becoming totally dependent on foreign sources in the future.

As with heavy-duty trucks, emission-control technologies will require improved lubricants to handle the increased soot loading from EGR and the formation of sulfuric acid.

Reliability and durability of components in the engine fuel system are vitally important for environmental reasons and for maintaining fuel efficiency. Very small amounts of wear in the orifices and valves of the fuel system can cause very large declines in the performance of the system. Cleaner diesel fuels and alternative fuels are expected to have much lower lubricity than do current diesel fuels. Low-friction, wear-resistant coatings for components of the fuel system or additives to the fuel probably will be needed to prevent premature failures.

Reducing friction in the axle bearings through improved seal designs or other means will not only increase fuel efficiency, but will help to prevent derailments due to damaged bearings.

V. EFFECTS OF EMISSION-REDUCTION TECHNOLOGIES ON FRICTION AND WEAR

The two components of diesel exhaust receiving the most attention are nitrogen oxides (NO_x) and particulate matter (PM). Industry has already made substantial progress in reducing both constituents, but additional efforts are required, especially for NO_x.

Between 1978 and 1998, NO_x emissions have been reduced by a factor of almost 4, from 15 g/hp-hr to 4 g/hp-hr. However, another factor of 2 reduction to 2 g/hp-hr will be required by October 2002. The four most likely technologies for meeting the new requirements are exhaust gas recirculation (EGR), higher fuel pressures, catalytic after-treatments, and alternative or improved fuels. In addition to causing an anticipated 5 to 10% decrease in fuel efficiency, each of these technologies also introduces new problems related to friction and wear. As explained earlier in this document, increased soot loading due to EGR will place new demands on the lubricant and may require wear-resistant coatings on critical parts. Higher fuel pressures will require tighter tolerances and produce higher stresses in fuel injectors, which probably will necessitate stronger materials and low-friction, wear-resistant coatings. Catalytic aftertreatment will require low-sulfur fuels and low-sulfur, low-phosphorus lubricants. It will be necessary to find a substitute for the current sulfur- and phosphorus-containing additive in order to maintain satisfactory life of components, such as parts of the valve train, that are subjected to high contact stresses. Alternative fuels, as well as higher-purity diesel fuels, will have lower lubricity, which will require development of an additive or new coatings for critical engine components.

Particulates have been reduced from about 1.5 g/hp-hr in 1978 to 0.1 g/hp-hr in 1994. That level meets the requirements for 2002. However, the health effects of PM are being investigated in many ongoing research programs. Recent evidence suggests that the mass emission rate may not be the most appropriate standard. Current standards deal with particles that are less than 10 micrometers (μm) in diameter. However, recent research has shown that much smaller particles – less than 50 nanometers (0.05 μm) in diameter – might be much more dangerous than particles of 0.1 to 10 μm. As is shown in Figure 9, these very small nanoparticles can represent a large fraction of the number of particles even though they account for a small fraction of the mass of the PM.[6] Furthermore, efforts to reduce the mass of the emissions sometimes can cause an increase in the number of nanoparticles. For example, soot in the exhaust will tend to suppress the formation and growth of nanoparticles by adsorbing sulfuric acid and hydrocarbons and by acting as substrates for the coagulation of nuclei.[6]

While there is much evidence to suggest that PM is not good, research to date has not defined how itshealth effects are related to factors such as particle number, density, surface area, shape, and chemical composition. In epidemiological studies, it has been difficult to separate the effects of particulate air pollution from the effects of other air pollutants.[7] Few of the epidemiological studies to date have isolated the effects of ultra-fine particles, and a consistent pattern is not apparent.[8] The anticipated high inflammatory potential from nanoparticles has not been demonstrated in traditional experimental animal studies unless very high concentrations, approaching 1 mg/m^3 and higher, were used. “Such studies with high doses have no environmental relevance and results should be interpreted with caution.”[9] There is general agreement that considerably more research must be done to clarify what kinds of particulate pollutants are harmful and what concentrations are dangerous.

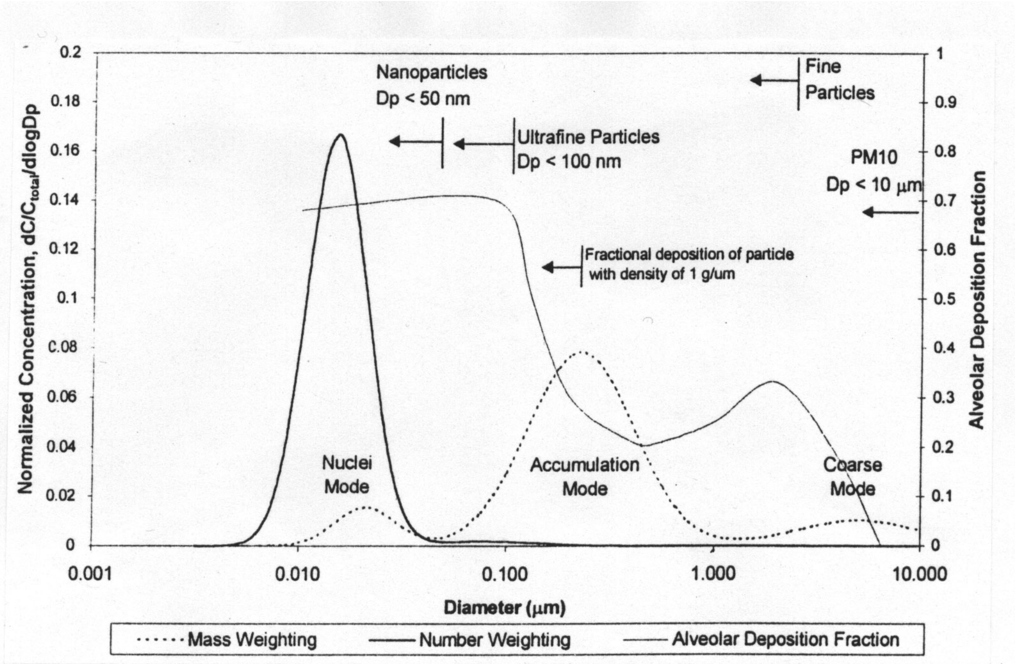


Figure 9. Typical Diesel Particle Size Distribution

Because of the ambiguity of current medical research, diesel engine and automobile manufacturers are in the difficult position of not knowing how to optimize systems for reducing particulate emissions. It will be important for them to monitor the results of future medical research in this area. As these data are accumulated, analyzed, and validated, the conclusions derived will influence the research agenda of the current dynamic program.

Lubricant and additive suppliers also must follow the medical research because lube oil constituents are likely to become a significant fraction of particulate matter in the future. In low-soot-emission engines, metallic ash from oil may constitute more than 50% of the number of particles and 10% of the mass.[6]

Concern about small particles is not restricted to diesel engines. Spark-ignition engines typically emit smaller particles than do diesel engines and thus are an important source of fine particles and nanoparticles. A recent study in Colorado showed that up to 2/3 of the fine-particle mass emitted by vehicles was from spark-ignition engines. New gasoline direct-injection engines emit much higher particle concentrations than do conventional engines and may approach diesel levels under some conditions.[6]

VI. BENEFITS OF REDUCING FRICTION AND WEAR

As stated previously, developing and implementing new technologies to reduce friction and wear could save the U.S. economy as much as $120 billion per year. This includes energy savings, repair and replacement costs, and downtime.

Within the transportation sector alone, potential fuel savings due to reducing friction could be as large as 830 million barrels of oil per year, which amounts to about $15 billion per year at the current price of crude oil.

Reducing fuel consumption will have a directly proportional benefit on reducing emissions from vehicles. In addition, new technologies for reducing friction and wear also are needed to meet forthcoming standards for diesel exhaust emissions. The dollar value of the health benefits, which obviously cannot be quantified, has not been included in the above figures, but the obvious potential beneficial effect on the nation's quality of life qualifies as a major driver for an aggressive research agenda.

In addition to the direct economic benefit to truckers, automobile owners, and railroad operators of lower fuel bills, reducing friction and wear will have important economic benefits associated with reduced downtime and lower costs for repair and replacement of worn parts.

Safety of vehicles also will be enhanced by making the components more durable. Two major causes of derailments of trains – wheel climb due to friction between the flange and the rail, and bearing failure – can be mitigated by reducing friction.

Advances in the basic understanding of friction and wear, along with the development of specific remedial measures, also will be beneficial to a broad range of industries well beyond the transportation sector, extending even into the area of military preparedness.

Friction, wear, and lubrication are important considerations in virtually every approach to reducing energy consumption and emissions, as described in the OHVT Technology roadmap. Examples include:

- Development of enabling technologies for Class 7 and 8 trucks to achieve a fuel efficiency of 10 mpg without sacrificing air quality will require the following:

    - To develop a 55% efficient engine, a 1% or more efficiency increase is expected from reductions in engine mechanical friction, and increased cylinder pressures will require improved friction control and piston/ring lubrication.

    - To reduce mechanical losses in transmissions and axles and parasitic losses in shaft-driven auxiliaries by 25%, new cost-effective coatings, materials, or designs will be required.

    - To meet federal and state emission requirements, soot and acid loading from EGR will require improved lubricants or coatings, and lubricant formulations without sulfur and phosphorus will be required to prevent contamination of catalysts for exhaust after-treatment.

  - To develop engines that can run on alternative liquid or gaseous fuels, lubricious coatings or fuel additives will be needed to compensate for the lower lubricity of the alternative fuels.

- To encourage significant dieselization of Class 1 and 2 trucks (pickups, SUVs), thereby achieving at least 35% fuel efficiency improvement over gasoline-fueled engines, while at the same time meeting emission requirements, new coatings, lubricants, or designs will be needed to minimize friction losses at part loads.

VII. RECOMMENDATIONS FOR FUTURE R&D

Methods for reducing friction and wear generally require improvements in one or more of four areas:

- Materials.
- Coatings and surface modifications/conditions.
- Lubricants.
- Design methods.

However, it is generally agreed that none of those areas should be treated independently of the others. For example, performance of a coating will depend on the properties of the substrate and the mating surfaces (materials), the nature of the lubricant, and the stresses and temperatures to which it is subjected (design). Different lubricants are needed for different mating surfaces (materials and coatings) and for different pressures and temperatures (design). Likewise, material selection depends on design stresses and temperatures, anticipated use of coatings, and effectiveness of lubricants; and designs are limited by the available or affordable materials, coatings, and lubricants. Looking at it another way, a given wear problem might be solved by using a more wear-resistant material or a wear-resistant coating or a better lubricant or a design that reduces the contact stresses. Therefore, for an optimal solution to a friction or wear problem, a systems approach should be taken by a team with expertise in each of the critical areas.

Recognizing the need for advances in all four areas, the workshop participants were divided into four working groups, each with an emphasis on one of the four areas. Each group was asked to prepare a list of research topics important to the transportation industry and appropriate for support from DOE. Despite the fact that each group had a specific technical focus, they were asked to consider solutions to problems broadly and not ignore the importance of the other three technical areas.

The following paragraphs summarize the recommendations from each of the working groups. The recommendations are not listed in order of priority. Priorities were developed later after considering input from all of the working groups.

A. Materials

1. **Develop materials or coatings for fuel lines, pistons, and valve trains that are compatible with alternative ethanol-containing or low-sulfur fuels.** The materials must be suitable for use between –40 and 66^0C.

   Many new fuels are corrosive to currently used materials, and they dissolve common lubricants, leading to lubricant washout, wear, and scuffing.

The approach would involve identification of candidate materials from the literature, laboratory testing, modification of materials if necessary, and finally full-scale tests.

2. **Develop a rotary seal system that requires less downtime for inspection and repair, either by extending the life or using sensors to indicate when maintenance is needed rather than relying on scheduled inspections.**

   Current seal materials are not expected to hold up well under proposed increases in engine power density. Two alternative or parallel approaches are suggested.

   a. Develop new seal designs, including the elastomer and the shaft surface, that would last 100,000 miles in automobiles or 1 million miles in trucks.

   b. Develop sensors to detect incipient failure of a seal. Initially, it would be necessary to conduct experiments to assemble a data base of incipient failure signs, such as noise or vibrations. The sensor systems would have to be designed to detect these changes. If successful, this approach would allow fleet operators to use a condition-based repair procedure rather than the less efficient time-based inspection procedure.

3. **Develop a bench-top test for piston-ring and cylinder-liner materials that is predictive of full-scale behavior.**

   New emission-control technologies such as EGR and alternative fuels are expected to put new demands on piston rings and cylinder liners in terms of wear and corrosion. Full-scale engine tests are very expensive, but current bench-top tests do not correlate well with full-scale behavior.

   The approach would first require a considerable amount of failure analysis to identify the major failure modes and then the design of experiments to reliably simulate those failure modes. Development of an analytical model of the failure mechanisms would also be necessary to convert the laboratory data to full-scale behavior with appropriate periodic validation checks.

4. **Develop materials and coatings for a high-pressure (2 kilobar), high-volume fuel-injection system with a minimum life of 10^9 cycles.**

   One of the important new emission-control technologies involves higher fuel-injection pressures, which will require higher stresses and closer tolerances in the fuel injectors. This could lead to shorter fatigue lives, along with cavitation, wear, and corrosion. The challenge will be to find affordable, durable, low-friction, wear-resistant coatings and affordable higher-strength materials.

5. **Develop premium steels that can tolerate the higher stresses and temperatures that will be experienced by gears and bearings in the drive train due to increases in power density.** The steel should have high strength to minimize weight, good wear resistance, and high contact-fatigue resistance.

6. **Develop a concept for an intelligent, self-lubricating surface that would sense when lubricant is needed and then secrete lubricant when necessary.**

   No specific approach was identified, but the concept probably would require embedded sensors and possibly MEMS-type pumps. Durability, reliability and cost are obvious challenges.

7. **Develop more cost-effective methods for producing low-friction, wear-resistant surfaces that would be practical for gears, bearings, and railroad wheels and rails.**

   A variety of approaches might be considered, including coatings, ion implantation, laser glazing, and laser peening.

8. **Develop a lubrication system that is compatible with engines made of light-weight materials.** The system must prevent or minimize wear, scuffing, distortion, noise, and vibration, and should be free of sulfur and phosphorus.

   Current oil additive packages are designed for ferrous materials, and they contain sulfur and phosphorus, which poison catalysts.

   Three alternative approaches could be considered:

   a. Develop an oil additive package that is free of sulfur and phosphorus and is compatible with lightweight materials.

   b. Develop new lightweight materials that are compatible with current lubricants.

   c. Develop an inexpensive means of modifying the surfaces of the light-weight materials that would either eliminate the need for liquid lubrication or be compatible with current and future lubricants.

9. **Develop, for a Class 8 truck, a braking system that will last for 1 million miles with little or no maintenance, be environmentally benign, and be lighter than gray iron.** The system must be able to stop a fully loaded truck weighing about 80,000 lb quickly and controllably. Brake temperatures may reach 600 to 700^{0}C.

   Increasing engine power and the concomitant increase in cargo weight, along with methods to reduce aerodynamic drag and engine drag, have greatly increased the demands on braking systems. Current designs depend on significant amount aerodynamic drag to help slow the truck. Currently available dry-brake materials have reached their limit in terms of dissipating the tremendous amounts of kinetic energy as heat without suffering excessive wear.

   Three alternative approaches should be considered:

a. Develop new materials for brake linings and drums that can withstand the increased service requirements. This probably would require laboratory testing of candidate materials, followed by dynamometer evaluations, and concluding with vehicle tests.

b. Develop regenerative retarders that would capture and store some of the kinetic energy, to be used for subsequent acceleration. The chief technical barrier would be to design a device that will work reliably for 1 million miles with little or no maintenance.

c. Develop a wet braking system to replace the dry braking system. Although wet brakes would easily meet the requirements for rapid and controllable deceleration, current wet brakes have unacceptable viscous drag.

B. Coatings

In addition to meeting specific requirements for wear-resistance, lubricity, corrosion resistance, and adhesion, any new coating also must be cost-effective, friendly to the environment, adaptable to high-volume manufacturing operations, and compatible with current and future lubricants and fuels. With this in mind, five research projects were recommended:

1. **Develop coatings for piston rings, cylinder liners, valves, and valve stems that can tolerate operating conditions under exhaust-gas recirculation (EGR).** This is consistent with Item 3 under Materials.

   Along with testing new or currently available coatings, attempts should be made to understand the fundamental mechanisms of wear and corrosion during EGR.

2. **Develop cavitation- and erosion-resistant coatings for fuel injectors operating at high pressures with current diesel fuels and with alternative low-lubricity fuels.** This is consistent with Item 4 under Materials.

3. **Develop coatings to replace ferrous cylinder liners in aluminum engine blocks with conventional and alcohol-containing fuels.** This is consistent with Item 8 under Materials.

4. **Develop a fundamental understanding of the interaction between coatings and lubricants and fuels.** The approach probably should involve in-situ experiments using sophisticated, high-technology facilities (neutron diffraction, x-ray diffraction, Raman scattering, etc.) at the national laboratories.

5. **Develop models to predict full-scale behavior from results of laboratory friction and wear tests.** Alternatively, develop new laboratory tests that correlate better with full-scale behavior. This is consistent with Item 3 under Materials.

C. Lubricants

1. **Develop meaningful laboratory tests to predict full-scale behavior of lubricated components.** This is consistent with Item 3 under Materials and Item 5 under Coatings.

   In addition to the obvious requirement that the laboratory tests correlate with full-scale performance, the tests should be inexpensive and rapid and treat all of the possible failure mechanisms. They should consider shear effects, time-dependent degradation of the lubricant, and interactions between lubricant and mating surfaces.

2. **Develop environmentally friendly lubricant systems that are compatible with the new emission-reduction technologies.** This is compatible with Item 3 under Materials and Item 1 under Coatings.

   The lubricant should be biodegradable, or provision should be made for effective recycling. It should contain low (zero if possible) levels of sulfur and phosphorus. Alternatively, phosphorus-tolerant catalysts should be developed.

3. **Develop a fundamental understanding of time-dependent contamination and degradation of lubricants.** This includes Item 4 under Coatings.

   Important issues to be considered include the following:

   a. Sludge and varnish formation.
   b. Soot suspension and its effect on lubricants.
   c. Oil degradation.
   d. Filtration.
   e. Additive depletion.
   f. Health and safety.

4. **Develop a system for extending oil-drain intervals, with the ultimate objective of "lube for life."**

   A variety of approaches should be considered, including burning the lubricant with the fuel and separating the top of the engine from the bottom. Issues to consider include changes in viscosity and rheology over time, corrosion, and seal compatibility.

5. **Develop predictive models of lubricant and material behavior, and validate the models experimentally.** This is consistent with Item 5 under Coatings.

D. Design Methods

1. **Develop a general-purpose friction/wear/lubrication code that could be used for designing lubricated components in much the same way that NASTRAN is used for structural analysis and KIVA is used for combustion analysis.**

Currently, lubricated components in engines and transmissions are designed with many different codes – usually one for each component – that have various degrees of sophistication in terms of modeling different phenomena such as elasticity, temperature, or non-Newtonian flow. The codes are proprietary to each manufacturer, and many smaller companies have no computer codes.

The new code should be designed with maximum flexibility to allow for future addition of models of phenomena such as wear and scuffing, which currently are still subjects of research. The code should model all known relevant phenomena, including hydrodynamics, thermohydrodynamics, elastohydrodynamics, non-Newtonian shear thinning, and effect of surface roughness on flow. The code should be validated with classical solutions, other analytical codes, and experimental data.

It is estimated that development of this code may require up to 10 people working for 5 years.

2. **Develop advanced analytical tools and experimental methods to be used in designing splash/mist lubrication systems for engines.**

The piston skirt, rings, and wrist pin are lubricated by splash/mist lubrication. Since the splash/mist lubrication process is poorly understood, there are no design tools for this purpose, and inefficient designs result. To avoid problems related to durability, scuffing, and noise, the lubrication system is oversized, which leads to losses; and compromises are made in the piston and ring design, which often result in higher friction. Some cylinders receive too much oil, resulting in excess oil consumption and thereby excess emissions; some receive too little, resulting in higher friction. To minimize piston noise, tighter clearances are used, which also results in higher friction. This is significant because the piston assembly is the main source of friction in the engine.

A two-pronged approach is needed for this problem. A computer code should be developed to calculate the amount of oil that is delivered to the various components of the piston assembly, and advanced experimental techniques need to be developed to validate the computations of the amount of lubricant delivered to the cylinder bore wall, piston pin, piston skirt, and rings.

It is estimated that this project would require about 5 persons working for 5 years.

3. **Develop and demonstrate additional concepts for a controlled-lubrication system.**

Current lubrication practice uses oil in excess quantities so that the least-oiled part receives sufficient oil. This practice wastes oil by sending excess oil to other engine parts. In addition to reducing oil consumption, solving this problem also would have the economic benefit of increasing intervals between oil changes and the environmental benefit of reducing emissions.

Two of the approaches that should be considered to address this issue are vapor-phase lubrication and self-lubricating materials or coatings.

It is estimated that this project would require 5 to 10 persons working for 3 to 5 years.

4. **Develop a fundamental understanding of cavitation damage and use the understanding to improve design tools for fuel injectors and cylinder liners.**

   This would supplement Item 4 under Materials and Item 2 under Coatings.

5. **Develop advanced experimental methods to continuously measure oil film thickness at the piston rings and to monitor the condition of the oil in the crankcase.**

   These techniques would be supportive of the computational efforts described above.

6. **Develop bench-top accelerated tests that would be predictive of full-scale behavior of piston rings, bearings, and valve-train components.**

   This is consistent with Item 3 under Materials, Item 5 under Coatings, and Item 1 under Lubrications.

VIII. PRIORITIES, GOALS, AND BARRIERS

It is interesting and comforting to note that a number of common themes emerged in several of the working groups, independent of the technical bias of the group. These themes involved the development of several classes of enabling technologies that could form the foundation upon which companies, individually or in consortia, could develop new products and techniques for significantly reducing energy consumption in transportation, as well as promoting emission reduction, and achieving durability and reliability of vehicles, profitability of freight transportation, and safety. The following paragraphs describe some of those common themes.

Quantitative understanding of failure mechanisms.

A quantitative understanding of failure mechanisms such as wear, scuffing, and fatigue is essential for the development of both computational design codes to mitigate (and possibly avoid) those problems and bench-top tests to predict full-scale behavior. This will require combining the results of basic research into those mechanisms, applied research into how those mechanisms are manifest in an engine or drive train, testing to develop correlations between fundamental properties and component behavior, and analytical and computational approaches to codify the understanding.

Bench-top tests that are predictive of full-scale behavior.

While a quantitative understanding of the various failure mechanisms would be extremely helpful in designing bench-top tests, in the meantime it should be possible to develop better correlations between lab behavior and full-scale behavior by taking greater care to duplicate in the laboratory the essential conditions that prevail in an operating engine or drive train.

Variety of affordable surface-modification technologies that would be suitable for various components (gears, bearings, piston rings, cylinder bores, valve-train components, fuel injectors, railroad rails, railroad wheels, etc.) in various fuels or lubricants, and under various operating conditions.

For many situations in which stresses, temperatures, or environments are becoming more severe, current bulk materials have reached, or soon will reach, their performance limits, and surface modification remains the only viable alternative for additional improvements. Surface-modification techniques for consideration include various coatings, thermal treatments (perhaps by lasers), ion implantation methods, and texturing or smoothing.

It is unlikely that any single surface-modification technique will be suitable for all applications. Therefore, a variety of techniques or coatings need to be characterized and, perhaps, further developed.

Better understanding of the chemistry of lubricants and how additives affect their interactions with rubbing surfaces.

Formulation of additive packages is largely empirical. A more scientific understanding of the role of additives would form the foundation for developing new lubricants that will be longer lasting, environmentally friendly, capable of handling increased soot loadings for EGR, compatible with catalysts (probably with very low sulfur and phosphorus levels), and/or compatible with nonferrous materials.

Advanced computer codes that model friction, wear, distribution of lubricants, and lubricant interactions with surfaces for designing low-friction, low-emission components and systems.

A general friction/wear/lubrication model is needed, along with more specific models of lubrication and vapor-phase lubrication.

Other subjects that were mentioned less frequently but still represent significant opportunities for energy savings include the following:

Affordable high-performance steels to withstand the higher stresses resulting from increasing power density and fuel pressure.

Improved rotary-seal systems for longer life.

Improved brake systems to compensate for heavier loads and reduced aerodynamic drag.

The status, goals, and barriers associated with the highest-priority research areas are summarized in Table 7.

Table 8 shows the relationships among the major research topics and the needs of the various stakeholders.

Table 7. Summary of Technical Targets and Barriers for Reducing Friction and Wear

Challenge	Current Practice	Technical Target	Barriers
Cost of validation testing	Engine tests costing about $60,000 each	Inexpensive, predictive bench-top tests for cylinder-liner and piston-ring materials, bearings, and valve-train components	Lack of quantitative understanding of failure modes. Lack of understanding of time-dependent in-situ contamination and degradation of lubricants. Lack of model to predict performance based on material properties and design features.
Cost-effective surface-modification technologies	Limit performance based on bulk-material properties	Coatings or other surface treatments to allow fuel injectors, pistons, cylinder liners, and valve-train components to tolerate higher stresses, lower lubricity, and higher corrosivity resulting from new emission-reduction technologies	High cost of current coatings and surface-modification technologies. Limited wear resistance, durability, and adhesion.
Lubricant and additive chemistry	Trial-and-error approach to lubricant formulation	Develop environmentally friendly lubricant that is compatible with new emission-reduction technologies	Need model to predict long-term performance of lubricants based on properties of base oil and additives. Need for sulfur and phosphorus for high-pressure applications, but deleterious effects sulfur and phosphorus have on catalysts. Disposal or biodegradability.
Comprehensive computer codes	Fragmented codes unable to handle lubricated parts in relative motion	General-purpose friction/wear/lubrication codes that include splash and mist lubrication for designing low-friction, low-emission lubricated components and systems	Extremely complex system. Lack of quantitative understanding of friction and wear as a function of basic material properties and loading conditions.

Table 8. Relationships among Stakeholder or Customer Needs, and Recommended Research Topics

Customer	Issue	Solution(s)	Barriers	Research Topic(s)
A) General Public	maintain fuel supply	-reduce demand for imported fuel through greater use of domestic and alternative supplies	-operation of fuel systems on alternative fuels	-surface modification
		-improve thermal efficiency of engine	-see Section E	-coatings, lubricants, bench-top tests, & design codes
		-reduce mechanical and parasitic losses	-mechanical losses (see E and G)	-coatings, lubricants, failure mechanisms, & design codes
	maintain & improve environment	-combustion control to lower NO_x & PM	-high pressure fuel system	-surface modification
		-After-treatment to lower NO_x	-NO_x catalysts require low-S fuels that have poor lubricity	-surface modification & low-S, low-P lubricants
		-EGR	-degradation of engine lubricants by EGR gases & particulates	-new lubricants, bench-top tests, & surface modification
B) Fleet Operators	owning & operating costs	-improve vehicle efficiency	-engine efficiency (see Section E)	-surface modification, bench-top tests, lubricants, & design codes
	maintenance costs (oil change interval)	-more durable engine lubricants with smart lube sensors	-see Section H	-lubricants, bench-top tests, & failure mechanisms

Customer	Issue	Solution(s)	Barriers	Research Topic(s)
C) Truck Manufacturers	cost effectiveness of vehicle	-lower manufacturing costs -increase fuel economy	-potential issues regarding advanced manufacturing processes -see Sections E & G	-design codes -surface modification, lubricants, & design codes
	emission standards	-lower-emission engines -after-treatment - EGR	-see Sections E & H	-see Section A
D) Off-Road Vehicles	uptime	-increase durability of subsystems	-durability of components (see Sections E & G)	-failure mechanisms, bench-top tests, surface modification, lubricants & design codes
	owning & operating costs	-lower manufacturing costs -improve vehicle efficiency -more durable lube systems & sensors	-see Section B	-see Section B
	emissions	-decrease production of emissions -after-treatment	-see Sections E & H	-see Section A

Customer	**Issue**	**Solution(s)**	**Barriers**	**Research Topic(s)**
E) Engine Manufacturers	achieving more stringent emission standards	-combustion control to lower NO_x & PM	-high pressure fuel system	-surface modification
		-aftertreatment to lower NO_x	-NO_x catalysts require low-S fuels, which have poor lubricity -effect of engine lube S and P on catalysts and performance of low-S, P engine lubes	-surface modification, lubricants, & bench-top tests
		-EGR	-degradation of engine lubricants by EGR gases & particulates	-lubricants & bench-top tests
	increasing efficiency	-improved combustion control	-high(er) pressure fuel delivery system	-surface modification
		-decrease mechanical losses (viscous and boundary lubrication losses)	-use of low viscosity lubes and associated wear -frictional losses under boundary-lube conditions	-lubricants, design codes, bench-top tests & surface modification
	improving durability	-engine design	-friction and wear data and modeling	-design codes & failure mechanisms
		-materials	-friction and wear data on new materials -friction and wear data on advanced coatings	-bench-top tests & failure mechanisms
		-lubricants	-performance of low-emission (e.g. low-S, P) engine lubes -interaction of engine lubes with advanced materials and coatings	-lubricants & bench-top tests
	power density	-designs -stronger materials -lubricants	-See Section E: improving durability	-design codes, failure mechanisms, surface modification, & lubricants

Customer	Issue	Solution(s)	Barriers	Research Topic(s)
F) Automobile Manufacturers	meeting CAFE standards	-increase vehicle fuel efficiency	-see Section E: engine efficiency	-see Section E: engine efficiency
	increasing performance	-downsizing vehicle -increasing engine power & power density	-see Section E	-see Section E
	increasing durability	-component design -stronger more durable materials	-see Section E	-see Section E
	alternative fuels	-design of fuel delivery systems -fuel delivery system materials	-friction and wear data on advanced fuel system materials and coatings with alternative fuels	-bench-top tests, design codes, & surface modification
	manufacturing costs	-new designs and materials	-wear/durability of materials and coatings used in manufacturing	-bench-top tests, design codes, & surface modification
G) Component Manufacturers	energy losses in rings, rods, camshafts	-new designs, lubricants, & materials	-friction & wear data for models -higher loads & stresses -surface finish (what surface finish is needed) -Pb-free coating replacements -lubricant-material interactions	-bench-top tests, design codes, lubricants & surface modification
	low-S fuel systems	-fuel lubricity additives -better fuel system materials	-data on additive-material interactions -abrasive and cavitation wear at higher pressures -fatigue resistant components -scuffing and wear with low-lubricity fuels -impact of friction on the response of fast acting components	-lubricants & bench-to-tests -surface modification, failure mechanisms, & bench-top tests

Customer	**Issue**	**Solution(s)**	**Barriers**	**Research Topic(s)**
	higher power density bearings	-new coatings, designs, or lubricants	-F&W data and models -wear of bearing materials and coatings (contaminated lubes, EGR, etc.)	-surface modification, design codes, failure mechanisms, bench-top tests, & lubricants
	low friction, durable seals	-new designs and materials	-friction & wear models	-design codes & bench-top tests
	high power density transmissions	-use of premium steels -surface treatments & coatings -forced lubrication	-pitting -wear -models of drag losses in friction systems	-failure mechanisms, surface modification, design codes, & bench-top tests
H) Lubricant Suppliers	emissions	-synthetic lubricants -non-emitting additives	-lack of fundamental understanding of lubricant/additive chemistry	-lubricants & bench-top tests
	catalyst poisoning	-low S, P base stocks and additives	ditto	ditto
	extended life	-base-stock and additive improvements	"	"
	universal lubes	ditto	"	"
	segmented lubes	-novel designs	-inadequate design codes	-design codes
I) Railroads	operating costs	-more efficient engines -lower wheel/rail losses	-see Section E -cost	-see Section E -lubricants & surface modification
	emissions	-locomotive design	-see Section E	-see Section E
	safety	-better control of wheel/rail forces	-cost	-lubricants
J) Locomotive Manufacturers	emissions	-lower production of emissions -after-treatment -EGR	-see Section E	-see Section E

Customer	Issue	Solution(s)	Barriers	Research Topic(s)
	efficiency	-improve combustion -decrease mechanical losses	-see Section E	-see Section E
	durability	-engine design -materials -lubricants	-see Section E	-see Section E

IX. REQUIRED FUNDING RESOURCES

Without knowing the specific approaches that will be proposed to solve the above problems, it is not possible to predict accurately the time and budgets that will be needed to solve them. Nevertheless, it is not unreasonable to expect that each major topic will require 5 to 50 person-years of effort. Together, that probably will amount to several hundred person-years, which would cost approximately $50 million. While that number is small compared to the billions of dollars of potential annual savings, it is not small compared to traditional DOE budget levels for research into friction, wear, and lubrication.

It is recommended that in the first year, projects be started in the areas of coatings, lubricants, and failure mechanisms, with the other topics added in subsequent years as the budget allows.

DOE funding should be about $2 million for the first year, $4 million for the second year, and eventually reach $7 to $10 million as all areas of research become active. Assuming that roughly half of the funding would go directly to industry and be matched on at least a one-to-one basis, total funding over 5 years would approach preliminary rough estimates of what will be required.

A summary of the yearly resource requirements for each of the highest-priority research areas is given in Table 9.

Table 9. Resource Requirements (in million dollars) for Top-Priority Projects on Reducing Friction and Wear

R&D Area	FY 01	FY 02	FY 03	FY 04	FY 05	Total
Surface-Modification Technologies	0.7	1.1	1.6	1.6	1.0	6.0
Chemistry of Lubes & Additives	0.7	1.1	1.6	1.6	1.0	6.0
Failure Mechanisms	0.5	0.7	1.0	0.8	0.2	3.2
Advanced Computer Codes		0.9	1.6	1.6	1.0	5.1
Predictive Bench-Top Tests		0.5	1.0	1.0	0.3	2.8
Other	0.1	0.1	0.5	0.7	0.5	1.9
TOTAL	2.0	4.4	7.3	7.3	4.0	25.0

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8. D. W. Dockery, “Epidemiologic Evidence for Health Effects of Fine and Ultrafine Particulate Air Pollution,” Presented at Diesel Engine Emission Reduction Workshop, Castine, ME (July 6-9, 1998).

9. G. Oberdorster, “ Current Understanding of the Toxicity of Ultrafine Particles,” Presented at Diesel Engine Emission Reduction Workshop, Castine, ME (July 6-9, 1998).

APPENDIX A:

List of Acronyms

ANL	Argonne National Laboratory
CAFE	Corporate Average Fuel Economy
DOE	U.S. Department of Energy
EGR	Exhaust gas recirculation
EPA	U.S. Environmental Protection Agency
GDP	Gross Domestic Product
HVST	Heavy Vehicle Systems Technologies
MEMS	Micro-electromechanical systems
NMHC	Nonmethane hydrocarbons
NO_x	Nitrogen oxides
OHVT	Office of Heavy Vehicle Technologies
OTT	Office of Transportation Technologies
PM	Particulate matter
PNGV	Partnership for a New Generation of Vehicles
R&D	Research & Development
SUV	Sport utility vehicle

APPENDIX B:

RESEARCH NEEDS FOR REDUCING FRICTION AND WEAR IN TRANSPORTATION

- AGENDA -

MONDAY, MARCH 22, 1999

Welcome and Introductory Remarks

ANL - Harvey Drucker
Associate Director, Argonne National Laboratory

DOE - Jim Eberhardt
Director, Office of Heavy Vehicle Technologies
Office of Transportation Technology

- Sid Diamond
Team Leader for Vehicle Systems Technology

Keynote Speech #1: The Effect of Friction and Wear on Fuel Efficiency
Speaker: Dennis Assanis
Professor of Mechanical Engineering
University of Michigan, Ann Arbor

Keynote Speech #2: Nanoparticle Engine Emissions - The Role of the Lube Oil
Speaker: David Kittelson
University of Minnesota, Minneapolis

Industry Needs

Brad Toole
Staff Engineer, Metallurgy
Mack Trucks, Hagerstown, MD

Yury Kalish
Manager, Mechanical Systems
Detroit Diesel Corporation, Detroit

Frank Kelley
Program Manager, Advanced Materials Technology
Caterpillar, Inc., Peoria, IL

Mark M. Shuster
Lead Scientist, Materials and Tribology
DANA Corporation, Ottawa Lake, MI

Robert Straub
V. P. Engineering
Diesel Technology Company, Kentwood, MI

Tony Wu
Engineering Manager, Heat Treat Business Unit
Diesel Technology Company, Kentwood, MI

Harvey Nixon
Timken Research, Canton, OH

Ronald Jackowski
Vice President Technology
CR Industries, Inc., Elgin, IL

Simon C. Tung
Fuels and Lubricants Department
General Motors Corporation, Warren, MI

Rohit Paranjpe
Powertrain Division
General Motors Corporation, Warren, MI

Jagadish Sorab
Senior Technical Specialist, Engine Tribology
Engine and Processes Department
Ford Motor Company, Dearborn, MI

Bulent Cavdar
Senior Scientist
Borg-Warner, Lombard, IL

William B. Chamberlin
Research Development and Testing
The Lubrizol Corporation, Wickliffe, OH

Michael P. Bujold
Program Manager
Eaton Corporation, Southfield, MI

Glenn W. Bowen
Director Laboratory Services
BNSF, Topeka, KS

Mike Iden
Union Pacific Railroad, Kildeer, IL

Norm Shilling
GE Corporate R&D, Schenectady, NY

Sudhir Kumar
Chairman and President
Tranergy Corporation, Bensenville, IL

Tour of Advanced Photon Source - Derrick Mancini

TUESDAY, MARCH 23, 1999

Technical State-of-the-Art Updates

Materials -	Pete Blau Oak Ridge National Laboratory, Oak Ridge, TN
Coatings -	Ali Erdemir Argonne National Laboratory, Argonne, IL
Lubricants -	Joseph M. Perez Department of Chemical Engineering The Pennsylvania State University, University Park, PA
Design Methods -	Sanjay Gulwadi Staff Engineer Ricardo Software, Burr Ridge, IL
Techniques for Characterizing Wear -	Miguel Salmeron Senior Staff Scientist E. O. Lawrence Berkeley National Laboratory, Berkeley, CA

Simultaneous Breakout Sessions to Develop Research Agendas

A. Materials -	Chair: Mike Bujold Eaton Corporation
B. Coatings -	Chair: Padma Kodali Cummins Engine Company
C. Lubricants -	Chair: Shirley E. Schwartz Fuels and Lubricants Department General Motors Corporation, Warren, MI
D. Design Methods -	Chair: Yury Kalish Detroit Diesel Corporation

Reports from Working Groups

Wrap-Up

Adjourn

Coatreport