ANL/ESD/02-6

Railroad and Locomotive Technology Roadmap

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Railroad and Locomotive Technology Roadmap

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December 2002

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SUMMARY

Railroads are important to the U.S. economy. They transport freight efficiently because they require less energy and emit fewer pollutants than other modes of surface transportation. Although the fuel efficiency of the railroad industry has improved steadily — by 16% over the last decade — more can, and needs to, be done. Fuel efficiency has recently become even more critical with the introduction of strict emission standards by the U.S. Environmental Protection Agency.

The approximately 4 billion gallons of diesel fuel that are used by locomotives each year is about 10% of the total diesel fuel used in transportation and 2.3% of all the fuel used in transportation in the United States (Davis 1997). Large freight carriers consume most of this fuel. U.S. railroads spend over \$2 billion per year, or approximately 7% of their total operating expenses, on diesel fuel (AAR 2002).[1] Because fuel costs represent a significant portion of the total operating costs of a railroad, fuel efficiency has always been an important factor in the design of locomotives and in the operations of a railroad. In terms of energy efficiency, these are dollars well spent. An important measure of rail energy efficiency is revenue ton-miles per gallon of fuel consumed. A revenue ton-mile is one ton of a customer's goods moved one mile. Simply stated, it measures the amount of real work that freight railroads do for their customers for every gallon of fuel used. (Passenger railroads use passenger-miles per gallon for a similar measure.) America's railroads have dramatically increased the number of ton-miles delivered per gallon — from 235 in 1980, to 332 in 1990, and then to 403 in 2001, which is an increase of over 71% (AAR 2002). This achievement was due to the combined effect of many technological advances and improvements in dispatching and operations, as well as to shifts in the mix of commodities transported and to longer shipment distances by dense commodities, like coal.[2]

The U.S. Environmental Protection Agency has established strict emission standards to be implemented in stages (Tiers 0, 1, and 2) between 2000 and 2005. Locomotives currently emit over one million tons of NO_x each year, which is about 5% of total NO_x emitted by all sources (Orehowsky 2001). Some of the technologies that could be employed to meet the emission standards may negatively affect fuel economy — by as much as 10–15% when emissions are reduced to Tier 2 levels. Lowering fuel economy by that magnitude would have a serious impact on the cost to the consumer of goods shipped by rail, on the competitiveness of the railroad industry, and on this country's dependence on foreign oil.

The ability of locomotive manufacturers to conduct research into fuel efficiency and emissions reduction is limited by the small number of locomotives manufactured annually. Each year for the last five years, the two North American locomotive manufacturers — General Electric Transportation Systems and the Electro-Motive Division of General Motors — have

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[1] The fuel share is computed as the ratio of total diesel fuel expenses to total expenses and taxes (i.e., excluding net operating income) for Class I railroads, as reported in AAR's *Railroad Facts* (AAR 2001).

[2] An estimated 43% of the gain came from the increased share of ton-miles represented by coal and other dense commodities (Vyas 2001).

together sold about 800 locomotives in the United States. With such a small number of units over which research costs can be spread, outside help is needed to investigate all possible ways to reduce fuel usage and emissions.

Recognizing the importance of fuel costs and emissions compliance to the railroad industry, the U.S. Department of Energy (DOE) convened a workshop in January 2001 (ANL 2001) to (1) determine the interest of the locomotive and railroad industries in crafting a shared vision of locomotive and railroad technology of the future and (2) identify critical research and development (R&D) needs for reducing fuel consumption and emissions while maintaining or enhancing system performance.

As a result, the railroads, their suppliers, and the federal government have embarked on a cooperative effort to further improve railroad fuel efficiency — by 25% between now and 2010 and by 50% by 2020, on an equivalent gallon per revenue ton-mile basis. They also expect to meet emission standards and achieve these goals in a cost-effective, safe manner. Achieving these goals will save 700 million gallons of fuel per year by 2010 and 1.3 billion gallons of fuel per year by 2020, at current traffic levels.

This effort aims to bring the collaborative approaches of other joint industry-government efforts, such as FreedomCAR and the 21st Century Truck partnership, to the problem of increasing rail fuel efficiency. DOE plans to bring similar efforts to bear on improving locomotives. The Department of Transportation's Federal Railroad Administration will also be a major participant in this new effort, primarily by supporting research on railroad safety.

Like FreedomCAR and the 21st Century Truck program, a joint industry-government research effort devoted to locomotives and railroad technology could be a "win" for the public and a "win" for industry. Industry's expertise and in-kind contributions, coupled with federal funding and the resources of the DOE's national laboratories, could make for an efficient, effective program with measurable energy efficiency targets and realistic deployment schedules.

Although it may be possible for the railroad industry to benefit from developments in the trucking industry (which is faced with a faster schedule for emissions reductions on a g/bhp-h basis), railroads have unique characteristics that pose different challenges than those facing the trucking industry:

1. Locomotive engines have larger bores and lower speeds, which means that fuel-system modifications developed for trucks cannot be directly transferred to locomotives;

2. Engine cooling is more difficult; consequently, engine air temperatures (which affect NO_x formation) are much higher than ambient; and

3. Long expected life (40 years) requires substantial built-in durability and the need to retrofit the many locomotives in service.

Industry and government teams convened after the workshop to identify the current status of train and locomotive technology, identify advanced technologies and potential fuel savings, identify technical barriers, and propose R&D to overcome the barriers. Details are contained in this report.

On the basis of the research objective of improving total railroad average fuel efficiency by 50% by 2020, the government's portion of funding for locomotive and railroad R&D to achieve this is estimated to be about $20 million annually for about 14 years, to bring funding on a level consistent with that of heavy trucks.[3] Assuming that the goals are met and railroad average fuel efficiency increases by 50% in 2020 (savings begin in 2005) and remains constant thereafter, a total of 600 million barrels of oil will be saved between 2005 and 2030. On the basis of this assumption, about $0.46 of government funding is expended per barrel of oil saved. With an estimated average industry cost-share of 25%, total R&D funding is about $0.58 per barrel saved.[4] These estimates exclude effects from a shift of freight from trucks to rail, which would further increase energy efficiency and improve cost-effectiveness. Additional global benefits will accrue from the sales of (1) advanced locomotives and train systems overseas and (2) engines for marine applications. Potential research topics are shown in Table S.1.

TABLE S.1. Potential Research Topics

- Train Systems
    - Operations Optimization
    - Consist Management
    - Aerodynamics
    - Wheel/Rail Friction
    - Rolling Resistance
- Locomotive Systems
    - Idle Reduction
    - Energy Recovery
    - Motors and Drives
- Locomotive Engines
    - High-Efficiency Turbo
    - Sensors and Controls
    - Fuel Injection/Combustion
    - NO_x Adsorber
    - PM Trap
- Advanced Powerplants and Fuels
    - HCCI
    - Alternative Fuels
    - Fuel Cells

Locomotive manufacturers and operating railroads would be required to make substantial investments to match the DOE funding and to implement the new technologies. Some financial stimulation by DOE is important because the primary beneficiaries of the savings are the general public and because many of the technical risks are high. An industry cost share of 25–50% would probably be required, depending on technical risk. Research priorities will be determined through ongoing peer-reviewed systems analysis of locomotive and train technologies and through industry response to DOE solicitations for financial assistance.

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[3] The DOE R&D budget in fiscal year 2002 to improve heavy truck fuel efficiency is $88 million. Assuming this funding continues until 2010, and considering past funding starting in 1996 on heavy trucks, a total of $1.1 billion will have been spent by the government. According to DOE, cumulative energy savings from heavy truck advanced technology will be 2,384 million barrels by 2030. (Source: http://www.ott.doe.gov/facts/pdfs/facts_quality_metrics_). Applying this cost-benefit to railroads, total R&D funding needed would be $280 million over about 14 years, or an average of about $20 million each year.

[4] Costs exclude capital equipment, infrastructure costs, and production costs needed to implement the technology.

1 INTRODUCTION

Railroads are important to the U.S. economy. They transport freight efficiently, requiring less energy and emitting fewer pollutants than other modes of surface transportation. While the railroad industry has steadily improved its fuel efficiency — by 16% over the last decade — more can, and needs to, be done.

The ability of locomotive manufacturers to conduct research into fuel efficiency and emissions reduction is limited by the small number of locomotives manufactured annually. Each year for the last five years, the two North American locomotive manufacturers — General Electric Transportation Systems and the Electro-Motive Division of General Motors — have together sold about 800 locomotives in the United States. With such a small number of units over which research costs can be spread, outside help is needed to investigate all possible ways to reduce fuel usage and emissions.

Because fuel costs represent a significant portion of the total operating costs of a railroad, fuel efficiency has always been an important factor in the design of locomotives and in the operations of a railroad. However, fuel efficiency has recently become even more critical with the introduction of strict emission standards by the U.S. Environmental Protection Agency, to be implemented in stages (Tiers 0, 1, and 2) between 2000 and 2005. Some of the technologies that could be employed to meet the emission standards may negatively affect fuel economy — by as much as 10–15% when emissions are reduced to Tier 1 levels. Lowering fuel economy by that magnitude would have a serious impact on the cost to the consumer of goods shipped by rail, on the competitiveness of the railroad industry, and on this country's dependence on foreign oil.

Clearly, a joint government/industry R&D program is needed to help catalyze the development of advanced technologies that will substantially reduce locomotive engine emissions while also improving train system energy efficiency.

DOE convened an industry-government workshop in January 2001 to gauge industry interest. As a result, the railroads, their suppliers, and the federal government[5] have embarked on a cooperative effort to further improve railroad fuel efficiency — by 25% between now and 2010 and by 50% by 2020, on an equivalent gallon per revenue ton-mile basis, while meeting emission standards, all in a cost-effective, safe manner.

This effort aims to bring the collaborative approaches of other joint industry-government efforts, such as FreedomCAR and the 21st Century Truck partnership, to the problem of increasing rail fuel efficiency. Under these other programs, DOE's Office of FreedomCAR and Vehicle Technologies has supported research on technologies to reduce fuel use and air emissions by light- and heavy-duty vehicles. DOE plans to bring similar efforts to bear on improving locomotives. The Department of Transportation's Federal Railroad Administration

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[5] Contributors to the draft roadmap are listed in the Appendix.

will also be a major participant in this new effort, primarily by supporting research on railroad safety.

Like FreedomCAR and the 21st Century Truck program, a joint industry-government research effort devoted to locomotives and railroad technology could be a “win” for the public and a “win” for industry. Industry’s expertise and in-kind contributions, coupled with federal funding and the resources of the DOE’s national laboratories, could make for an efficient, effective program with measurable energy efficiency targets and realistic deployment schedules.

This document provides the necessary background for developing such a program. Potential R&D pathways to greatly improve the efficiency of freight transportation by rail, while meeting future emission standards in a cost-effective, safe manner, were developed jointly by an industry-government team as a result of DOE’s January 2001 Workshop on Locomotive Emissions and System Efficiency and are presented here. The status of technology, technical targets, barriers, and technical approaches for engine, locomotive, rail systems, and advanced power plants and fuels are presented.

2 BACKGROUND

U.S. railroads spend over $2 billion per year, or approximately 7% of their total operating expenses, on diesel fuel (AAR 2002).[6] New emission standards — to be implemented in stages between 2000 and 2005 — may reduce the fuel efficiency of new locomotives by as much as 10–15%. With the potential to substantially increase operating costs and further erode already tight net operating income, meeting those standards could become a major obstacle to the economic health of the industry.

2.1 FREIGHT TRANSPORTATION AND THE ECONOMY

The U.S. economy is heavily dependent on the efficient and economical movement of people and goods over a network of transportation systems. Those systems evolved over decades in response to our pattern of economic development and the need to move passengers and goods over relatively long distances. Waterways were the first mode to be used for transportation, but the locations of rivers and canals and their lack of year-round availability limited their use. Railroads solved that problem and were instrumental in linking vast areas of the country. During the early part of the twentieth century, railroads became the dominant transport mode, carrying most of our passenger and goods traffic. Once the interstate highway system and a ubiquitous highway network were developed, however, trucks began to carry more traffic. Trucks could provide timely door-to-door service, an advantage that railroads have only recently begun to challenge. Rail's share of ton-miles of travel (TMT) declined to a low of 35.2% in the late 1970s, as shown in Figure 1. Since 1978, however, railroads have regained some of that share and now carry over 40% of all TMT (Wilson 1997; AAR 2002). The deregulation of freight carriers in the early 1980s played a key role in this railroad revival.

Today, over 3.5 trillion ton-miles of freight are transported each year by five modes: rail, truck, water, pipeline, and air (AAR 2002; EIA 2002). Ton-miles have been growing steadily, although at a rate slower than gross domestic product (GDP) over the last two decades. This effect is due to relatively faster growth in services and such high-value low-density sectors as computer software, electronics, and telecommunications, which generate few ton-miles. Growth trends for GDP and TMT are shown in Figure 2. Excluding the early 1980s when fuel price increases, recession, and deregulation combined to change the historic relationship, TMT generally tracks GDP growth.

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[6] The fuel share is computed as the ratio of total diesel fuel expenses to total expenses and taxes (i.e., excluding net operating income) for Class I railroads, as reported in AAR's *Railroad Facts* (AAR 2002).

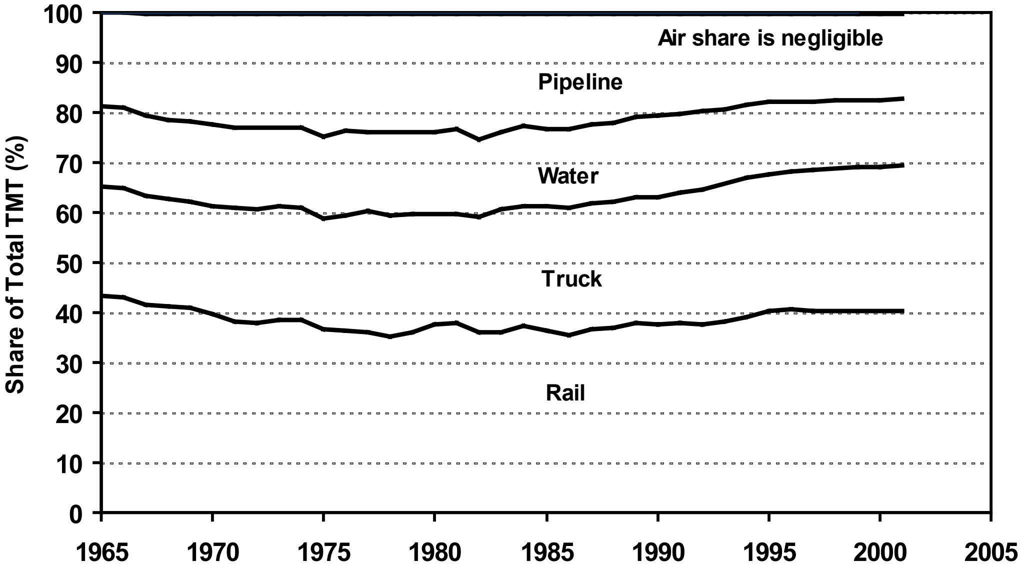

FIGURE 1 Share of Total Ton-Miles of Travel (TMT) by Mode, 1965–2001 (Wilson 1997, AAR 2002)

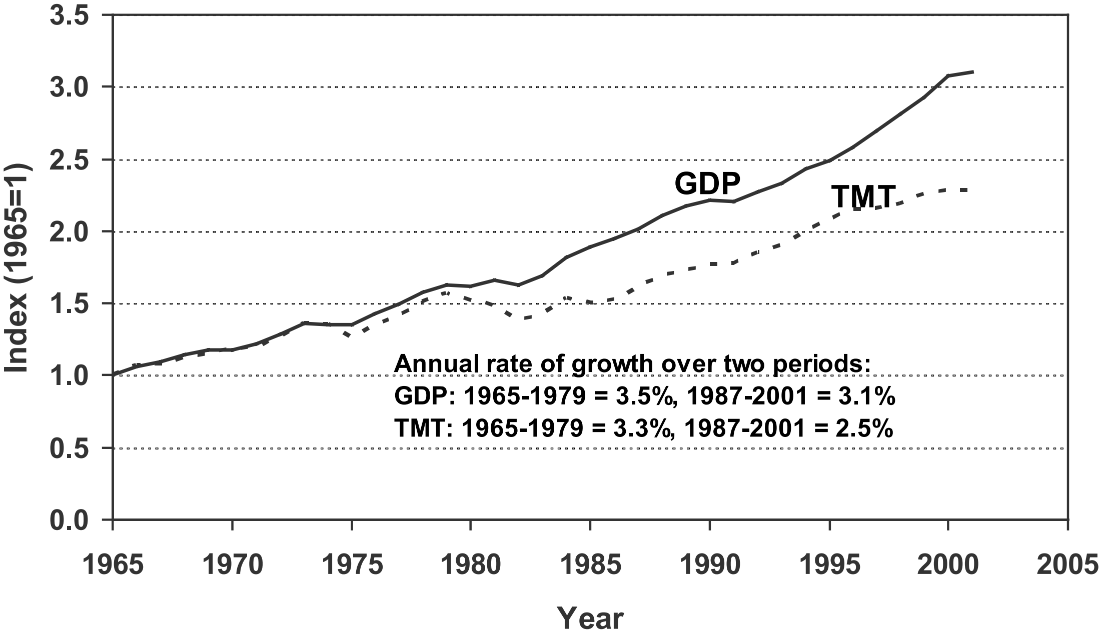

FIGURE 2 Trends in Gross Domestic Product (GDP) and Total Ton-Miles of Travel (TMT) by All Modes, 1965–2001 (AAR 2002)

2.2 RAILROADS AND NATIONAL SECURITY

Railroads are also important for our national security. America's armed forces have relied on the ability of commercial rail carriers to meet many of their U.S. landside logistics needs to support the overseas deployment of personnel and materiel. According to the U.S. Transportation Command, meeting those needs may become increasingly difficult because rail-system carrying capacity and motive power availability are limited. In the past two decades, the rail infrastructure has shrunk and excess capacity has been eliminated as carriers have consolidated operations and cut costs. When international crises that require U.S. military response arise, this leaner capacity may limit railroads' ability to quickly move troops and equipment to ports and airlift sites; modern locomotive technologies and advanced rail system operating capabilities will be essential to successfully undertake these missions.

2.3 RAILROAD ENERGY USE

In 2001, Class 1 freight railroads consumed over 3.7 billion gallons of diesel fuel (AAR 2002). Factoring in consumption by the other freight railroads and Amtrak increases this figure to over 4.1 billion gallons, or $2.2 billion spent on diesel fuel.

In terms of energy efficiency, these are dollars well spent. An important measure of rail energy efficiency is revenue ton-miles per gallon of fuel consumed. A revenue ton-mile is one ton of a customer's goods moved one mile. Simply stated, it measures the amount of real work that freight railroads do for their customers for every gallon of fuel used. (Passenger railroads use passenger-miles per gallon for a similar measure.) As shown in Figure 3, America's railroads have dramatically increased the number of ton-miles delivered per gallon — from 235 in 1980, to 332 in 1990, and then to 403 in 2001, which is an increase of over 71% (AAR 2002). Corresponding to a cut of over 40% in gallons of fuel consumed per ton-mile, this achievement was due to the combined effect of many technological advances and improvements in dispatching and operations, as well as to shifts in the mix of commodities transported and to longer shipment distances by dense commodities, like coal.[7]

For many years, restructuring and consolidation in the rail industry enabled railroads to reduce their fuel use, even as ton-miles traveled (TMT) grew. Thus, diesel fuel use by U.S. Class 1 railroads is no greater today than it was in 1965. However, the trend in diesel consumption, which had been declining steadily through the 1970s and 1980s, was reversed in the early 1990s and rose at an annual rate of over 2.5% in the last decade. Trends in rail TMT and fuel use are shown in Figures 3 and 4. Dividing the time period into two roughly 14-year periods, from 1965 to 1979 and from 1987 to 2001, rail TMT increased at annual rates of 1.9%

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[7] An estimated 43% of the gain came from the increased share of ton-miles represented by coal and other dense commodities (Vyas 2001).

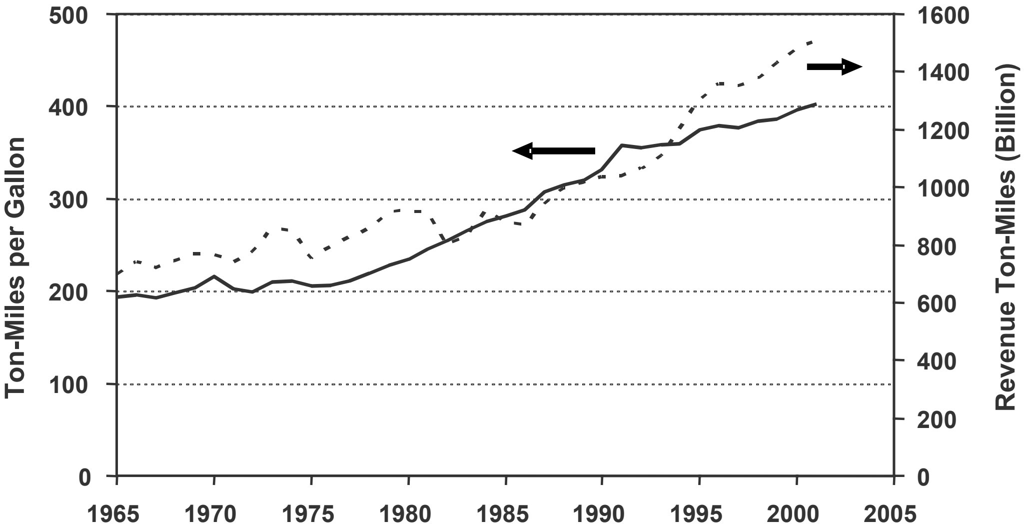

FIGURE 3 Rail Energy Efficiency and TMT, 1965–2001 (AAR 2002)

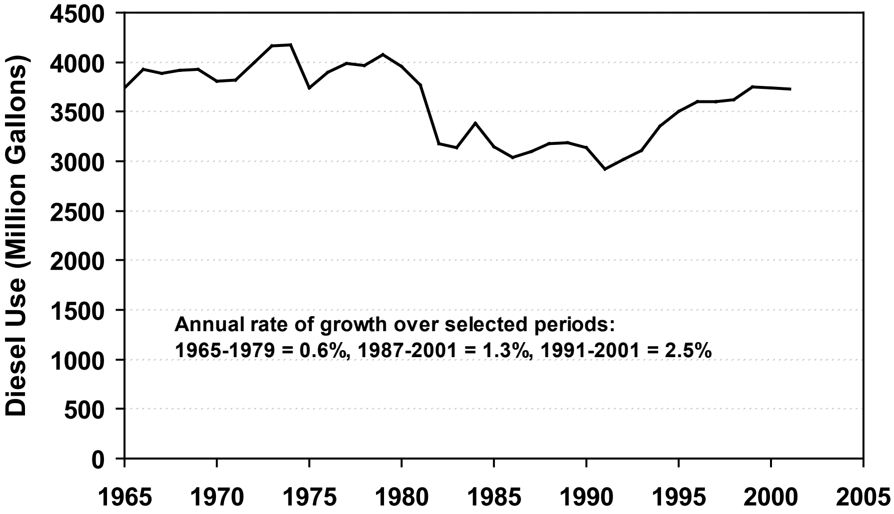

FIGURE 4 Diesel Fuel Consumed by U.S. Class 1 Railroads, 1965–2001 (AAR 2002)

and 3.8%, respectively. Through operations improvements and increased use of more energy-efficient equipment, railroads were able to limit annual growth in fuel use to 0.6% and 1.3% over the same two periods. In the past decade, however, the trend in railroad fuel use has come to more closely mirror growth in TMT. Absent changes in technologies and operating practices, or in the mix of rail freight traffic, this relationship may be expected to continue.

For the same commodity, transportation by rail is almost four times more fuel-efficient than transportation by truck, on a ton-mile basis (Stodolsky et al. 1998). Moreover, in spite of the relatively high emissions level on a per-gallon-of-fuel basis, on a ton-mile basis, NO_x and PM_{10} emissions from current-technology locomotives are almost one-half those from trucks — and could be reduced further if advanced emission-control technologies are implemented (Stodolsky et al. 1998).

2.4 EMISSIONS REGULATIONS

The approximately 4 billion gallons of diesel fuel that is used by locomotives each year is about 10% of the total diesel fuel used in transportation and 2.3% percent of all the fuel used in transportation (Davis 1997). That is less than 1% of the total U.S. energy use, but locomotives currently emit over one million tons of NO_x each year, which is about 5% of total NO_x emitted by all sources (Orehowsky 2001). Consequently, in 1998, the U.S. Environmental Protection Agency established emission standards that apply to all new and remanufactured locomotives as of January 1, 2000. The primary focus of the rulemaking is reduction of NO_x emissions (expected to be about 40% by 2010). Reduction of hydrocarbon (HC) emissions and particulate matter (PM) is a secondary focus. The acceptable levels of emissions are shown in Figure 5. Tier 0 applies to locomotives manufactured between 1973 and 2001, when they are rebuilt, Tier 1 to locomotives manufactured between 2002 and 2004, and Tier 2 to locomotives manufactured in 2005 and beyond. Separate standards were established for a high-power duty cycle based upon typical line-haul operation and a low-power duty cycle based upon typical switch operation.

Participants in the workshop indicated that Tier 0 limits could be achieved primarily through additional charge-air cooling, retarded injection timing, and retrofit of improved-design

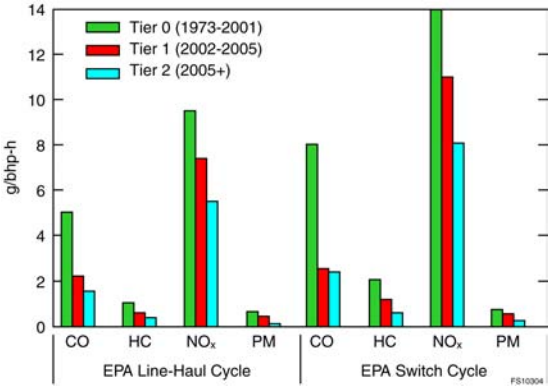

FIGURE 5 EPA Locomotive Emission Regulations

injection nozzles at locomotive servicing, and that the technology to achieve these limits is currently available and has actually been in use since about 1994. Engine rebuild kits intended to meet Tier 0 standards have relied largely on injection timing delay to reduce in-cylinder temperature and, hence, NO_x formation. As new locomotives began entering the fleet in 2002, incremental control measures for Tier 1 standards included a mix of aftercooling, combustion-chamber redesign, and fuel-charge shaping. Achievement of all Tier 2 (2005 and later) standards for locomotives may require exhaust-gas recirculation (EGR), very low sulfur diesel fuels, and possibly aftertreatment devices (such as particulate traps and oxidation catalysts).

Unfortunately, most of the techniques for reducing NO_x also decrease the fuel efficiency of the engine and raise PM emissions. This decrease in fuel efficiency would have a serious negative effect on the financial stability of the railroads and, thus, provides an additional urgency to finding ways to improve fuel efficiency. As is shown in Figure 6, the decreases in fuel efficiency to achieve the Tier 1 limits are expected to be between 5 and 15% if EGR is not used. Cooled EGR may help recover some of the losses in engine efficiency and power density caused by retarded injection timing but may adversely affect engine durability. Furthermore, cooled EGR is difficult on a locomotive because of the lack of ram air.

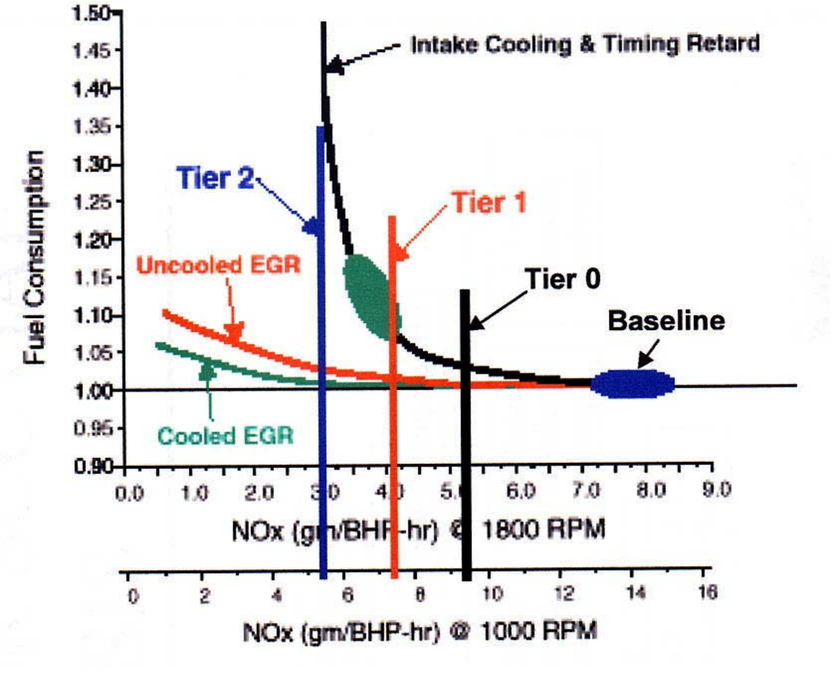

FIGURE 6 Fuel-Efficiency Penalties of Various Emission-Reduction Approaches (Flynn 2001)

3 APPROACHES

3.1 UNIQUE ASPECTS OF RAILROADS

Although it may be possible for the railroad industry to benefit from developments in the trucking industry, which is faced with a faster schedule for emissions reductions, railroads have unique characteristics that pose different challenges than those of the trucking industry.

- Trains have much less freedom in choice of speed because their schedules must be coordinated with those of many other trains on the same track. In addition, locomotives must be able to pass through long tunnels, limiting the size of mechanisms that can be attached to the exterior and producing special challenges with respect to thermal management.

- On-road trucks have large exposed radiators in the front, and with speeds usually maintained above 50 mph, ample air (ram air) is available for both engine and aftercooler cooling. In contrast, locomotives usually run in consists (i.e., groups) of two or more, often run in "reverse" or in the middle of the train, and spend most of their time at speeds below 45 mph. The radiators are mounted in the roof and cooling fans are required to remove engine heat. Air-to-air aftercooling is difficult; consequently, engine air temperatures (which affect NO_x formation) are much higher than ambient.

- Trains have less flexibility in operations because they cannot change their routes to go around a problem, and they may need to sit on a siding while another train passes.

- Locomotive engines, which have up to 6,000 horsepower, are, of course, much larger than truck engines. Their larger bores and lower speeds mean that fuel-system modifications developed for trucks cannot be directly transferred to locomotives, although many of the approaches (e.g., higher pressures, multiple injections, shaped injections) could be used in modified form. Also, locomotives have considerably less power per ton carried than do trucks.

- Truck engines are coupled directly to a mechanical transmission and are required to operate over the entire engine speed and load map, whereas locomotives employ a diesel-electric system and only eight specific power settings (notches). Notches correspond to eight set engine speeds.

- Locomotive engines are expected to last for at least 40 years, which places greater emphasis on durability. This low turnover rate also limits the penetration rate of new technologies; however, locomotives undergo many overhauls, providing opportunities for modifications throughout their lives.

- Diesel fuel for locomotives can contain 10 times more sulfur than diesel fuel for trucks contains. Sulfur contributes to formation of engine-out particulate matter, corrosive exhaust gases, and rapid poisoning of some aftertreatment devices.

- Whereas trucks are severely limited by weight and size, it is relatively easy to add another car, such as a fuel tender, to a train when more space is required for additional equipment. However, adding a car that does not carry freight can impact the productivity of the train.[8]

3.2 SYSTEM ANALYSIS

A structured analytical process is necessary to properly plan and implement a complex R&D undertaking. The process contains five major steps: (1) identify goals, objectives, milestones, and responsibilities; (2) analyze scope, technical measures, and necessary resources; (3) plan tasks, schedule, and available resources; (4) implement program, focusing on milestones; and (5) evaluate progress in a peer-review process (Hardy 2001).

Systems analysis is a key element; it falls under the second step. It is the comprehensive, integrated modeling and assessment of the vehicle platform and its components with respect to program objectives and performance requirements to help guide the R&D agenda. Appropriate models have been developed to assess locomotive and train performance and help guide R&D, but additional models are needed. Systems analysis helps technology decision-makers focus on the best technology options by enabling an objective evaluation of cost, benefit, and risk.

By using vehicle and component models, competing technologies and vehicle concepts can be compared against vehicle performance requirements and program goals. System analysis also provides focus and guidance to ensure that component technologies are developed from a common, vehicle-system perspective. The activities must be coordinated among DOE, industry, and other federal agencies and national laboratories to ensure the maximum payoff in technology advancement.

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[8] Replacing a freight car with a fuel tender on a 100-car train, for example, reduces revenue by 1%, which is not insignificant in view of the low profit margin of railroads.

4 OPPORTUNITIES FOR ENERGY SAVINGS IN LOCOMOTIVE DIESEL ENGINES

The engine system of choice for the locomotive has been the diesel combustion cycle (i.e., direct-injection compression-ignition) because of its high thermal efficiency, higher power delivery, reliability, and low life-cycle costs. The diesel engine is the most efficient transportation power plant available today. Thermal efficiency of locomotive diesel engines is 40% or higher, which results from high power density (via high turbocharger boost), high turbocharger efficiencies, direct fuel injection with electronic timing control, high compression ratio, and low thermal and mechanical losses. Many locomotive engines achieve the equivalent of one million miles before overhaul (36,000 megawatt-hours).

Significant research effort has enabled diesel engines to reach today's fuel efficiency levels. Developments such as advanced materials (e.g., thermal barrier coatings, titanium), new enabling technologies, advanced combustion concepts (e.g., homogenous-charge compression ignition, cooled exhaust-gas recirculation), and advanced analytical tools for optimization have contributed to, or are likely to contribute to, the gains in efficiency. A focused research and development program could enable the locomotive diesel engine to achieve thermal efficiencies of 50–55%, resulting in a reduction in specific fuel consumption of about 20%.

Since a trade-off exists between NO_x emission and fuel consumption, the new emissions requirements (see Figure 5) impose a difficult challenge on the diesel engine designer. Given the 2007 U.S. Environmental Protection Agency's ruling for heavy-duty trucks (0.2 g/bhp-h NO_x and 0.01 g/bhp-h PM), it is likely that future locomotive standards will be even lower. Future technologies that meet emission standards and maintain high efficiency are likely to rely on an integrated approach of in-cylinder combustion control and exhaust treatment (aftertreatment) technologies.

Meeting the technical targets for high efficiency and simultaneously reduced emissions will require advances in four areas: in-cylinder combustion and emission control, aftertreatment, thermal (exhaust gas) management, and sensors and controls.

4.1 FUEL INJECTION/COMBUSTION AND IN-CYLINDER CONTROLS

Experience has shown that adjusting in-cylinder conditions to control fuel/air mix and combustion has allowed significant improvements in emissions while maintaining high efficiency. The transient interaction of fuel-jet and in-cylinder flow field and subsequent combustion is complex and depends on many factors. As the processes of diesel combustion and emissions formation are better understood, alternative and superior locomotive engine combustion systems may be designed.

Emission standards have been met thus far in new engines by improvements in injection rate control with electronic fuel injectors, higher injection pressures, lower charge air temperatures, and turbocharger improvements. Engine rebuild kits intended to meet Tier 0 standards have relied largely on injection timing delay to reduce in-cylinder temperature and, hence, NO_x formation. However, timing delays result in decreased engine efficiency. In-cylinder controls that reduce NO_x also tend to increase PM production. Future low NO_x emission standards are likely to require more significant changes, including an injection system, exhaust-gas recirculation, and/or aftertreatment.

Technical Barriers. While a large amount of research into combustion and fuel-injection technology has been conducted for relatively small-bore, high-speed truck engines, those results are not directly applicable to the large-bore, medium-speed locomotive engines.

The key barrier to achieving the technical targets for locomotive engines is maintaining high engine efficiency while simultaneously reducing NO_x emissions and avoiding the NO_x/PM trade-off that has traditionally limited diesel engine-out exhaust emissions.

Suggested R&D. Research into the following topics will be important for achieving the desired objectives:

- *Fuel-injection technology.* Improve fuel injection technology by:
  - Optimizing electronic control of injection timing, injection rate, and fuel pressure. Speed and load changes require different injector operating conditions for optimal performance.
  - Developing variable orifice diameters, smaller orifice diameters, multiple orifice sizes, and multiple injectors in a single cylinder. The large orifice diameters required to supply sufficient fuel at high-load conditions (Notch 8) may not be optimal at other conditions.
- *Combustion-chamber geometry.* Optimize combustion-chamber geometry and flow field.
- *Exhaust-gas recirculation (EGR).* Optimize cooled EGR for maximum NO_x reduction without PM increase. The pumping work required to cool, filter, and mix EGR with inlet air should be considered because typical locomotive high-load operation results in high inlet pressures, making EGR addition difficult. Durability should be addressed through improvements in materials or reduction in fuel sulfur level because of the corrosive effect of sulfur-containing exhaust.
- *Advanced combustion strategies.* Pursue advanced technologies that allow mixed combustion strategies, such as variable valve timing and homogeneous-charge compression ignition (HCCI).
- *Advanced numerical codes.* Further develop state-of-the-art, in-cylinder computational fluid dynamics code (i.e., KIVA) capabilities for advanced combustion concepts such as high-pressure injection, EGR, HCCI, stratified

charge compression ignition (SCCI), and water addition. Advanced numerical models are needed that accurately represent these processes.

- *Alternative fuels.* Explore the effects on combustion and emissions processes of alternative fuels, such as natural gas, oxygenates, water emulsion (or addition), or low-sulfur fuels.

- *Rebuild kits.* Investigate improved in-cylinder combustion and emission-control technologies for engine-rebuild applications.

- *Thermal-barrier coatings.* Reduce heat losses to cylinder walls, thus improving in-cylinder combustion efficiency and increasing the energy transfer to the turbocharging and turbocompounding systems.

- *Optical engine.* Develop an optically accessible large-bore, medium-speed diesel engine for investigation of in-cylinder processes with advanced optical diagnostics.

- *Optical constant-volume combustion vessel.* Develop an advanced facility to provide detailed spray and combustion diagnostics for inputs to computer codes and for basic understanding.

4.2 AFTERTREATMENT

Exhaust treatment emission control devices for NO_x and PM reduction have not been demonstrated or implemented in locomotive engine applications, but they may be necessary to meet future emission regulations. The highly effective three-way catalysts used in gasoline engines are not applicable to diesel or other lean-burn engines, and so other approaches are required. NO_x control technologies (such as selective catalytic reduction using ammonia or urea) have been used for years in stationary diesels. Although not widely implemented in mobile applications, NO_x control efficiency has been recorded at 80–90% in heavy-duty truck experiments; however, lower efficiencies are experienced during transient or low-temperature operation (Johnson 2000).

Alternatively, NO_x adsorber catalysts, consisting of a NO_x adsorbent and a precious metal catalyst, have recently proven effective in NO_x aftertreatment. Periodically, the exhaust stream is depleted of oxygen, and NO_x stored by the adsorbent is reduced by fuel-rich components (CO and HC) in the presence of the catalysts. The NO_x adsorber-catalyst becomes ineffective in the presence of sulfur, requiring fuel sulfur of 5 ppm or less and very low lubricating oil consumption (because the sulfur in the oil can also hinder performance). In initial tests with low-sulfur fuel, 90% NO_x reduction has been achieved (DECSE 1999); however, the durability of the adsorber is not known, nor is its effectiveness for typical locomotive operating cycles.

Control technologies for PM have progressed in recent years, to the point of limited commercial application in heavy-duty trucks. Catalyzed diesel particulate filters trap PM on ceramic filter elements and regenerate with a catalytic coating on the element. Engines operated on low-sulfur fuel can achieve PM reductions well over 90%. The filter technology has demonstrated impressive durability (Warren et al. 2000). The need for regeneration and added pressure loss of aftertreatment devices is expected to reduce fuel efficiency by at least 5% (21st Century Truck 2000).

The railroad industry probably will be able to meet its near-term emissions regulations without resorting to aftertreatment devices, whereas the trucking industry will require the devices sooner and is therefore conducting an intensive R&D program. Although the unique characteristics of locomotives may prevent direct transfer of the technologies developed for trucks, much can be learned from that industry. The most cost-effective strategy probably would be to delay research in this area for 5−10 years.

Potential for Fuel Savings. Adding aftertreatment devices will have a negative effect on fuel economy, but developing more efficient devices could reduce the magnitude of that effect.

Technical Barriers. In addition to the host of barriers faced by the trucking industry, the railroad industry will need solutions tailored to its durability requirements, its space and size limitations, and the higher levels of sulfur in locomotive fuel, which can rapidly poison aftertreatment catalysts.

Suggested R&D. Development of aftertreatment devices will require basic research in addition to an unprecedented level of engine and aftertreatment integration.

- *Database.* Generate a shared database of operating regimes and exhaust conditions to promote collaboration and development of locomotive engine-sized aftertreatment devices.

- *Simulation capability.* Improve simulation capability of aftertreatment devices to optimize designs for locomotive applications.

- *Cost analysis.* Develop sufficient knowledge of the total system performance to determine the impacts of aftertreatment on overall system efficiency and cost.

- *Packaging.* Develop methods for packaging the aftertreatment device and reductant storage.

- *Temperature control.* Study parameters that can be manipulated to control the temperature and composition of the exhaust and aftertreatment device temperature, while recognizing interactions with turbocompounding devices.

- *Urea supply.* Develop suitable technologies and procedures for supplying urea to a selective catalytic reduction system. Research (1) the advantages and disadvantages of urea-selective catalytic reduction infrastructure and storage vs. the impact of ultra-low sulfur fuels that would be required for NO_x

adsorbers or (2) the use of SO_x (oxides of sulfur) traps or other onboard sulfur removal techniques in conjunction with NO_x adsorbers.

- *Retrofit applications.* Include features to make the aftertreatment devices suitable in retrofit applications on existing locomotives.

4.3 EXHAUST GAS UTILIZATION

Utilization of the “waste” energy contained in the locomotive diesel engine exhaust stream has the potential for improving system efficiency. Research is required to find and exploit opportunities to recover this energy in a cost-effective manner. Unlike for stationary generation applications, optimal thermal management is necessary over a wider range of operating conditions. Turbine-based machines offer the best opportunity for efficient utilization of exhaust gas.

Technical Barriers. The main barriers to the development of a higher-efficiency turbine-based machines are related to cost-effectiveness and integration with other locomotive systems.

Suggested R&D. These topics show promise for significant improvements in fuel efficiency:

- *Turbocharging.* Develop turbocharging technologies with optimum performance over a wide range of operating conditions, possibly using variable geometry or other technologies.

- *Turbocompounding*. Develop and optimize turbocompounding capability. The locomotive has an inherent advantage over trucks in implementing a turbocompounding scheme, because the “electric” system is already in place. Integration of the system with other design constraints, such as the exhaust temperature required for aftertreatment and EGR intercooling, will also need to be considered.

- *Intercooling.* Devise strategies for cooling intake and EGR and turbocharger that minimize heat load on the rest of the cooling system and optimize efficiency. This item deserves special attention because air-to-air aftercooling schemes, which can be implemented in trucks, are much more difficult in locomotive engines.

4.4 SENSORS AND CONTROLS

Future improvements in the locomotive engine’s efficiency and emissions reduction rely on accurate monitoring and control of the entire system. The development of hardened sensors and rugged computer systems will be essential to the management of these systems.

Potential for Fuel Savings. Significant improvements before 2010 are not likely because of the expected duration of the research and the time required to develop and implement the processes (e.g., exhaust aftertreatment and in-cylinder combustion control) for which the sensors will be needed.

Technical Barrier. The primary technical barrier is related to the durability that is required for the severe locomotive environment.

Suggested R&D. The following subjects merit research:

- *Durability*. Improve the durability of all sensors used in locomotive applications. Locomotives are subject to variable and harsh operating conditions that require significant improvements in sensor durability.

- *Emissions sensors*. Develop NO_x and PM sensors together with closed-loop emission control systems. The ability to sense NO_x and PM emissions will allow needed combustion (in-cylinder) and aftertreatment device control.

- *Adaptive control*. Develop fast-response sensors and individual-cylinder sensors to monitor and control performance of individual cylinders as well as the entire system. Adaptive control would allow variations in the performance of an individual cylinder to be known and corrected and to make adjustments as the engine wears or as operating conditions change.

- *Systems control*. Develop control strategies and hardware that allow efficient combustion and aftertreatment management over all speeds and loads.

- *Integration*. Integrate in-cylinder combustion control and aftertreatment devices.

5 OPPORTUNITIES FOR ENERGY SAVINGS IN LOCOMOTIVE SYSTEMS

5.1 IDLE REDUCTION

Locomotive engines are idled because heating is required to keep the engine coolant from freezing (locomotive cooling water contains no antifreeze, so the engine must be drained of coolant if the cooling-water temperature approaches freezing). Idling also supplies hotel loads because the crew must remain in the cab while cars are changed or while the train waits on sidings for other trains to pass and to keep the water in the toilets from freezing. The impacts from locomotive idling are significant, both in terms of energy use and emissions and in terms of dollars.

For a switcher locomotive that idles 75% of the time (Association of American Railroads switcher duty cycle), 27% of the fuel is consumed and 25% of the NO_x emissions are produced at idle. An idling locomotive consumes 3.5–5 gallons of fuel per hour. Actual fuel consumption might be higher because locomotives are occasionally idled in Notch 3 (using more fuel) in cold weather. The same argument can be made for road locomotives, even though they spend less time at idle than switchers do. The fuel savings for road locomotives in an idle reduction program would also be significant.

An idling locomotive consumes up to 10% as much oil as it does diesel fuel, and much of this oil is burned or emitted unburned. In addition, idling the engine causes wear and tear, which reduces the time until overhaul. Idling locomotive engines sometimes result in noise complaints from the public.

Two approaches to idle reduction are starting to gain acceptance by the industry: automatic start/stop systems and auxiliary power units (APUs). Both major U.S. locomotive manufacturers can supply new locomotives with systems that automatically turn the engine of a stationary locomotive on or off depending on the temperature and the state of charge of the batteries. One operating railroad has installed APUs — 50-horsepower diesel engines — in about 800 of its locomotives to supply electricity and heat in this way rather than by idling the prime mover; the company has committed to installing APUs on 3,600 locomotives over the next four years. Data are being collected on the costs and amount of fuel savings.

Other options that could be or have been borrowed from the trucking industry include direct-fired heaters and wayside power.

Potential for Fuel Savings. Considering the high percentage of time that locomotives spend idling, it would not be unreasonable to expect idle-reduction technologies to be able to reduce fuel consumption by at least 10% in the long term. A conservative estimate based on a detailed analysis of the Class I locomotive fleet showed potential savings of 230 million gallons per year, or 6.3% of Class I fuel use (Hewson 2001).

Technical Barriers. Some locomotive designs may have space limitations that would make it difficult to fit an APU. Also, any device added to a locomotive must be durable enough to withstand the shocks and vibrations that will be encountered.

Suggested R&D. Technologies for idle reduction are fairly well developed. Probably the most useful research would be to collect data to document the costs and fuel savings for various types of service. Advanced sensors and control algorithms could also be beneficial. It would also be useful to determine actual engine wear due to idling.

5.2 ENERGY RECOVERY

While the locomotive traction horsepower and downhill grades supply all the energy to move a train, a significant amount of that energy is dissipated by braking action. Braking is necessary to reduce speed and to keep the train from exceeding speed limits on downgrades. All rail cars and locomotives have air brakes; in addition, diesel-electric locomotives usually also have the capability for *dynamic braking* (DB), where the traction motors retard the train by running as generators, producing excess electrical power that is dissipated in the locomotive as heat in the resistance grids. Recovery of this DB electrical energy to do useful work would provide considerable benefits. When DB energy is recovered and utilized, it reduces net energy required from the diesel prime mover, thereby reducing fuel usage and emissions.

Both AC and DC locomotives have DB capability and reject the recovered energy in the braking resistance grids. A small portion of that energy is used in fans to cool the braking grids, but no other use is made of the energy.

A useful measure of the potential savings is the percentage of the train's kinetic energy that is dissipated as heat in the dynamic brake resistance grids. This percentage varies considerably with train and route characteristics. For freight operations, a slow (15 mph) train traversing a mountainous route showed a 64% braking energy ratio, and a fast (60 mph) train on a flat route showed a braking energy ratio below 10% (Addie and Concannon 1978). For passenger and commuter operations on generally flat routes, the braking energy ratio ranged from 8 to 60%, depending on the average speed and the frequency of stops.

The instantaneous power level of DB is relatively high, so the DB energy cannot be effectively used by the locomotive at the time it is generated. For a significant portion of the recovered DB energy to be utilized, it must be either stored during braking for later use over the route or sent off the locomotive for use elsewhere. An electric locomotive can regenerate DB energy back into the third rail or catenary, but this option is not available for the diesel-electric locomotive.

The primary hurdle to the recovery of DB energy is the lack of a suitable way to store the energy until it is needed. Significant advances are being made in energy-storage technology for road transportation. Many candidate energy-storage technologies for these applications are also relevant to DB energy recovery, including electrochemical batteries (electrochemical storage), superconducting magnetic energy storage, flywheels (rotating energy storage), capacitors (electrostatic storage), regenerative fuel cells (electrochemical storage), and compressed gas (see Balachandra et al. 2000 and INTELEC 1998). However, since the electric traction motors generate electricity during braking and the diesel engine generator set also generates electricity, some type of electrical energy storage is preferred.

Key technical parameters for DB energy storage need to be quantified. They include:

- Volumetric-specific energy density (kilowatt-hour per liter) and mass-specific energy density (kilowatt-hour per kilogram),
- Charging and discharging volumetric specific power densities (kilowatt per liter), and
- Mass-specific power densities (kilowatt per kilogram).

Just as important are:

- Round-trip energy-storage efficiency (from locomotive system to storage medium and back to locomotive system),
- Energy-storage cycle life, and
- Ability to accept power at extremely high rates.

The energy-storage system must perform its function while installed on the locomotive system and subject to the environmental variations experienced by the locomotive.

Electrochemical batteries. Electrochemical storage batteries are the predominant form of energy storage for the few automotive hybrid and pure electric vehicles on the market. Battery technologies include lead acid, nickel-cadmium, nickel-metal hydride, lithium ion, and lithium polymer. Lead acid batteries are relatively inexpensive and have high energy density but are quite heavy and have low power density and short calendar and cycle life. They have been demonstrated in hybrid bus applications. Two production hybrid automobiles (Toyota Prius and Honda Insight) use nickel-metal hydride batteries, which are lighter than lead acid but are very expensive, run hot, and require cooling. Lithium ion batteries are used extensively in computers but need more development before they find large-scale use in hybrid propulsion systems. Lithium polymer batteries are very light and offer the prospect of high power and energy densities, but they are extremely expensive and must be developed to reduce their cost before they can be considered as candidates for hybrid propulsion systems. The ability of all these battery types to withstand the high vibration and shock levels of a locomotive must be demonstrated.

Ultracapacitors. Ultracapacitors are very-high-capacitance devices that store electrical energy in the form of an electrostatic charge between two electrodes. They may be a good choice for the recovery of braking energy because they have the potential for higher specific power density and much longer cycling life than batteries. On the other hand, ultracapacitors have lower specific energy density than batteries. Ultracapacitors may play a role in a combined storage system with electrochemical batteries.

Electric flywheels. Electric flywheels use an electric motor/generator to (1) spin up the flywheel to store energy during braking or when excess power is available and (2) decelerate the flywheel to recover energy for propulsion. Depending on motor size, electric flywheels are capable of very high power operation, which is advantageous for regenerative braking; however, today's flywheel systems have only moderate energy density. The very high rotational speed of the rotor requires a high-performance bearing and appropriate containment. The tolerance of this bearing to high vibration and shock levels must be demonstrated, along with the gyroscopic effect of the flywheel in a locomotive environment.

Technical Barriers. The main technical barrier to recovering DB energy is the lack of an affordable storage device with sufficient energy density and a high rate of energy storage. Although energy-storage technologies in stationary and road-vehicle applications have met with some success, the lack of on-the-rails experience is a major barrier to developing manufacturer and railroad user credibility and confidence in the applicability, robustness, benefits, safety, reliability, and lifespan of DB energy-recovery technology. The cost of DB energy-recovery technology also is expected to be a barrier to its application. Electric flywheels have a unique technical barrier in that their motor/generator is a variable-frequency machine. To overcome this barrier, power electronics capable of efficient conversion of variable-frequency AC to DC to fixed-frequency AC will be required.

Potential for Fuel Savings. The potential fuel savings from DB energy recovery are tremendous if a suitable storage technology can be developed.

Suggested R&D. It must be recognized that other energy-storage applications (highway vehicles, power quality) will serve broader markets than the freight locomotive and railroad market — and so will drive energy-storage technology R&D and commercialization. These applications are rapidly maturing in the 2001–2010 time frame, and the time is now ripe for studying DB energy recovery. Therefore, railroad-specific R&D should target adaptation to railroad requirements of energy-storage technologies that are under development or have been developed for highway vehicles.

Evaluation of the hardware of energy-storage technologies under railroad transportation conditions, underpinned by an analysis of fuel benefit vs. energy-storage-system sizing parameters, is required to select the appropriate energy-storage technology. Such a combined program will yield insights into the adaptation of this technology to DB energy recovery and identify energy-storage-technology performance gaps and the engineering requirements to qualify the technology for railroad application.

The results of the subscale evaluation should drive the enhancement of energy-storage and storage-system technology features to meet identified railroad application performance gaps. With these enhanced technology features in hand, a full locomotive-scale field demonstration of DB energy recovery should be carried out with the participation of an end user, with accurate evaluation of the user costs and benefits. The results of this full-scale field demonstration will unequivocally establish the benefits of DB energy recovery and set the stage for its commercialization.

Safety of energy storage devices needs to be addressed in a comprehensive R&D program. Batteries will store electricity at about 1,000 volts, and flywheels will spin at high speeds. In maintenance and accident situations, the stored energy must be dissipated without endangering railroad personnel or the public.

To maximize the efficiency of the locomotive system, an optimized energy-management and control strategy will be required. The control strategy must recognize the selected mode and be flexible enough to maintain optimized operation. Some of the variables that must be considered are train type (passenger, freight, switching), loading, route, energy-management mode (e.g., regenerative braking or consist management), and energy-storage medium (battery, ultracapacitor, flywheel, or combination). Electronic control hardware that is rugged enough for locomotive use is readily available. Control strategies, however, must be developed to deal with this new technology.

5.3 MOTORS AND DRIVES

Locomotive traction motors are very reliable and effective and are based on mature DC and AC electric-motor technologies. Finding an electric drive mechanism that can handle the tremendous power demanded by trains has always been a design challenge. Any improvement to the efficiency of traction motor operation will need to be weighed against the demands of the operational environment. The optimization of price vs. performance is highly competitive, and specific design details are proprietary.

Traction motors are rebuilt typically upon failure. Rebuilt motors must not lose efficiency, and if possible, should be retrofit with improvements. However, the traction motor rebuild process introduces large variability into the efficiency values of the rebuilt motors, which can have a big effect on performance. A small drop in efficiency can produce a large increase in heat generated and cause the motor to burn out early.

Technical Barriers. The main technical barrier to improving the consistency of the rebuild process is a lack of understanding of the causes of variability.

Suggested R&D. Research into the causes of inconsistency in the rebuild process would help to identify ways to improve it.

6 OPPORTUNITIES FOR ENERGY SAVINGS IN TRAIN SYSTEMS

6.1 OPERATIONS OPTIMIZATION

Safe and efficient train operation relies on the combined skills of the dispatcher and the on-board crew — the dispatcher to schedule a trip with a minimum of stops and the crew to follow the plan in as safe and fuel-efficient a fashion as possible. Engineers receive extensive education, including in-cab and hands-on computer simulation of train operation, to learn the many details of safe train handling with the diversity of power and loads required over varying terrain and track conditions.

Crews commonly work the same territory day-in and day-out, so that, even through trial and error, one might assume that low fuel consumption could be achieved. However, the workload involved in managing variable train makeup and loading, new and old locomotive consists, the constraints of schedule, opposing traffic on single-rail, dynamic slack handling, and dynamic changes in speed limits (slow orders) are impediments to knowing how to achieve the most fuel savings on a given day. Moreover, the fact that the engineer has very limited feedback about the time rate of fuel consumption or what is happening to the 150 or so trailing rail cars in the train makes paying attention to fuel use during a trip difficult. One consequence is that fuel usage on the same route can vary among crews by 12–20%, according to studies at Union Pacific and Burlington Northern Santa Fe railroads (Stehly 2001).

Experienced and motivated crews who repeatedly operate the same train equipment, such as a unit coal or grain train, can learn from experience how to save fuel. But all of the factors noted above, plus the mix of changing weather conditions, deteriorated track and locomotive condition, and the inevitable changes in schedule or speed restrictions, make it difficult for engineers to determine how to operate most efficiently. The challenge is to help engineers operate efficiently by integrating current information about the consist, load, track profile, operating constraints, and condition of the equipment to synthesize an optimal operating plan that they can adapt to the inevitable changes that occur en route.

Aside from the costs of excess fuel use from suboptimal operation, variability (inconsistency) in fuel use is a major problem. The average tank refuel quantity is typically 1,000–1,500 gallons, which is only 20–30% of capacity (interestingly, out-of-fuel locomotives are a frequent reason for in-route road failures). Variance in fuel use forces more frequent fuel stops. In addition to decreased asset utilization when time is spent refueling, the variability has the impact of increasing average fuel inventory in the locomotive fleet. By carrying around more fuel in inventory, carrying costs are increased, and energy is spent accelerating/decelerating the stored fuel.

A control system that employed innovative optimization, navigation, and estimation methods would enable train crews to operate as efficiently as consist, track, and traffic conditions allowed. Such a system would have the flexibility to achieve optimal performance on one trip by one train, or to trade off across the fleet to minimize total fuel used.

Potential for Fuel Savings. The development and full deployment of a fuel-optimal locomotive system control should ultimately increase fuel efficiency. The chances for some success in this area are high.

Technical Barriers. The main technical barriers to achieving fuel-optimal locomotive system control are related to the algorithms for modeling the system and the sensors for characterizing it. The most significant barriers include the following:

- *Complexity of models.* Optimization of a plan to minimize fuel use will be as good as the models on which the strategy is based. Large FORTRAN codes (such as TOES™/TEM™, which were developed for the Association of American Railroads) have been accurate predictors of train behavior, including fuel use, but they are proprietary and not generally available. Until recently they had been far too complex to run in real time, but that problem is being overcome. Tools are needed to provide models with varying levels of abstraction and detail, together with a means to identify and track changes in parameters used as input to these models.

- *Formulating and solving very large optimization problems.* Calculating efficient plans requires solving very large optimization problems with constraints on operating speeds, arrival times at meet-pass sidings, crew time-outs, train handling, weather-restricted adhesion, and other variables. Thousands of variables and constraints are not uncommon. Further, solutions must be repeated periodically to accommodate inevitable changes from breakdowns, late arrivals, trains added to schedules, and priority passenger traffic. Human interfaces to optimization tools must be highly automated and simplified for results to be reliable. Approaches that require system-wide, complex, and/or costly databases on fixed assets (track), power equipment, rolling stock, and communication infrastructure before any financial return can be achieved will not likely be accepted by the industry. Systems should be designed to derive benefits from the smallest practicable configuration, ideally a single locomotive consist. Failure to do this with incremental payback is a barrier to implementation and building acceptance in the conservative railroad culture.

- *Lack of common database standards among railroads.* Most traffic passes through multiple railroad territories, so optimizer systems that only work with one railroad's environment will be a barrier to acceptance. Optimizer solutions must either have the flexibility to work in the heterogeneous data world of the Class I railroads or be independent of them.

Suggested R&D. Optimizing locomotive fuel use requires development of methods and software tools to generate a consist-movement plan that produces speed, notch settings, and brake settings over time or milepost. The plan will depend upon train and power-consist makeup, constraints on arrival schedule, track conditions (slow orders, adhesion limits), locations of maintenance operations, opposing-traffic time windows, and track-geometry constraints (grade, single vs. double track, siding locations, and curvature).

The movement plan requires models describing behavior of the locomotive, train, and track as "inputs" to the optimization procedure, along with the specific trip and operating constraints that apply. Because of the large size and complexity of the optimization that might result in this formulation, it may be critical to look at multiple levels of abstraction to compute solutions. For example, one approach could take a less-detailed description over a very long time horizon without detailed train dynamics and constraints but include logistical variables, like crew placement and asset assignment. For the short time horizon, an optimization could be formulated that considers only the detailed notch and brake commands and operating-speed constraints. Adapting techniques like these, which are widely used in the communications networking field, would require significant innovation to develop reliable computer codes.

Two key types of models will be required as input to the optimization procedure.

- *System models for dynamic planning and train control.* Dynamically model train and rail systems to predict speed, acceleration fuel usage, and other parameters as functions of power notch and brake settings. Models must capture tractive effort produced, rate of fuel consumed, emissions produced by multiple locomotive consists, and the train reaction forces produced by gravity and wheel-rail reaction forces in cars, depending on train makeup, grade, and track conditions. Models must balance complexity in faithfully capturing behavior against the time required for the optimization.

- *Tools for estimating and tracking changes.* Develop methods to estimate values of, and track variations in, model parameters, including fuel-use characteristics of the multi-locomotive power consist, drag characteristics of the trailing load, and the effects of weather. A key challenge is determining which parameters are key to the performance of the planning algorithms. If new sensors are required, they must be justified by the derived benefit traded off against any decreased reliability of the system. Algorithms for performing the estimation/parameter identification could exploit classic "aerospace/industrial" model-based Kalman filter techniques, statistical methods, or even neural-networks. Selection of the approach requires deeper knowledge of the models and either field data or benchmark simulation tools, like the Association of American Railroads' TOES™.

Early prototype evaluations and feedback from real train crews will be essential in all parts of a program of this type, to verify the modeling assumptions and simplifications and to allow verification of predicted benefits. Collaboration with one or more Class I railroads will increase the likelihood that the goals can be achieved.

6.2 CONSIST MANAGEMENT

Consist management is the manipulation of train length, car placement, and locomotive placement based on operating speed, tonnage, and terrain. When multiple locomotives coupled together are operating at less than full power, the total energy consumed can vary considerably, depending upon the relative ratings of the locomotives and the throttle position of each. For example, it may be much more efficient to run one locomotive at full throttle (Notch 8) and the others at much lower power levels rather than running all of the locomotives at the same power setting.

Technical Barriers. More effective consist-management practices could be adopted across the industry if a model were developed to relate fuel efficiency to throttle position of each locomotive for various operating conditions and if real-time computation and communication capabilities between locomotives in the consist were developed.

Suggested R&D. A relatively modest R&D effort should be sufficient to provide the technologies needed for more effective consist management.

6.3 TRAIN FLEET MANAGEMENT

While the previous section covered technologies that optimize individual train efficiency, this section covers the optimization of train fleets. Opportunities exist for improving train scheduling with information-based technologies. Often referred to as Intelligent Railroad Systems, they consist of sensors, computers, and digital communications to collect, process, and disseminate information to improve the management, planning, and safety of train operations. Intelligent Transportation Systems for highways and mass transit are based on these technologies, as are the new air traffic-control and maritime vessel-tracking systems. The military services; the major parcel delivery companies; pipeline operators; and police, fire, and ambulance services also use these technologies.

Currently, only approximate locations and speeds of trains and maintenance-of-way vehicles are known by dispatchers and control-center computers. Optimization of meets and passes with tactical traffic planners is not possible without precise locations and speeds. Flow control with strategic traffic planners is not possible without tactical traffic planners to implement the decisions. Consequently, it is difficult to keep freight trains on schedule, so it is difficult to schedule cars, locomotives, and crews onto trains. Digital data-link communications networks provide the means for moving information to and from trains, maintenance-of-way equipment, switches, wayside detectors, control centers, yards, intermodal terminals, passenger stations, maintenance facilities, operating data systems, and customers. Digital data-link communications have been tested but have not been implemented in an integrated manner.

Positive train control (PTC) systems are integrated command, control, communications, and information systems for controlling train movements with safety, precision, and efficiency. PTC systems will improve railroad safety by significantly reducing the probability of collisions between trains, casualties to roadway workers, damage to their equipment, and overspeed accidents. In-cab PTC displays will provide status information and command-and-control instructions to the locomotive crews. The National Transportation Safety Board has named PTC as one of its "ten most-wanted" initiatives for national transportation safety.

PTC systems consist of digital data-link communications networks, continuous and accurate positioning systems, computers with digitized maps on locomotives and maintenance-of-way equipment, in-cab displays, throttle-brake interfaces on locomotives, wayside interface units at switches and wayside detectors, and control-center computers and displays. PTC systems also may interface with tactical and strategic traffic planners, work-order reporting systems, and locomotive-health reporting systems. PTC systems issue movement authorities to train and maintenance-of-way crews; track the location of the trains and maintenance-of-way vehicles; have the ability to intervene to prevent any violations of the movement authorities; and continually update operating data systems with information on the location of trains, locomotives, cars, and crews.

In addition to providing a greater level of safety, PTC systems also enable a railroad to run scheduled operations and provide improved running time, greater running-time reliability, higher asset utilization, and greater track capacity. They will assist railroads in measuring and managing costs and in improving energy efficiency. Pilot versions of PTC were successfully tested a decade ago, but the systems were never deployed on a wide scale. Other demonstration projects are currently in the planning and testing stages. Deployment of PTC on railroads is expected to begin in earnest later this decade.

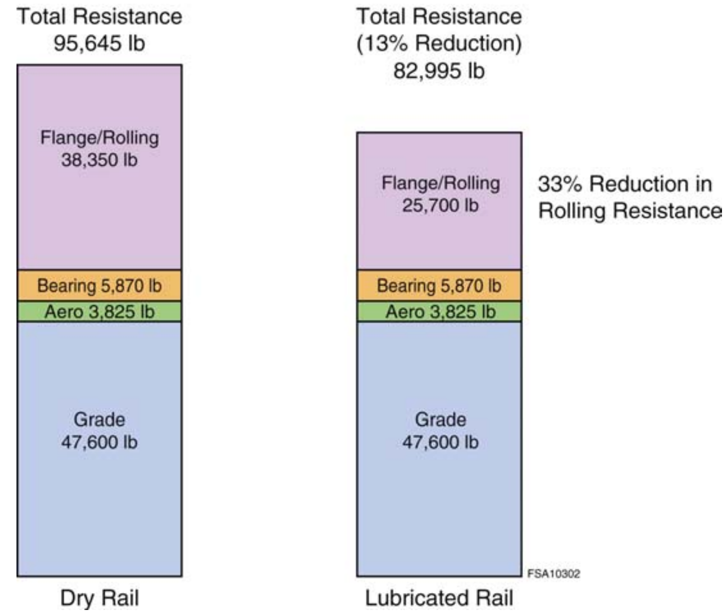
Technical Barriers. The implementation of Intelligent Railroad Systems is not without impediments, including the magnitude of the costs and competition for capital within railroad companies. Railroads will need to understand that a well-executed investment in Intelligent Railroad Systems, by increasing asset utilization, will reduce the capital needed for locomotives, cars, and track.

Suggested R&D. Although Intelligent Railroad Systems offer the potential for significant improvements in efficiency and, thus, fuel savings, the primary motivation is safety. Therefore, that subject falls within the scope of the Federal Railroad Administration, which has been working with the railroad industry on this for some time and is expected to continue to do so. Therefore, it will not be included in this DOE plan.

6.4 WHEEL/RAIL FRICTION

A significant fraction of the energy consumed in rail transport is due to wheel/rail friction. The magnitude of the wheel/rail frictional energy losses relative to other losses (bearings, aerodynamic, and grade) depends on the condition of the track (dry or lubricated), whether the track is curved or tangent, truck design, wheel rail profile conformance, truck wear resulting in poor steering, and train speed. As seen in Figure 7, typically, for curved track, a 33% reduction in the rolling resistance can produce a 13% reduction in total resistance, while for tangent track, a similar reduction produces a 3% reduction in total train resistance. A

(a) Train Resistance Components
Curved Track



(b) Train Resistance Components
Tangent Track

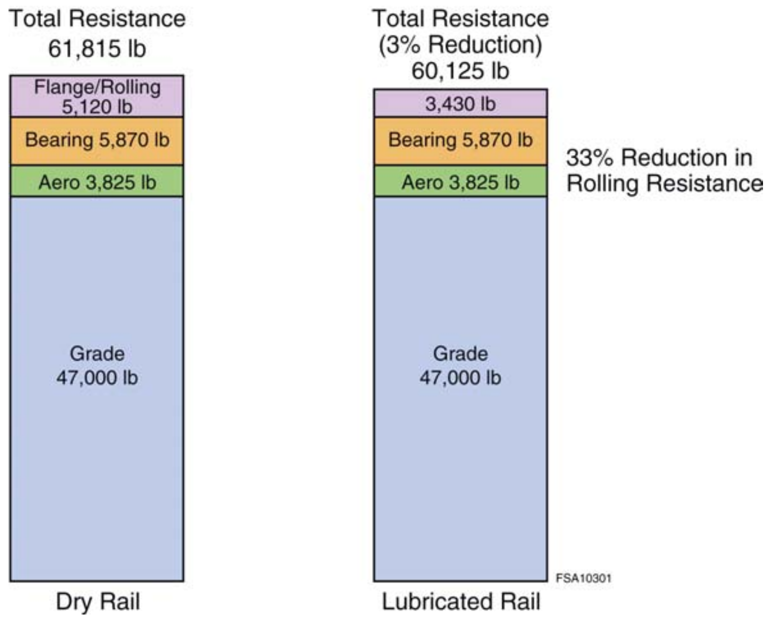


FIGURE 7 Typical Train Resistance Losses (flange/rolling, bearing, aerodynamic, and grade) for 5,800-ton Train on (a) Curved and (b) Tangent Track (figure courtesy of TTCI)

condition known as “truck hunting”[9] (occurring typically on tangent track with lightweight cars above 45 mph) significantly increases energy use. Flange lubrication reduces friction loss from flange contact, while top-of-rail (TOR) lubrication increases the onset speed for hunting.

Trains rely on high friction under locomotives to keep wheels from slipping and sliding when power is applied. Past studies have indicated that energy savings could be as high as 24% when friction at the wheel/rail interface is properly managed (Fenske 2001). Friction is also required under braking conditions to control train speed down hills or to bring a train to a safe stop. Much lower friction levels are desirable under normal train operations and can significantly reduce the energy required to pull a train. Therefore, the key is to apply the lubricant just where it is needed and to make sure that it does not cover the track where high friction is needed for traction or braking.

Flange lubrication is the most common wheel/rail lubrication concept employed and is effective in reducing parasitic losses generated between rail gages and wheel flanges. The lubricant can be applied by stationary (wayside) or on-board applicators. Overapplication of lubricant and a propensity for flange lubes to migrate are issues that need to be addressed to ensure wider acceptance and use of flange lubricators.

Research sponsored by Federal Railroad Administration and DOE has recently led to TOR lubrication concepts to reduce parasitic losses between the wheel tread and the top of the rail. Several approaches apply a degradable lubricant to the rail (after the locomotive) to minimize losses between the rail and car wheels. Another TOR strategy uses friction modifiers applied to locomotive wheels to more precisely control the traction (in a narrower range) between the wheels and rail. While TOR lubrication shows considerable potential, it is still in trial tests and thus not widely implemented. Lubricant buildup, robustness of equipment, compatibility with flange lubrication, cost effectiveness, and safety are issues that need to be addressed.

Technical Barriers. Reliability of devices for applying lubricants to the rail or wheel flange is the major barrier to wider use. The devices must operate in very harsh environments. Locomotive-mounted lubricators may cause excess lubricant to migrate to carriage underbodies and truck sides, which increases the potential for fires and produces a difficult environment for maintenance operations. Lubricant from either wayside lubricators or locomotive-mounted lubricators may migrate to the top of the rail, where it causes poor traction. Concerns about TOR lubrication include buildup of lubricant on the rail, reliability of applicator devices, and compatibility of TOR with flange lubrication.

Suggested R&D. The most important objective would be to develop a more reliable, robust system for applying lubricant in the proper amounts and only where it is needed. Sensors to ensure the proper application of lubricant also would be important. Ideally, one would prefer

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[9] Truck: One of the swiveling frames of wheels under each end of a railroad car or trolley car. Source: http://dictionary.reference.com/search?q=truck.

to use a friction modifier (a material that produces a desirable coefficient of friction) rather than a traditional lubricant that simply lowers the coefficient of friction as much as possible. Both developments carry a moderate technical risk due to the harsh operating environment.

6.5 AERODYNAMICS

There appears to be little room to improve the aerodynamic design of locomotives. However, considerable aerodynamic-drag losses are found for certain car configurations, especially those that include empty coal cars and intermodal cars. One company has found that aerodynamic drag accounts for about 15% of the round-trip fuel consumption for a coal train, and that fuel consumption is approximately the same for an empty train as it is for a full one (Stehly 2002). In an experiment with simple fairings or foils (not a full cover) to direct the air flow over the empty cars, about a 25% reduction in aerodynamic drag was achieved, which resulted in a 5% fuel savings for the round trip. For intermodal cars (two containers stacked on a flat car), about 30% of the energy loss is due to aerodynamic drag.

Potential for Fuel Savings. Coal transport consumes approximately 1.5 billion gallons of fuel annually; a 5% savings due to reduction of aerodynamic drag would be 75 million gallons, or 2% of total Class I railroad fuel consumption (AAR 2002).[10]

Technical Barriers. The primary challenge is to develop a system for covering empty coal cars that does not interfere with loading and unloading and that does not require much time to install. Other challenges are limited maintenance requirements and high reliability and durability.

Suggested R&D. It should be possible to develop suitable methods for reducing the aerodynamic drag of intermodal cars and empty coal cars, and the technical risks are reasonably small.

6.6 ROLLING RESISTANCE

Some possibilities for reducing rolling resistance are:

- Optimized wheel/rail interface profile. An added benefit would be a reduction in wear of the wheels and the rails.
- Advanced trucks with improved suspensions and components. The objective would be to provide better alignment in curves and tangents, which should significantly reduce fuel consumption and wear. This work can build upon the "radial" truck concept available on new locomotives. The radial truck has

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[10] 750 million tons transported 1,000 miles at 500 ton-mi/gal.

provided increased locomotive tractive effort on curved or graded sections of track.

- Advanced end-of-axle bearings.

Potential for Fuel Savings. Each of the suggested ways to reduce rolling resistance would require considerable expenditures by the railroads either for increased maintenance (grinding) of the rails and wheels or for infrastructure costs. The return on investment would be limited until the entire fleet was modified.

Technical Barriers. The primary barriers are financial rather than technical.

Suggested R&D. Very little research would be required to define a standard wheel/rail profile.

7 OPPORTUNITIES FOR ENERGY SAVINGS WITH ADVANCED POWER PLANTS AND FUELS

Today's locomotives are designed to perform in an economically acceptable manner according to the types of present-day service, duty cycles, and methods of railroad operation. Present-day railroad operations may be optimized to reflect best utilization according to the operational characteristics of the locomotive. A reasonable argument, at least theoretically, is that the process for choosing alternative power plants and fuels for locomotives can be greatly affected by new kinds of railroad operation. A prime mover rejected in the past may have much better utilization and a favorable business case for a different railroad operational scheme. New schemes for railroad operation should define the requirements for the locomotive system — a specification enabling the design of a new locomotive unlike those presently available or envisioned.

7.1 HOMOGENEOUS-CHARGE COMPRESSION IGNITION

Homogeneous-charge compression ignition (HCCI) is an alternative piston-engine combustion process that can provide high diesel-like efficiencies while producing ultra-low NO_x and particulate emissions. HCCI engines operate on the principle of having a dilute, premixed charge that reacts and burns simultaneously throughout the cylinder as the charge is compressed by the piston.

In some regards, HCCI incorporates the best features of both spark ignition (SI) and diesel combustion. Like an SI engine, the charge is well mixed, which minimizes particulate emissions. Like a diesel engine, it is compression ignited and has no throttling losses, which leads to high efficiency. However, unlike either of these conventional engines, the combustion occurs simultaneously throughout the volume rather than in a flame front. This important attribute of HCCI allows combustion to occur at much lower peak temperatures, dramatically reducing engine-out emissions of oxides of nitrogen.

In theory, HCCI could be used as the sole combustion mode of an engine; however, the more likely outcome will be a multi-mode combustion system that uses early, late, and multiple fuel-injection strategies to achieve different modes of combustion (e.g., conventional diesel combustion, HCCI, stratified-charge compression ignition) as needed. This multi-mode approach will allow each combustion strategy to be used to its fullest advantage at each engine load/speed setting. This approach may also be more adaptable to staging retrofit improvements to existing locomotive engines.

The advantages of HCCI are numerous and are dependent on the combustion system to which it is compared. Relative to SI gasoline engines, HCCI engines are more efficient, approaching the efficiency of a diesel engine. This improved efficiency results from three sources: the elimination of throttling losses, the use of high diesel-like compression ratios, and shorter combustion duration (since it is not necessary for a flame to propagate across the cylinder). Relative to diesel engines, HCCI engines have substantially lower emissions of PM and NO_x. These low emissions are a result of the dilute homogeneous mixture and low combustion temperatures.

Combustion control is the biggest challenge that must be faced before HCCI engines become a commercial success. For this reason, a great number of methodologies have been proposed for achieving HCCI engine control over the wide range of operating conditions required for typical transportation-engine applications. Some of the proposed methodologies include variable compression ratio, variable valve timing, ignition-enhancing additives, and thermal control.

Potential for Fuel Savings. Substituting an HCCI engine for a diesel engine would not directly affect fuel efficiency because both engines have essentially the same efficiency. However, because of the lower emissions from an HCCI engine, other efficiency-reducing emission-reduction technologies could be eliminated, resulting in a net gain in efficiency. Since HCCI would be applicable only to new engines and considerable development is needed, this technology probably would have little effect on fleet fuel efficiency by 2010.

Technical Barriers. HCCI combustion is achieved by controlling the temperature, pressure, and composition of the fuel/air/residual mixture so that it auto-ignites near TDC (top dead center) as it is compressed by the piston. This mode of ignition is fundamentally more challenging than using a direct-control mechanism (such as a spark plug or fuel injector) that dictates ignition timing.

While HCCI has been known for some 20 years, it is only with the recent advent of electronic engine controls that HCCI combustion can be considered for application to commercial engines. Even so, there are several technical barriers that must be overcome before HCCI engines could be viable for high-volume production and application to a wide range of vehicles. The more significant challenges follow.

- *Control of ignition timing over a range of speeds and loads.* Expanding the controlled operation of an HCCI engine over a wide range of speeds and loads is probably the most difficult hurdle facing HCCI engines. HCCI ignition is determined by the charge-mixture composition and its time-temperature history (and to a lesser extent pressure). Changing the power output of an HCCI engine requires a change in the fueling rate and hence in the charge mixture. As a result, the time-temperature history must be adjusted to maintain proper combustion timing. Similarly, changing the engine speed changes the amount of time for the auto-ignition chemistry to occur relative to the piston motion. Again, the time-temperature history of the mixture must be adjusted to compensate. Several potential control methods have been proposed to provide the compensation required for changes in speed and load.

- *Extending the operating range to high loads.* Although HCCI engines have been demonstrated to operate well at low to medium loads, difficulties have been encountered at the high-load conditions that are routinely accomplished by existing diesel engines. The combustion process can become very rapid and intense, causing unacceptable noise, potential engine damage, and eventually unacceptable levels of NO_x emissions.

- *Cold-start capability.* At cold start, the compressed-gas temperature in an HCCI engine is low because the charge receives no preheating from the warm intake manifold or combustion-chamber walls. Without some compensating mechanism, these low temperatures could prevent an HCCI engine from firing. Various mechanisms for cold starting in HCCI mode have been proposed, including using a different fuel or fuel additive and increasing the compression ratio by using a variable compression ratio or variable valve timing. Perhaps the most viable approach would be to start the engine in spark-ignition mode and change to HCCI mode after warm-up.

- *Hydrocarbon and carbon monoxide emissions.* HCCI engines have inherently low emissions of NO_x and PM but relatively high emissions of HC and CO. Controlling HC and CO emissions from HCCI engines will require exhaust aftertreatment. Catalyst technology for HC and CO removal is well understood and has been standard equipment on automobiles for many years. However, the lower exhaust temperatures of HCCI engines may increase catalyst light-off time and decrease average effectiveness.

Suggested R&D. The main areas requiring R&D on HCCI are outlined below.

- *Ignition timing control.* Ignition timing must be maintained in the optimal range as the engine load and speeds are varied. This task is more challenging for HCCI engines than for conventional engines because there is no positive mechanism, such as spark or fuel injection, that determines ignition timing. In HCCI engines, ignition timing is determined by the chemical kinetic reaction rates of the mixture. These are controlled by time, temperature, and mixture composition.

- *High-load operation.* At low and moderate loads, the heat release rate in HCCI engines is generally slow enough for smooth operation and acceptable noise levels. However, for high power, the heat release rate from HCCI can become very rapid, causing unacceptable noise and eventually engine damage. The solution to this problem may be to switch over and run as a conventional SI or diesel engine at high loads.

- *Cold start.* HCCI combustion is strongly dependent on the charge temperature. During cold start, the fuel/air charge receives no preheating from warm intake manifolds and ports, and there are high rates of heat transfer from the compressed charge to the cold combustion chamber walls. This phenomenon can significantly reduce the compressed-gas temperature and could prevent an HCCI engine from firing.

- *Emission control.* Although HCCI engines are very efficient, they emit unacceptable levels of unburned HC and CO, particularly at low loads. At low and moderate loads, HCCI engines emit very low levels of NO_X and no emissions control is required; however, as the operating range is extended to high loads, NO_X emission can become an issue in addition to the heat release rate becoming too rapid.

- *Transient operation.* Rapid transients present difficulties for current HCCI research engines mainly because the charge temperature is not correctly matched to the operating condition as the speed and load are changing. However, this problem is much less significant for locomotive engines than for truck engines because of the differences in typical operating patterns.

- *Multi-cylinder effects.* In multi-cylinder engines, manifold wave dynamics can cause small differences in the amounts of hot residuals and of fresh charge delivered to the various cylinders. Temperature differences in the coolant between cylinders may also cause some cylinders to be hotter than others. HCCI auto-ignition is very sensitive to small changes in compressed-charge temperature, and these small differences can lead to significant cylinder-to-cylinder variation in combustion timing.

- *Combustion modeling.* Combustion modeling is central to the development of practical HCCI engine combustion systems and control methodology. Chemical-kinetic modeling and kinetic modeling combined with traditional engine computational fluid dynamics models (such as KIVA) have already been used with success to investigate some aspects of HCCI. However, considerably more development and testing of predictive numerical models will be required to advance the HCCI concept. Efforts are needed in three main areas: chemical-kinetic mechanisms, computational fluid dynamics models, and submodels development (turbulence, sprays, and vaporization). It is important that all levels of modeling be conducted in close coordination with experiments for validation and feedback.

7.2 FUEL CELLS

The fuel cell is generally considered to have the greatest potential for replacing the internal combustion engine on vehicles. When one considers that present day locomotives are electrically driven (via direct overhead wire, third rail, or diesel-generator set electrification), the fuel cell can potentially replace both diesel-electric and electric locomotives if the technology can progress to be physically feasible and economically viable. With the potential for high efficiency and very low emissions, this technology has been monitored for many decades with great interest; however, the technical and economic challenges have inhibited serious commercialization plans. Applications have been limited to endeavors where the unique requirements justified the cost.

The increasing need for more fuel-efficient and environmentally friendly sources of energy worldwide is now stimulating increased R&D investment for many commercial applications ranging from small battery replacements to stationary power plants. The emergence of so many electronic and other electrically operated devices commonplace in business and the general public has created a need for increased battery performance that, thus far, does not meet the needs of the consumer. Serious investment leading toward the demonstration of reliable, higher-power-density fuel-cell technology could lead to physically and economically viable devices.

Locomotives require significant horsepower for transport. The development of smaller fuel-cell power supplies, such as providing head end power (HEP) for passenger locomotives, might be a means toward development of the larger locomotive propulsion systems.

There are many varieties of fuel cells; however, the technologies most often discussed or written as worthy of consideration are:

- PEMFC – proton-exchange-membrane fuel cell,
- SOFC – solid-oxide fuel cell,
- PAFC – phosphoric acid fuel cell,
- MCFC – molten-carbonate fuel cell, and
- AFC – alkaline fuel cell.

Fuel-cell technologists have made significant progress in demonstrating devices with higher power density. While recent advances in power density may enable consideration for locomotive applications, much work remains to demonstrate adequate operational life and to develop highly efficient methods to reform (or process) hydrocarbon fuels to generate sufficient quantities of hydrogen for the locomotive application. Hydrogen storage technology (regardless of source) remains challenging and requires more research and development.

Fuel cell research needs to be conducted with a focus on components that, when integrated together as a total system, will demonstrate an operational utility equal to or better than the electric and diesel-electric locomotives presently in operation or contemplated for the future.

Specifications for each subsystem (according to the requirements for a locomotive application) are to be defined and established to enable appropriate research direction. Information in the public domain generally indicates that current programs for automobile and stationary power applications will not meet locomotive application requirements; therefore, dedicated research for the locomotive propulsion system is required. Some of the unique application requirements for the locomotive include (but are not limited to) physical size, vibration and shock, operational temperature range, voltage magnitude and electrical-current output capability, sufficient fuel storage to enable an operational range equivalent to present locomotive operations with No. 2 diesel fuel, and reformer technologies for fuels having higher energy demands.

Potential for Fuel Savings. The thermal efficiencies of fuel/cell reformer combinations and diesel engines are roughly equivalent, so a direct replacement of one for the other would have little effect on fuel efficiency, until an inexpensive, low-impact H_2 source is developed. The main driving force for fuel cells, of course, is emissions reductions, and their use might eventually produce some additional fuel efficiency if they can be used instead of energy-consuming emission-control techniques with diesel engines.

Technical Barriers. Important technical barriers remain for application of fuel cells to locomotives.

- The general public considers hydrogen to be very dangerous and unacceptable. Technical papers and presentations by fuel-cell and fuel reformer researchers continue to refer to the “Hindenburg Syndrome.” Familiarity may overcome this perception.

- Efficient reformation of hydrocarbon fuels is a major barrier, which greatly counteracts and negates the efficiency gains from the fuel-cell stack. This is the subject of much research. Again, development of efficient H_2 production, transport, and storage would overcome this barrier.

- Most fuel-cell R&D does not address the more stringent locomotive operational environment. The locomotive application does not generate interest among researchers because the annual production volume for locomotives is extremely small compared with much higher-volume applications (e.g., automotive). Whereas automotive volume may enable lower fuel-cell cost, those devices will not be applicable to a locomotive without dedicated research to meet locomotive requirements.

- Sulfur levels in many fuels are too high for most present or proposed fuel-cell systems. Proposed regulations will reduce this problem.

- Requirements for the fuel-cell auxiliary and support systems remain a packaging challenge.

Suggested R&D. The following research activities would be necessary to develop fuel-cell technology to a point at which it would be suitable for locomotives.

- Intensify research for storing larger quantities of hydrogen safely and reliably.

- Initiate a broad research program for reforming hydrocarbon fuels specifically for locomotive application.

- Continue research toward higher kilowatt output per unit volume and weight for the most promising fuel-cell technologies (PEMFC, SOFC, PAFC).

- Continue research for providing either (1) fuel-cell devices that are more tolerant of impurities in the air and hydrogen supply systems or (2) air supply and hydrocarbon fuel reformers capable of delivering purity levels required by the respective fuel-cell technologies.

- Seek and create research partnerships with fuel-cell researchers and developers and leverage their programs to consider and include work for locomotive operational requirements. Development of a three-phase 480-volt head-end-power system for passenger locomotives may be a reasonable approach toward developing the larger locomotive traction system.

The most cost-effective way for the railroad industry to deal with fuel cells may be to monitor and take advantage of the many other fuel-cell programs directed at other applications, and then in 5–10 years reevaluate the situation and decide what, if any, research would be useful. However, some participants think that railroad R&D should take the lead.

7.3 GAS TURBINES

Gas turbines have seen only niche application as railroad prime movers over the last 50 years. The most notable applications were the Union Pacific 8,500-horsepower double-cab units of the 1950s and the Amtrak Turbotrain that operates in the Northeast. Recently, the Federal Railroad Administration funded the application of a 4,000-horsepower gas turbine on an Amtrak Acela locomotive.

The developmental emphasis of gas turbines over the last few decades has been on increases in power and efficiency and, more recently, on lower emissions. There has been a tendency to develop the aerodynamic technology in aircraft engines and then flow it down to land-based power turbines.

Lean-burn combustors have been developed to produce levels of NO_x in gas turbines that are an order of magnitude lower than those in the best diesel engines. In this size of gas turbine, it is possible to achieve 35% efficiency and 50 ppm NO_x (about 0.5 g/bhp-h) at rated power, compared with 42% efficiency and 5.5 g/hp-h for railroad diesels. As shown in Figure 8, the lower efficiency of a gas-turbine engine extends over the entire operating range. The ratio of efficiency to NO_x at full load is significantly better than current diesel technology and may provide an impetus to reconsider gas turbines as a legitimate prime mover in freight locomotives.

Potential for Fuel Savings. The gas turbine has no potential for fuel savings compared with a diesel engine, but it could be used to reduce emissions.

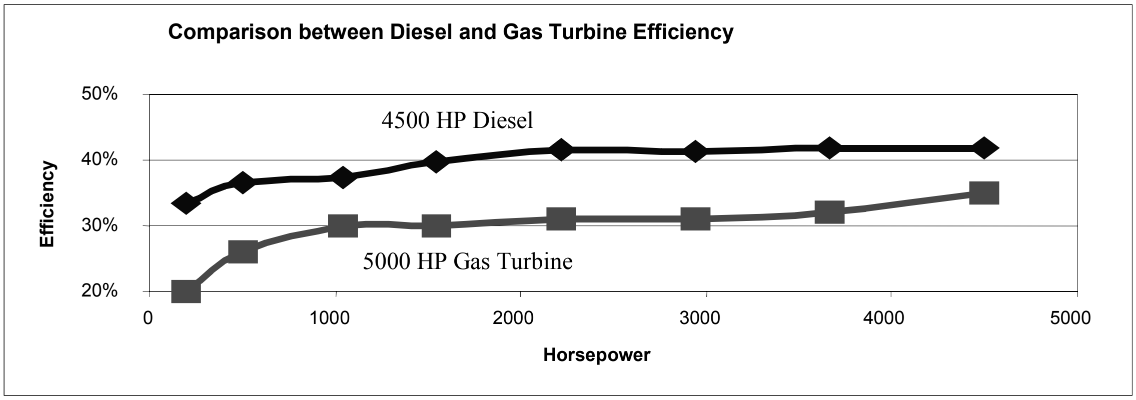

FIGURE 8 Comparison of Efficiencies of Diesel and Gas-Turbine Engines (Courtesy of Flynn, P.L., General Electric Transportation, Erie, Pa., 2001)

Technical Barriers. Gas turbines are continuous-combustion heat engines and therefore have the ability to burn a wide variety of gaseous and liquid fuels. Impurities, such as vanadium and sulfur, that affect the high-temperature parts, are problematic, but gas turbine combustors can be designed to burn most environmentally friendly fuels, such as natural gas, hydrogen, synthetic fuels, and alcohols.

In the past, high cost and low-duty-cycle efficiency have been the biggest technical barriers to the application of gas turbines on U.S. railroads.

The Union Pacific 8,500-horsepower turbines were used as long as the nearly free supply of bunker fuel was available. When the cheap fuel was exhausted, the units were scrapped. Amtrak limits its Turbotrain to high-speed applications where its relatively good efficiency at high power levels can be utilized. At low-duty factors, high fuel consumption at idle and low load make the turbine uneconomical. A typical railroad duty cycle puts a 5,000-horsepower gas turbine at a 25% fuel consumption disadvantage compared with today's locomotive diesel engine.

The cyclic load profile of the typical locomotive is a challenge to gas turbines. Locomotives experience several full load swings per hour. The typical aircraft gas turbine sees one cycle per flight, and power plant turbines see nearly constant speed operation. Transience is also a problem for gas turbines in terms of fuel efficiency.

First cost is another significant barrier. The typical cost of a 5,000-horsepower gas turbine is roughly the same as the entire diesel locomotive, which is three to four times higher than a comparable diesel engine. If gas turbine locomotives are to be widely utilized, the higher first cost of the turbine must be offset by its environmental value and operating costs.

Suggested R&D. Because of the inherent fuel penalty associated with gas turbines, and the fact that the technology has been well developed by the aircraft industry, no research into this subject is recommended.

7.4 LOCOMOTIVE ELECTRIFICATION

There are two main methods for supplying power to electric locomotives: an overhead wire system (catenary) or a third electric rail. High-voltage AC currently provides most overhead power supply. Higher voltages, with less current, limit heat losses in the overhead transmission of electricity; however, there is a trade-off because of potential hazards and the need for costly on-board equipment to use the higher voltages. Power levels of about 25 kilovolts are used in new catenary systems and represent a compromise of efficiency and cost.

Locomotive electrification is well established in the industry. It is useful where rapid acceleration is important, such as some commuter rail systems, but it is not currently economical for long-haul freight service. R&D could lower the costs; even if it does not, the potential for integration of diesel-electric locomotives on an electrified grid, especially in urban areas where diesel emissions are a problem, may prove fruitful.

7.5 ALTERNATIVE FUELS

The use of alternative fuels in locomotives could help reach national goals related to fuel diversity, use of domestic energy resources, energy efficiency, and lowering of exhaust emissions. However, most alternative fuels, with the exception of biodiesel and oxygenated diesel (oxydiesel), cannot be used directly without substantial modifications to engine and locomotive systems, as well as to the refueling infrastructure.

DOE and the U.S. Department of Transportation have established programs to promote research, development, and deployment of alternative fuel technology for the automotive and trucking industries. Much of this technology may be transferable to the railroad industry. Alternative fuels are most readily used in the trucking industry by fleets having central refueling and maintenance facilities (similar to those of the railroad industry). Natural gas — either as compressed natural gas (CNG) or liquefied natural gas (LNG) — or Fischer-Tropsch fuel and other renewable fuels (such as ethanol, biodiesel, and oxydiesel) might find application to locomotives. Additional research is needed.

The truck and bus industries have conducted fleet studies to compare the performance of natural gas, ethanol, methanol, and biodiesel with that of diesel fuel. These fleet studies have shown that alternative-fueled vehicles generally have higher operating and maintenance costs than conventional diesel-powered vehicles. The operating costs can vary significantly because the fuel price is strongly dependent on the location of the fleet operation. Maintenance costs are generally higher for alternative-fueled vehicles since their technologies are less mature.

Natural gas in CNG or LNG form shows promise because of lower NO_x and PM emissions and favorable environmental image. Use of CNG or LNG typically adds 15–25% to vehicle cost as compared with diesel-fueled vehicles because of the higher cost of the engine and fuel storage and delivery systems. In addition, on a BTU basis, LNG costs about 60% more than diesel fuel. Field tests of a CNG-powered locomotive by the Burlington Northern Railroad in the mid-1980s showed that CNG is impractical for wide-scale railroad use because of its relatively low energy density (Fritz 2000). However, LNG has a considerably higher energy density, and locomotive engines have been successfully converted to operate well on LNG.

While LNG can produce a 60% reduction in NO_x and some decrease in PM compared with a conventional diesel engine, the amount of unburned HC and CO from a LNG engine can be much higher (Fritz 2000). Diesel fuels produced from natural gas feedstocks, such as Fischer-Tropsch fuel, are extremely attractive because they have very low levels of sulfur and aromatics. Numerous engine experiments have shown substantial reductions in PM emissions when Fischer-Tropsch fuel is used in unmodified diesel truck engines. Other fuels — such as methanol, dimethyl ether, dimethoxy methane, and diethyl ether — also have been shown to reduce PM emissions in laboratory tests.

Experiments and field tests are under way with blended alternative fuels, such as vegetable oils (biodiesel) and ethanol (oxydiesel). Both types of fuels are typically blended 10–20% in conventional petroleum diesel fuel, although biodiesel can be used in neat form. The blended fuels offer a displacement of petroleum and modest emissions benefits, especially a reduction of PM. With regard to ethanol, a secondary water/ethanol injection system may result in significant reductions in NO_x and PM emissions.

Current locomotive engine emissions standards and potential future standards may require significant reduction in the sulfur level of locomotive-grade diesel fuel. The potential for use of aftertreatment devices to control emissions is very dependent on very low sulfur levels for system durability and effectiveness.

Potential for Fuel Savings. Because of the current cost penalties associated with alternative fuels, it is unlikely that they will make an appreciable impact before 2010. After that time, ever stricter emissions regulations may force their use in regions such as Southern California.

Technical Barriers. The primary barriers for alternative fuel use are not technical — they are cost, market acceptance, reliability, and deployment. Because of the additional cost of most alternative fuel technologies, an incentive (such as lower alternative-fuel cost or a perceived threat of a fuel shortage) will be required to create a market for their use.

The primary barriers for the use of natural gas pertain more to fuel storage and refueling facilities. If extra fuel tanks are required, then space availability on the locomotive can be a barrier.

The primary barriers for Fischer-Tropsch diesel are economic. Feedstock would be most economically available in remote locations where large quantities of natural gas are available, but capital costs for production facility construction would be high in these locations because of a lack of general infrastructure. Fischer-Tropsch diesel also could be produced from solid fuels (such as coal) through a gasification step, but that would require additional capital investment in the fuels-processing plant. The abundance of coal resources in the United States could make this option more attractive if supplies of natural gas become tight. Direct firing of micronized coal/water slurries has been investigated, but that process requires very deep and potentially expensive processing of the coal to remove ash and other contaminants, as well as extensive modifications to the fuel-handling and injection equipment on the engine. Reliability of the engine and fuel equipment is another barrier.

The primary barrier for biodiesel, oxydiesel, and water/diesel emulsions is high production costs. Additionally, untreated biodiesel has issues related to oxidation, high viscosity, and thermal stability, and oxydiesel has issues related to lower lubricity, corrosion, and high vapor pressure. For example, the lower lubricity of oxydiesel, in excess of 5% ethanol, has shown to contribute to abrasive wear and cavitation in high-pressure fuel injectors in durability testing. Long-term stability of water/diesel emulsions is considered a barrier, as is the durability of fuel-injection-system components.

Suggested R&D. Unmodified diesel engines can be operated on the various liquid fuels, such as Fischer-Tropsch, biodiesel, oxydiesel, dimethyl ether, dimethoxy methane, and diethyl ether, as well as various blends thereof. However, there has been relatively little basic research and optimization with regard to locomotive engines using these or other alternative fuels. The following activities would need to be undertaken to determine which of these fuels offer the benefits in emission control and support aftertreatment device development.

- Conduct basic research on liquid fuels and blends to better understand the combustion process.

- Undertake R&D targeted at creating a high-efficiency engine optimized for use with a “best” fuel. Examine emissions and efficiency trade-offs for all fuels.

- Investigate low-cost fuel additives that have the potential to lower engine-out emissions and increase fuel efficiency.

- Conduct research to solve engine and component problems associated with using various alternative fuels.

- Make low cost a priority on all development projects. Identify technologies that overcome the other barriers at the lowest cost.

Gaseous fuels present additional barriers that require a significantly different approach. Their use will require a major redesign of the basic engine to address such issues as how to ignite the fuel (either by using an ignition system or a micro-pilot diesel injection). The following R&D projects would be needed to determine the viability of using gaseous fuels in a locomotive application.

- Dedicated gaseous-fueled locomotive engine. Work may include developing a direct-injection system, micro-pilot injection, advanced control systems, variable valve timing, skip firing, Miller cycle, or other strategies.

- Sensors or other technology to detect fuel-quality variations and to adapt engine controls to extend the lean limit of operation.

- Low-cost ignition system.

- Durable and corrosion-resistant engine components.

- Safe, lightweight fuel tanks and fuel-storage media.

8 PROJECTED RESOURCE REQUIREMENTS

In 2000, the U.S. Class I railroads consumed about 4 billion gallons of diesel fuel. On the basis of the research objective of improving total railroad average fuel efficiency by 50% by 2020,[11] an annual fuel savings of about 1.3 billion gallons (31 million barrels of oil) is projected. The government's portion of funding for locomotive and railroad R&D to achieve this objective is estimated to be about $20 million annually for about 14 years, to bring funding on a level consistent with that of heavy trucks (see sidebar).

Locomotive manufacturers and operating railroads would require substantial investments to match the DOE funding and to implement the new technologies. Some financial stimulation by DOE is important because the primary beneficiaries of the savings are the general public and because many of the technical risks are high. An industry cost share of 25–50% would probably be required, depending on technical risk.

Research priorities will be determined through ongoing, peer-reviewed systems analysis of locomotive and train technologies and through industry response to DOE solicitations for financial assistance.

PROJECTED DOE FUNDING

The DOE R&D budget in fiscal year 2002 to improve heavy truck fuel efficiency is $88 million. Assuming this funding continues until 2010, and considering past funding starting in 1996 on heavy trucks, a total of $1.1 billion will have been spent by the government. According to DOE, cumulative energy savings from heavy truck advanced technology will be 2,384 million barrels by 2030. Applying this cost-benefit to railroads, total R&D funding needed would be $280 million over about 14 years, or an average of about $20 million each year.

These calculations assume that railroad average fuel efficiency increases by 50% in 2020 (savings begin in 2005) and remains constant thereafter, saving a total of 607 million barrels of oil between 2005 and 2030. About $0.46 of government funding per barrel of oil is saved. With an estimated average industry cost-share of 25%, total R&D funding is about $0.58 per barrel saved.

Note that these estimates exclude effects from a shift of freight from trucks to rail, which would further increase energy efficiency and improve cost-effectiveness. Additional global benefits will accrue from the sales of advanced locomotives and train systems overseas.

Sources: http://www.ott.doe.gov/facts/pdfs/facts_quality_metrics_2003.pdf; http://www.trucks.doe.gov/pdfs/V/65.pdf

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[11] On an equivalent revenue ton-mile/gallon basis, relative to a fleet average of 393 revenue ton-mi/gallon in 2000.

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