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Comparative Evaluation of Rail and Truck Fuel Efficiency on Competitive Corridors

November 19, 2009

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13. ABSTRACT

This study provides a comparative evaluation of rail and truck fuel efficiency on corridors and services in which both modes compete. For the purposes of this study, competitive movements are defined as those of the same commodity having the same (or proximate) origin and destination (O-D) pairs. This study also provides an analysis of past and future trends of rail and truck fuel efficiency.

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List of Acronyms

AAR	Association of American Railroads
AC	Alternating current
APU	Auxiliary power unit
ARB	Air Resources Board
ASTM	American Society for Testing and Materials
ATA	American Trucking Association
ATC	Automatic train control
ATRI	American Transportation Research Institute
BAU	Business as usual
bhp-hr	Brake-horsepower hour
BNSF	Burlington Northern Santa Fe Railway
BTU	British thermal unit
CAD	Computer aided dispatching
CAGR	Compound annual growth rate
CARB	California Air Resources Board
CO	Carbon monoxide
CP	Canadian Pacific
CTC	Centralized train control
CTC	Centralized traffic control
CVT	Continuous variable transmission
DOJ	Department of Justice
DP	Distributed power
ECP	Electronically-Controlled Pneumatic
EGR	Exhaust gas recirculation
EIA	Energy Information Administration
EMD	Electro-Motive Division
EPA	Environmental Protection Agency
ETMS	Electronic train management system
FE	Fuel efficiency (ratio)
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
GE	General Electric
GEVO	General Electric Evolution Series
GPS	Global Positioning System
GTM	Gross ton-miles
GTO	Gate turn-off
HC	Hydrocarbon
HCCI	Homogenous charge compression-ignition
hp	Horsepower
HVAC	High-voltage alternating current
IGBT	Insulated gate bipolar transistor
kW	Kilowatt

lb	Pound
LCV	Longer combination vehicle
MIS	Management information systems
MOVES	Motor Vehicle Emission Simulator
mph	Miles per hour
MW	Megawatt
MY	Model year
NEMS	National Energy Modeling System
NOx	Nitrogen oxides
NS	Norfolk Southern Railway
O-D	Origin-Destination
OEM	Original equipment manufacturer
ORNL	Oak Ridge National Laboratory
PERE	Physical Emission Rate Estimator
PM	Particulate matter
PTC	Positive Train Control
ROI	Return on investment
RTM	Revenue ton-miles
SCR	Selective catalytic reduction
STCC	Standard Transportation Commodity Code
TIH	Toxic by inhalation
TIUS	Truck Inventory Use Survey
TOFC	Trailer on flat car
USDOT	U.S. Department of Transportation
USGS	U.S. Geological Survey
VIUS	Vehicle Inventory Use Survey
VMT	Vehicle miles traveled

Chapter 1. Introduction and Summary of Findings

1.1. Study Objectives

This study provides a comparative evaluation of rail and truck fuel efficiency on corridors and services in which both modes compete. For the purposes of this study, competitive movements are defined as those of the same commodity having the same (or proximate) origin and destination (O-D) pairs. This study also provides an analysis of past and future trends of rail and truck fuel efficiency.

A competitive movement is defined herein as one in which mode share is comparable between rail and truck. The term *competitive* is here used in an economic sense, which indicates that cost and level of service are close economic equivalents for shippers in a given market. In other words, this study does not evaluate any of the individual criteria that influence mode choice (e.g., cost, transit time, reliability, safety), and competitive movements do not imply equivalent levels of service.

This study is strictly about fuel efficiency, and it does not compare the economic efficiency of rail and truck movements. Economic efficiency concerns not only transportation costs, on which fuel efficiency has a strong influence, but also accessibility, quality of service, speed of delivery, transit time reliability, and safety. This study compares rail and truck movements on the sole basis of fuel efficiency and consumption.

1.2. Study Background

There have been many studies that compared rail and trucks in terms of energy/fuel consumption and emissions. The most relevant, a study commissioned by the Federal Railroad Administration (FRA) in 1991 (from hereon referred to as the 1991 Study), compared rail and truck fuel efficiency along corridors in which both modes competed in selected commodity markets.[1] The analysis relied on simulations of rail and truck fuel consumption over specific corridors, using representative equipment configuration and operations and route characteristics for the commodity and O-D pair being modeled. The study accounted for the fact that the first and last legs of an intermodal movement are generally performed by a drayage truck, usually older and less fuel efficient than a long-haul truck, operating in congested conditions.

Although the 1991 Study provided a comprehensive "apples-to-apples" comparison between rail and truck fuel efficiency, the study is now dated. Many technological and operational improvements on both modes have since been realized, including the proliferation of double-stack intermodal rail service, new railcar designs, and the use of distributed power (DP) in unit trains. There have also been changes in commodity mix and flows on both modes. The methodologies used in this study were constructed to ensure that the two studies are directly

[1] Abacus Technology Corporation (1991): Rail Vs. Truck Fuel Efficiency: The Relative Fuel Efficiency of Truck Competitive Rail Freight and Truck Operations Compared in a Range of Corridors. Report Prepared to the Federal Railroad Administration. DOT/FRA/.RRP-91/2.

comparable, thus providing a time-series of data points that may be used to gauge how rail and truck fuel efficiency have evolved since 1991.

Since the release of the 1991 Study, new tools and models aimed at analyzing rail and truck fuel efficiency have become available and have been used. These tools were applied to post-1991 data for the current study. Methodological improvements were made in the selection of comparable movements, in the treatment of local branchline movements and yard switching operations, in the modeling of truck movements, in the consideration of empty movements, and in the inclusion of operational constraints (e.g., train meets, road congestion). Wherever possible, this study isolates any areas of deviation from the 1991 Study methodology in order to enable the most direct comparison of results.

1.3. Study Organization

The study is divided in four chapters:

Chapter 2 Past Trends in Rail and Truck Fuel Efficiency

This chapter evaluates trends in rail and truck fuel efficiency since 1990. The analysis starts with the overall evolution of rail and truck fuel consumption and efficiency. Some technologies have had little market penetration to date, and therefore have not had much impact on fuel efficiency since 1990. Because it is challenging to categorize technologies and trends between those that have had an impact on fuel efficiency and those that will likely have an impact on future fuel efficiency, there is some overlap between Chapters 2 and 5.

Chapter 3 Identification of Competing Services and Commodities

This chapter identifies services and commodities in which rail and trucks compete. In total, 23 movements are selected for the comparative analysis. Each movement analyzed in this study is associated with an O-D pair, a route, a commodity, and a service offering, from which rail and truck equipment are configured.

Chapter 4 Calculation of Rail and Truck Fuel Efficiency

This chapter characterizes rail and truck movements and provides a comparative analysis of rail and truck fuel efficiency. Rail and truck fuel efficiency are compared in 23 movements, which represent lanes, service, and commodities in which rail and truck compete.

Chapter 5 Future Trends in Rail and Truck Fuel Efficiency

This chapter provides an analysis of anticipated future trends in rail and truck fuel efficiency over the next 20 years. This chapter builds on Chapter 2, which includes an analysis of past trends in rail and truck fuel efficiency from 1990 to 2006.

1.4. Methodology

The identification of competitive movements relies mainly on secondary data, but rail industry experts were also consulted to validate the list of movements. The criteria utilized in the selection of competitive movements include:

1. Movements that had comparable rail and truck mode shares;
2. Movements that were representative in terms of freight activity (measured in ton-miles);
3. A mix of short, medium, and long-distance movements;
4. A mix of different commodities (and thus different equipment types);
5. A mix of geographic regions.

The 23 movements identified in this study consist of origin, destination, route, commodity, and service offering, from which rail and truck equipment are configured, and any operating characteristics that would affect fuel efficiency in either mode is determined.

The comparative evaluation of rail and truck fuel efficiency on the 23 competitive movements considers fuel efficiency at the load level, measured in lading *ton-miles per gallon*. This metric reflects the number of tons[2] of freight (excluding equipment tare weight) and the distance (in miles) that can be moved with one gallon of fuel. The *rail-truck fuel efficiency ratio*, which is the ratio between rail and truck fuel efficiency (both measured in lading ton-miles per gallon), is also used in the comparative evaluation. Two additional metrics are considered to analyze modal efficiency individually: (1) *trailing ton-miles per gallon* (rail fuel efficiency at the train level), and (2) *miles per gallon* (truck fuel efficiency).

The calculation of line-haul fuel consumption for both modes takes into consideration distance, circuity, grade profile, speed profile, vehicle characteristics, vehicle weight, and vehicle aerodynamic profile, amongst other parameters.

The calculation of rail fuel efficiency also considers short branchline movements, which consist of those between shippers/consignees and rail yards, which are assumed to be done by rail in the case of mixed freight trains and by truck (drayage movement) in the case of intermodal trains. These movements are assumed on both ends of the trip. In the case of truck movements, it is assumed that freight moves directly from shipper to consignee. Fuel consumption associated with truck idling, either during breaks or overnight idling, is also considered.

Line-haul rail fuel consumption was calculated by two participating railroads with in-house train simulators. Fuel consumed in truck drayage, intermodal terminal operations, short branchline rail movements, and rail car switching were added separately to the line-haul rail fuel consumption. Line-haul truck fuel consumption was calculated with MOVES/PERE, a model designed by the U.S. EPA to estimate truck emissions and fuel consumption. The fuel consumed during truck idling operations was added separately.

[2] All references to tons in this report refer to short tons.

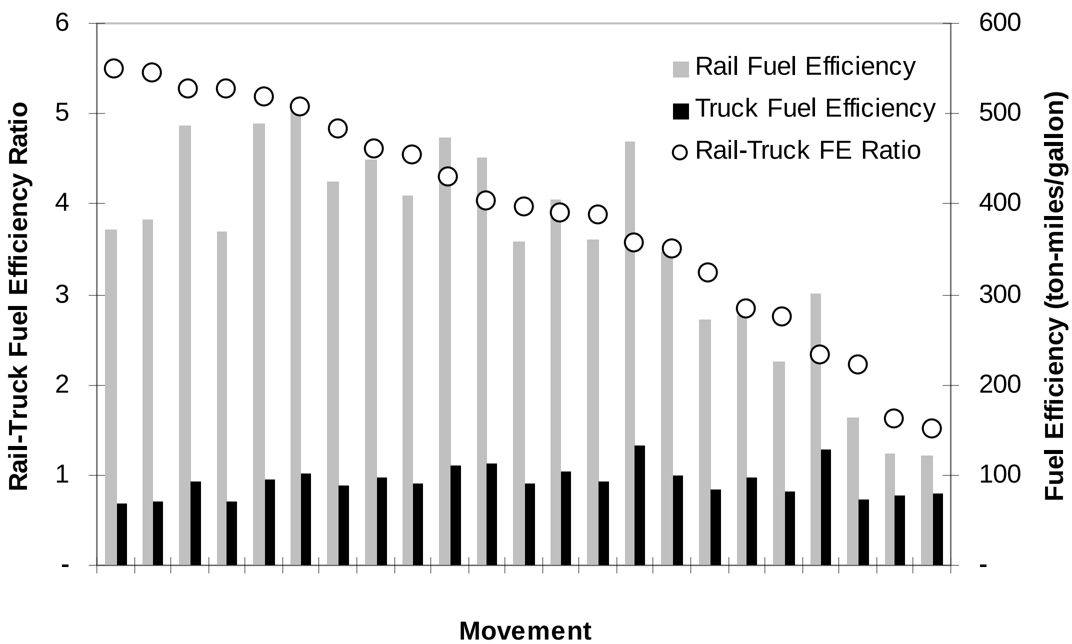
1.5. Summary of Findings

The detailed results from the comparative evaluation of rail and truck fuel efficiency are presented in Chapter 4, and are summarized in 11 main findings.

Finding 1: Rail is more fuel efficient than truck on all 23 movements.

For all movements, rail fuel efficiency is higher than truck fuel efficiency in terms of ton-miles per gallon. The ratio between rail and truck fuel efficiency indicates how much more fuel efficient rail is in comparison to trucks. As illustrated in Exhibit 1-1, rail fuel efficiency varies from 156 to 512 ton-miles per gallon, truck fuel efficiency ranges from 68 to 133 ton-miles per gallon, and rail-truck fuel efficiency ratios range from 1.9 to 5.5.

Exhibit 1-1. Comparison of Rail and Truck Fuel Efficiency*

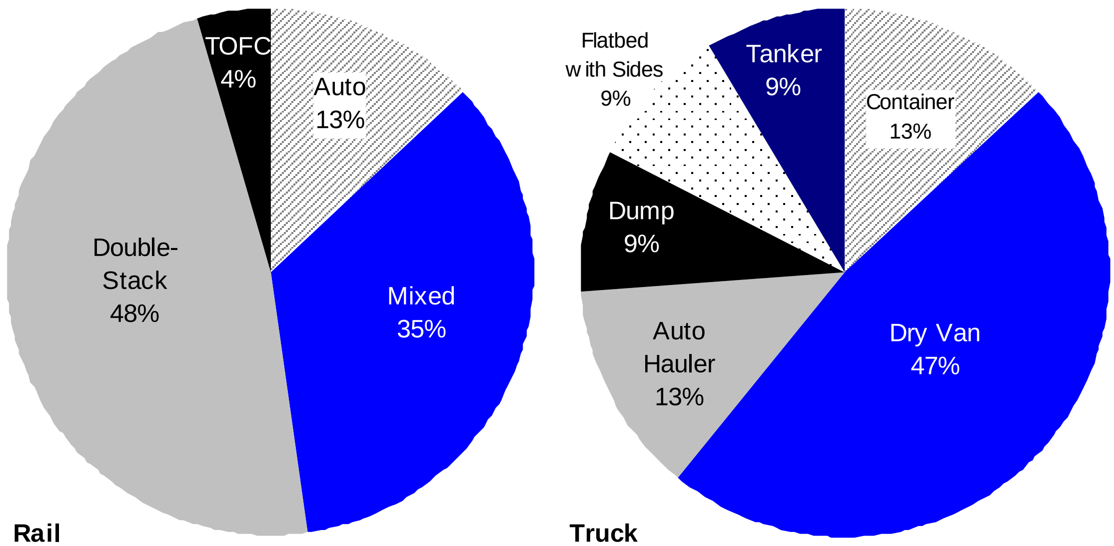


***The 23 moves were ordered by descending rail-truck fuel efficiency ratios.**

Finding 2: Double-stack trains and dry van trailers are the predominant equipment types in this study.

Double-stack trains account for 11 out of 23 rail movements, while dry van trailers are the equipment of choice for 12 truck movements. Double-stack service has become more predominant in the past two decades due to their fast and reliable transit times, while 53-foot dry vans provide large capacity while utilizing tractor aerodynamic aids that reduce fuel consumption. Exhibit 1-2 illustrates the distribution of equipment types across rail and truck movements.

Exhibit 1-2. Representation of Equipment Types in Study Movements



Finding 3: There is a strong correlation between rail-truck fuel efficiency ratio and equipment type.

Exhibit 1-3 provides the range of rail-truck fuel efficiency ratio by rail equipment type.[3] The tank car movement resulted in the highest ratio, followed by double-stack, covered hopper, and gondola movements. Auto rack movements resulted in the lowest ratios. The wide variation in rail-truck fuel efficiency ratios in double-stack movements is a result of the higher number of double-stack movements considered in this study.

Exhibit 1-3. Range of Rail-Truck Fuel Efficiency Ratios by Rail Car Type

Rail Equipment	Min	Max
Tank Car	5.3	5.3
Double-Stack	2.7	5.5
Covered Hopper	3.7	4.3
Gondola	2.3	4.0
Box Car	3.6	3.9
TOFC	3.2	3.2
Auto Rack	1.9	2.2

[3] Rail-truck fuel efficiency ratio is calculated as the ratio between rail and truck fuel efficiency, both measured in lading ton-miles per gallon.

Finding 4: The range of rail fuel efficiency is wider than the range of truck fuel efficiency.

Exhibits 1-4 and 1-5 illustrate the range of rail and truck fuel efficiency across all movements included in this study. Rail fuel efficiency has a much wider range, varying from 156 to 512 ton-miles/gallon, while truck fuel efficiency ranges from 68 to 133 ton-miles/gallon.

Exhibit 1-4. Range of Rail Fuel Efficiency (ton-miles/gallon)

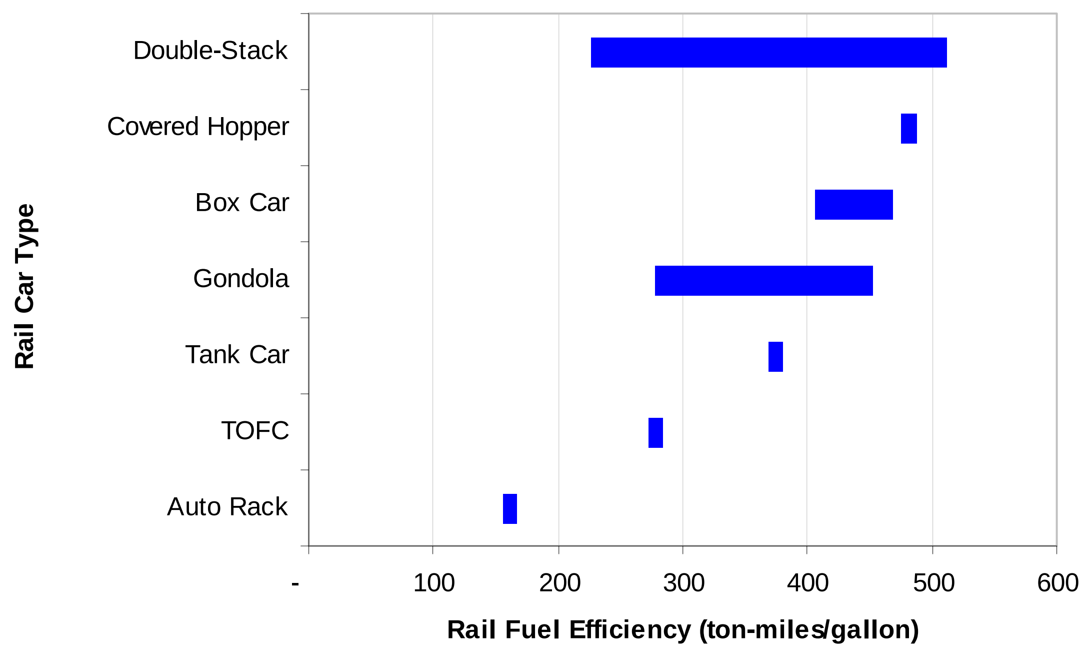
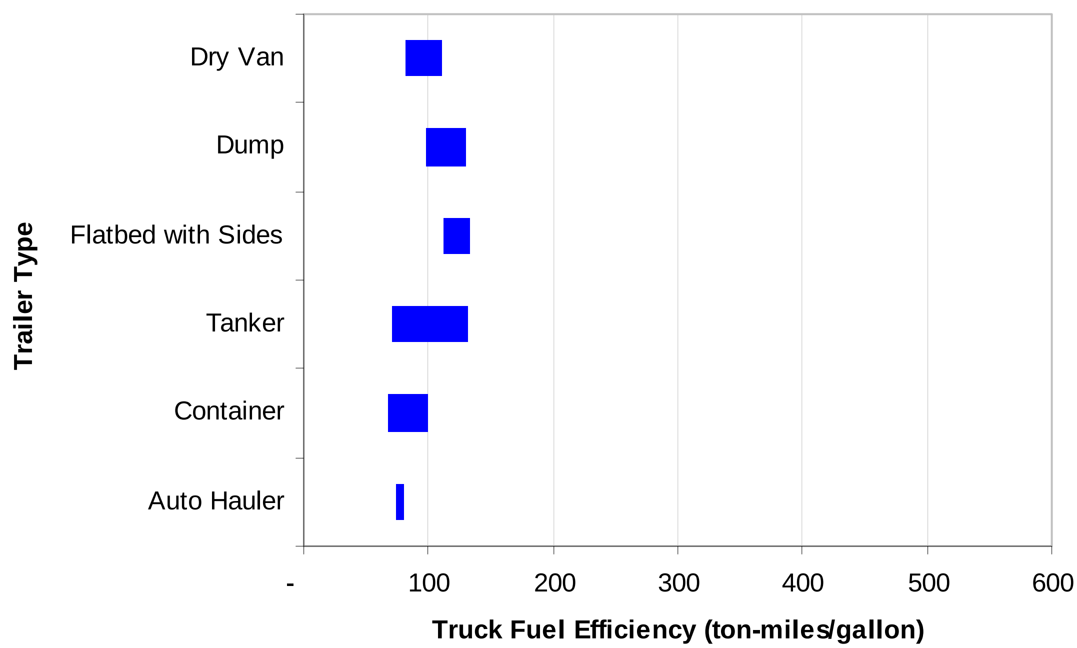


Exhibit 1-5. Range of Truck Fuel Efficiency (ton-miles/gallon)

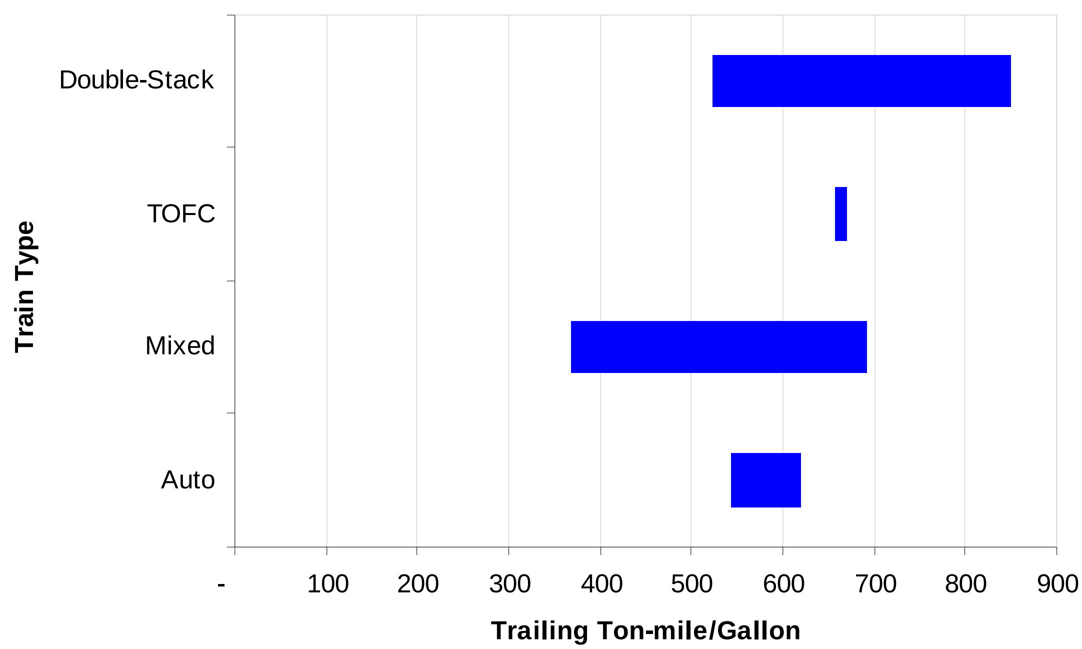


Finding 5: The variation in rail fuel efficiency is narrower if analyzed in terms of trailing ton-miles per gallon.

Rail fuel efficiency can be measured at the train level in trailing ton-miles per gallon. Exhibit 1-6 illustrates the range of trailing ton-miles per gallon for different types of trains, and the most fuel efficient train is about 2.3 times more fuel efficient than the least fuel efficient train. In contrast, the ratio between the highest and the lowest fuel efficiencies measured in lading ton-miles per gallon at the car level is 4.2.

Double-stack trains tend to be more fuel efficient than other types of trains, despite their higher average speeds and poorer aerodynamic performance. The fact that intermodal operations do not require subsequent switching operations to classify rail cars contributes to the better performance of double-stack trains. The wide variation in fuel efficiency of double-stack and mixed trains as opposed to auto and TOFC trains is justified by the smaller number of movements analyzed in the latter trains.

Exhibit 1-6. Train Fuel Efficiency by Train Type



Finding 6: Route circuity plays a role in the total fuel consumption and fuel efficiency associated with rail and truck movements.

Typically, distances by rail are greater than those over the road, but truck distance was longer in some movements due to the fact that truck routing minimized travel time rather than travel distance. In this study, truck routes are shorter in 17 out of 23 movements.

Because the comparisons of rail and truck fuel efficiency reflect ton-miles per gallon, circuity is not taken into account, and consequently the fuel savings from using rail versus truck are not proportional to the ratio between rail and truck fuel efficiency. Rail resulted in fuel savings for all remaining movements, ranging from 18 to 1,108 gallons per carload.

Rail-truck fuel efficiency ratios can also be adjusted to account for route circuity. As indicated in Exhibit 4-20, the ratios were reduced for all 17 movements in which truck routes are shorter. In contrast, the rates increased in the remaining six movements in which rail routes are shorter.

Finding 7: Short branchline movements, switching operations, truck drayage, terminal operations and truck idling have very different impacts depending on the movement analyzed.

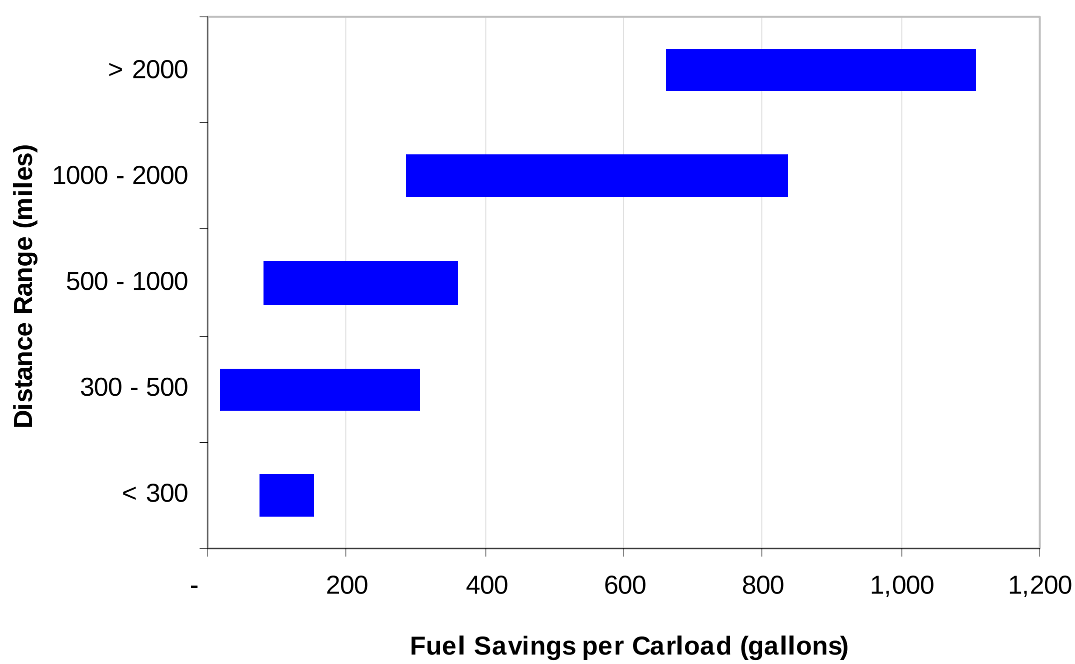
While truck idling accounts for less than 7% of total truck fuel consumption, short branchline movements, switching operations, truck drayage, and terminal operations represent a more sizeable share of total rail fuel consumption. Truck drayage and intermodal terminal operations account for 7-27% of total fuel consumed by intermodal trains, with the wide range justified by the fact that the analysis assumed a fixed distance for all drayage movements independently of the route distance. Therefore, the fuel share allocated to truck drayage was higher for shorter routes and lower for longer routes. Similar conclusions can be drawn for short branchline movements and yard switching operations, which combined make up 6-45% of fuel consumed by mixed trains.

Finding 8: Fuel savings from using rail can be significant.

Rail results in fuel savings when compared to their counterpart truck movement, ranging from 18 to 1,108 gallons per carload. Because the range of variation in fuel savings is more dependent on route distance than equipment type, Exhibit 1-7 illustrates the range of savings by distance segments.

Fuel savings can also be analyzed at the train level. For example, if trucks were to carry the equivalent payload included in the double-stack rail movements, fuel savings would evidently be much greater, varying from 1,549 to over 80,000 gallons per double-stack train.

Exhibit 1-7. Rail Vs Truck Fuel Savings by Distance Segment



Finding 9: The effects of empty mileage associated with rail and truck movements can be significant.

This study analyzes the effects of empty mileage separately because of two factors. First, many analyses of rail and truck fuel efficiency do not account for empty trips, and this study aims at providing a transparent comparison to previous analyses. Second, the logistics of empty equipment is highly complex, and the empty mileage associated with individual movements can vary quite dramatically, thus increasing the uncertainty associated with empty ratios.

This study concludes that all intermodal movements (double-stack and TOFC) and gondola movements are even more fuel efficient than comparable truck movements when accounting for empty miles. In the case of box cars and covered hopper movements, the opposite is true. In those cases, rail is still more fuel efficient than trucks, but the gap between rail and truck narrows with the inclusion of empty miles. This analysis is inconclusive for auto movements.

Finding 10: Congestion has an effect on fuel efficiency.

Some rail movements were modeled with and without consideration of current traffic levels on the rail segments traveled, and the fuel consumption between the opposed (with rail traffic) and unopposed (without rail traffic) simulations ranged from 0.7 to 3.6%. Although this study did not include a sensitivity analysis of different road levels of service on truck movements, previous research has indicated that truck fuel economy can be reduced quite dramatically as the road level of service deteriorates.

Finding 11: Rail double-stack shows improved fuel efficiency while mixed freight and unit auto rail fuel efficiency diminished since the 1991 Study. Truck fuel efficiency diminished in each category.

Finally, the study compared the current results with those included in the 1991 Study. Exhibits 1-8 and 1-9 provide a comparison of the ranges of rail and truck fuel efficiency for both periods, respectively. Exhibit 1-8 also illustrates the rail-truck fuel efficiency ratio range for the two studies. Overall, double-stack trains appear to have become more fuel efficient. At the same time, dry vans and container on chassis are somewhat less fuel efficient in this study, possibly because of the more realistic representation of truck movements.[4] These two factors explain why the rail-truck fuel efficiency ratios increased for commodities moved in double-stack trains. The most striking difference between the studies relates to mixed trains, where the current study estimates much lower rail fuel efficiencies, possibly because of the inclusion of more fuel used in short branchline movements and switching operations.

[4] Truck fuel consumption is measured with micro modal simulation models, which account for specific route elevation profiles as well as driving cycles that are consistent with long-distance truck movements. As explained in Appendix F, standard driving cycles were also adjusted for the fact that heavy-duty trucks need to decelerate during uphill road segments. The fuel consumption from idling operations is also included.

Exhibit 1-8. Evolution of Rail Fuel Efficiency (ton-miles/gallon)

Train Type	Rail Fuel Efficiency Range		Rail-Truck Fuel Efficiency Ratio Range	
	1991 Study	Current	1991 Study	Current
Double-Stack	243 - 350	226 - 512	2.5 – 3.4	2.7 – 5.5
TOFC	196 - 327	273	1.4 – 2.1	3.2
Mixed	414 - 843	278 - 487	2.8 – 5.5	2.3 – 5.3
Unit Auto	206	156 - 164	2.4	1.9 – 2.2

Exhibit 1-9. Evolution of Truck Fuel Efficiency (ton-miles/gallon)

Trailer Type	Truck Fuel Efficiency Range	
	1991 Study	Current
Dry Van	131 - 163	82 – 110
Container	97 - 132	68 - 100
Dump	N/A	98 - 129
Flatbed with Sides	147	112 - 133
Tank	N/A	70 - 132
Auto Hauler	86	74 - 81

Chapter 2. Past Trends in Rail and Truck Fuel Efficiency

This chapter includes an analysis of past trends in rail and truck fuel efficiency from 1990 to 2006. The analysis starts with the overall evolution of rail and truck fuel consumption and efficiency. Section 2.1 includes locomotive technology improvements, fleet composition, non-locomotive technology improvements, operational and train control improvements, as well as impediments to the implementation of fuel-saving actions. Section 2.2 describes truck engine improvements and the effects of emission regulations, non-engine technology improvements and changes in fleet composition, operational improvements, and impediments to the implementation of fuel-saving actions.

Some technologies have had little market penetration to date, and therefore have not had much impact on fuel efficiency since 1990. Because it is challenging to categorize technologies and trends between those that have had an impact on fuel efficiency and those that will likely have an impact on future fuel efficiency, there is some overlap between Chapters 2 and 5.

2.1. Rail Fuel Efficiency

Between 1990 and 2006, rail fuel efficiency[5] has improved by about 20%, or 1.1% per year.[6] These figures represent the overall industry average for U.S. Class I railroads and are the net outcome of multiple changes in railroad traffic mix, technological improvements, and operating practices. Most of this improvement took place without the strong incentive of rising diesel fuel prices after 2004. The principal factors behind rail fuel efficiency improvements were:

- Changes in traffic mix, especially the steady growth of unit-train traffic and in particular, coal and intermodal traffic;
- Technological improvements in locomotives, freight cars, signal, train control and dispatching systems, and track systems;
- Changes in operating practices that lowered fuel consumption, such as the optimization of train meets and passes at sidings, crew training in fuel-saving operating techniques, and improved scheduling to avoid delays.

Overall fuel efficiency gains over the period from 1990 to 2006 were a combination of gains due to individual changes in railroad technology and operations, with the mix of factors varied by traffic type. The challenge in this task was not only to document the overall gain but to understand as far as possible how this gain was distributed among the different traffic types and individual improvement areas.

[5] Measured in gallons per million revenue ton-miles.

[6] Association of American Railroads (2006): Railroad Facts – 2006 Edition.

2.1.1. Overall Evolution of Railroad Traffic and Fuel Consumption

This section describes the changes in railroad traffic, traffic mix, average fuel consumption, and other selected traffic and operations statistics that may have influenced rail fuel efficiency. Unless otherwise stated, all data used in the analysis were for the period from 1990 to 2006 and were derived from Association of American Railroads publications.[7] These publications provide data for Class I railroads operating in the U.S. There are also approximately 550 regional, short line, and terminal railroads in the U.S. that collectively operate 32% of the railroad route miles but carried only about 5% of U.S. freight revenue ton-miles (2006 figures). Data for these railroads are not included in the numbers discussed below. Note that the Class I railroad network has shrunk by 33,000 miles in the review period as low-density lines were taken out of service or sold to local and regional railroads.

Changes in Traffic Volume and Mix

Railroad traffic has been growing rapidly over the 16-year period (1990 – 2006), as shown in Exhibit 2-1. The overall growth in revenue ton-miles of 71% (a compound annual growth rate (CAGR) of 3.4%) was the highest rate of growth in rail traffic since World War II. ICF estimates of the distribution of this growth among key commodity and traffic types shows that coal traffic growth has been the strongest at 86% (4.0% per year), largely driven by increasing shipments of low-sulfur coal from the Powder River Basin in Wyoming. The next strongest growth was in intermodal traffic (container and trailer on flat car) with 79% growth (3.7% per year) over the 16-year period. Intermodal growth was also driven primarily by external factors, in this case the surge in imports of containerized manufactured goods through West Coast ports. Note that intermodal ton-miles as counted in railroad statistics include the weight of the container or trailer, its contents and the weight of any empty containers shipped. The growth in other traffic (excluding grains) reflects the ability of the railroads to retain their share of the overall U.S. freight transportation market. This is a change from previous years, where rail steadily lost market share.

Exhibit 2-1. Summary of Rail Traffic Growth

Year	Quantity	Coal	Intermodal	All Other	*Total*
1990	Revenue Ton-miles (billion)	385	155*	495	1034
2006	Revenue Ton-miles (billion)	718	278*	776	1772
Change	Percent	+86%	+79%	+57%[8]	+71%
1990-2006	CAGR (percent)	4.0%	3.7%	2.8%	3.4%

*ICF Estimate

[7] Association of American Railroads (multiple years): Railroad Ten Year Trends, 1988-1997; Railroad Ten Year Trends, 1996-2005; Analysis of Class I Railroads, 2006.

[8] Grain +30%; Remainder +63%

The implications for fuel consumption of these changes are summarized in Exhibit 2-2.

Exhibit 2-2. Fuel Consumption Effects of Rail Traffic Changes

Commodity	Factors	Overall Effects
Coal	• Mostly unit trains (no switching) • High ratio of payload to empty car weight • Longer, heavier trains • 100% empty return • Best available technology used for coal trains • Low-moderate speeds	Best fuel efficiency of all traffic, with lowest GTM/RTM ratio (approx. 1.4).*
Intermodal	• All unit trains (no switching) • Low ratio of payload to empty car weight • Few empty miles (approx. 10%) • High speeds (up to 80 mph) • Shift from trailers on flatcars (TOFC) to double-stack containers	Relatively high fuel consumption per revenue ton-mile, due to high speeds and high GTM/RTM ratio (approx. 2.5, including weight of container or trailer).
Other	• Mostly carload service with classification yard visits and local switching • Moderate ratio of payload to empty weight • Empty miles about 80% of loaded miles, with many commodities using specialized cars with 100% empty miles (e.g. tank cars) • Moderate train speeds • Sale or closure of low-density lines	Medium to high fuel consumption due to switching and yard visits, high empty miles and medium to high GTM/RTM ratio (approx. 2.0). Loss of low-density local routes will eliminate some low-efficiency operations.

* GTM: Gross ton-miles; RTM: Revenue ton-miles. Because GTM account for empty cars as well as the weight of the car itself, a lower GTM/RTM ratio indicates a better rail fuel efficiency.

Exhibit 2-3. Intermodal Equipment

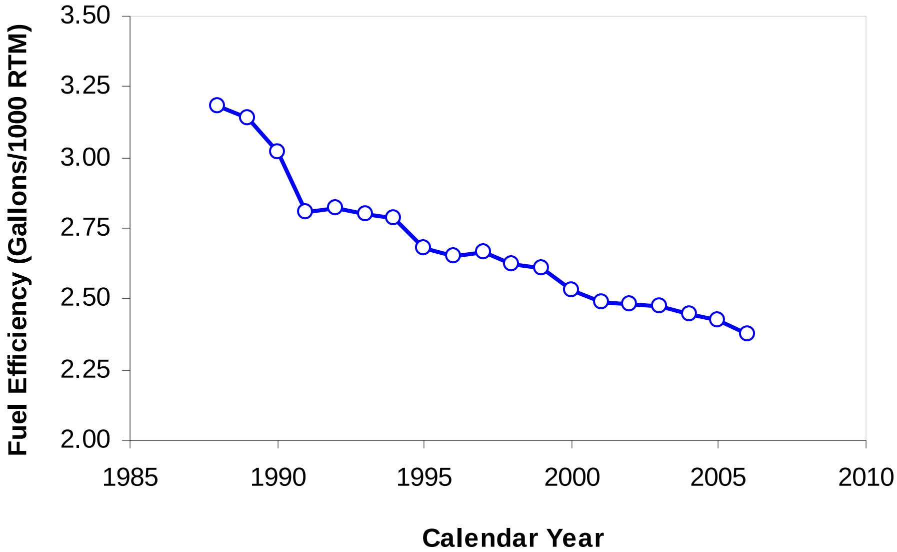
Basic TOFC

Double-stack containers in articulated well cars

Overall Fuel Efficiency of Freight Railroads

Overall fuel efficiency of Class I freight railroads, as measured by gallons of diesel fuel consumed per 1,000 RTM, has improved from 3.18 to 2.37, a reduction of 21.5% (1.22% per year), as shown in Exhibit 2-4.

Exhibit 2-4. Rail Fuel Efficiency Trend (1988-2006)



Similar calculations with GTM instead of RTM indicate a decrease from 1.64 to 1.29 gallons/1,000 GTM, an improvement of 17.8% (1.03% per year). GTM account for the total weight of the train, including empty cars and the weight of the cars, but excluding locomotives. Comparing the decrease in gallons per 1,000 RTM with that for gallons per 1,000 GTM indicates that changes in railroad equipment and car management systems that reduced the ratio of gross to revenue ton-miles was responsible for about 3.7% of the overall improvement in fuel efficiency. However, estimates of GTM/RTM ratios by traffic type suggest that the bulk of this efficiency gain derived from the increasing percentage of highly efficient coal movements in the traffic mix and the growing application of lightweight high-capacity coal cars.

There have been similar but more modest efficiency gains in the intermodal sector that do not show up fully in railroad statistics. The shift from TOFC to double-stack containers enabled the more efficient use of rail cars, improved aerodynamics, and a reduction in the GTM/RTM ratio. Because railroads include the equipment (trailer or container) weight when calculating RTM metrics, the efficiency benefit from using lighter containers in place of trailers is not represented in the results quoted. Corresponding improvements in other types of traffic have been more limited. Incentives for investment in new car technology were weaker due to their low utilization, but there have been reductions in empty car mileage (from 94 to 79% of loaded mileage). All traffic types benefited from infrastructure investments, such as in train control and communications systems, improved tracks (i.e., fewer delays for track repairs), and management information systems.

2.1.2. Railroad Locomotive Fleet Composition and Technology Developments

This section describes the principal developments in railroad locomotive technology that have contributed to fuel efficiency gains since 1990. The discussion starts with an analysis of the change in composition of the Class I railroad locomotive fleet to indicate the extent to which innovations have been put into service. This is followed by discussions of developments in each principal locomotive component or sub-system.

For readers not familiar with the diesel-electric locomotive technology, a brief description is provided. Appendix A also includes the basic locomotive layout, as well as the functions of the major locomotive components. The main diesel engine is coupled to an alternator to produce alternating current (AC) electric power, which is then converted into direct current (DC) power by a solid state rectifier. Prior to the availability of reliable high power rectifiers (early to mid 1960s), diesel locomotives used DC generators, and some locomotives of this type are still in service. From the output of the rectifier, DC power is supplied to traction motor controls and thence to the AC or DC electric traction motors mounted on the trucks.

There are two main elements to the control system. The first element comprises the "supervisory" modules that control the diesel engine itself and matches diesel engine output to the power demanded by the operator. The second element comprises the power switching and regulating devices that convert DC input from the rectifier into the desired traction motor input. For a DC motor, power is usually controlled by rapid on/off switching using solid-state power electronics, with power output determined by the relative length of on/off periods. For an AC motor, solid state power electronic devices produce variable voltage and variable frequency output for each AC traction motor. Most of the key developments in the diesel locomotive in the period 1990-2006 have been in the supervisory and power controls. Evolutionary development of the diesel engine itself has also continued, generally in line with developments in the wider diesel engine industry.

Evolution of the Locomotive Fleet

The actual impact of locomotive developments on the overall fuel efficiency of the freight railroad industry depends on the combination of technical locomotive developments and the extent to which those developments have been put into service by the railroads. This section discusses the evolution of the locomotive fleet from 1990 to 2006. It also introduces the models and model designations used by the two main locomotive manufacturers: General Motors Electro-Motive Division (EMD) and General Electric (GE). Note that General Motors sold EMD to an investor group in 2005, and it is now an independent company.

In 1990, the Class I railroad fleet was dominated by six models from EMD, comprising about 10,500 locomotives or about 55% of the 1990 fleet, as summarized below.

- **Four-axle GP 38 and GP 38-2:** These locomotives used a 2,000 horsepower (hp) un-turbocharged version of EMD's 16-cylinder, two-stroke 645 engine ("645" refers to cylinder size). These locomotives were and are still primarily used in secondary main line and local freight service, where two-axle trucks impose lower lateral forces on the tightly-curved tracks in industrial plants than the longer three-axle truck. The -2 model features an alternator in place of the DC generator. A total of about 2,800 were built, including minor variants. Almost all these locomotives remain in service (after rebuilds, including replacing the DC generator of a GP 38 with an alternator and updates to other systems), as no comparable locomotive has been built since the late 1980s;
- **Four-axle GP 40 and GP 40-2:** These locomotives use a turbocharged 3,000 hp version of the 645 engine. The basic GP 40 had reliability and control problems that gave impetus to the move towards 6-axle locomotives for all main line freight service. The problems were corrected in the -2 version. A total of 2,000 locomotives of both models were put into service, many of which are still in service;

- **Six-axle SD 40 and SD 40-2:** These locomotives are six-axle versions of the GP 40 and GP 40-2, using the same turbocharged 645 engine. About 4,300 SD 40 and 40-2 locomotives were sold. In addition, EMD produced the SD 45 with a 20-cylinder version of the 645 engine, of which about 1,500 were built. The 20-cylinder engine suffered crankshaft and bearing problems and most have been retired. Many SD 40 and SD 40-2s have also been retired and replaced by newer six-axle locomotives, as the high weight and three-axle trucks render them unsuitable for local service.

The contemporary models from GE were the Dash 7 series, produced in both four and six-axle versions, with 12- and 16-cylinder versions of GE's turbocharged, four-stroke FDL engine. GE was also able to increase the rating of the FDL 16 to 3,600 hp to compete with the SD 45. A total of only about 1,500 locomotives of all Dash 7 versions were built, but this locomotive was the first GE locomotive series able to match the performance of the EMD equivalents in all respects and provided the impetus that propelled GE toward its lead role in the future.

In the mid 1980s, both EMD and GE increased the power of the six-axle locomotives to 4,000 hp and adopted the extensive use of microprocessor controls. The EMD SD 50 was essentially an up-rated SD 40 providing 3,500 hp with the 16-cylinder 645 engine. The bigger step involved the SD 60 with a new larger 710 engine with 4,000 hp and microprocessor controls. GE developed the Dash 8 series using an up-rated version of the FDL-16 engine, also with microprocessor controls. Although these were significant technical advances, total locomotives purchases during this period were modest (at about 500/year from both builders combined). Thus, by 1990, the new-technology locomotives only comprised about 15% of the fleet and had a limited impact on overall fuel economy.

Except for a few four-axle high-power locomotives sold by both manufacturers in the early 1990s and a short-lived effort to promote 6,000 hp locomotives, all new locomotives have been six-axle with 4,000-4,500 hp diesel engines. The models, key technical characteristics, and the numbers delivered to Class I railroads between 1990 and 2006 are given in Exhibit 2-5. The numbers built are approximate but are of the correct order of magnitude.

In total, over 13,000 new locomotives were delivered, of which about 5,200 were AC motor models. This is 56% of the fleet operating at the end of 2006, but a significantly higher percentage of traffic would have been hauled by these locomotives by 2006, given their higher average horsepower and more intensive use compared with pre-1990 locomotives. ICF estimates that 70-80% of total RTM are hauled by locomotives built since 1990. Current production models from both manufacturers (EMD's SD 70M-2 and SD 70MACe, and GE's ES44DC and ES44AC) are all EPA tier 2 compliant.

Exhibit 2-5. Deliveries of Locomotives to Class I Railroads (1990-2006)

Builder	Model	Years Produced	Traction Motor	Number of Axles	HP	Number Built
EMD	SD 60/GP60	To 1994	DC	4 (GP 60), or 6 (SD 60)	4,000	800
	SD 70M	1993-2004	DC	6	4,000-4,400*	2,100
	SD70MAC	1993-2004	AC	6	4,000-4,400	1,800
	SD 80/90 MAC	1995-1998	AC	6	Up to 6,000hp	80
	SD 70M-2	2005-	DC	6	4,000-4,400	300
	SD 70MACe	2005-	AC	6	4,000-4,400	350
GE	Dash-8	To 1994	DC	6	4,000	1,000
	Dash-9 44CW	1994-2003	DC	6	4,000-4,400	2,400
	AC4400CW	1994-2003	AC	6	4,000-4,400	2,100
	AC6000CW	1995-1998	AC	6	6,000 hp,	100
	ES44DC	2003-	DC	6	4,000-4,400	400
	ES44AC	2003-	AC	6	4,000-4,400	650

* Some railroads, notably NS, request a slightly down-rated version of the basic 4,400hp models.

Locomotive Technology Developments

The key developments in locomotive technology from 1990 to 2006 have been:

- Adoption of electronic controls in all locomotive subsystems, associated with the application of advanced sensors and fault diagnostic systems;
- Continuing development of the diesel engine itself, including low-emissions models to meet EPA Tier 2 requirements for emission standards (see Section 2.1.5);
- Development of AC traction systems;
- Locomotive truck and brake improvements, including radial (steering) trucks and wheel spin/slide protection systems that maximize adhesion available for traction;
- Operator’s cab improvements;
- Development of 6,000 hp engines;
- Hybrid and Genset Locomotives.

ELECTRONIC CONTROLS

Starting with the EMD SD 60 and GE Dash 8 models that were in production at the beginning of the review period, both manufacturers have gradually expanded the application of electronic and microprocessor controls to all locomotive systems. These include:

- The primary controls for engine power output in response to operator controller setting;
- Electronic fuel injection controls to time and shape the fuel charge;
- Control of power electronics that drive the AC or DC traction motors, especially including the three-phase variable voltage, variable frequency invertors that supply AC traction motors;
- Control of engine cooling systems to maintain optimum engine temperature and minimize power consumed by the cooling fan and circulation pump;
- Improved control of power supply to all auxiliary systems including the controls themselves, cab systems (e.g., high-voltage alternating current (HVAC), displays), and brake air compressors.

These improvements yield multiple benefits for fuel economy, increasing the maximum power output from an engine of a given size while reducing harmful emissions and maintaining excellent reliability, availability and maintainability. Improved fuel economy is achieved by:

- Optimizing the fuel/air mixture entering the engine;
- Increasing the efficiency of fuel combustion in the engine cylinder;
- Reducing the fuel consumed by locomotive auxiliary systems such as engine cooling pumps and fans, turbochargers, air compressors, traction motor cooling fans and control electronics;
- Improving the efficiency of the electric transmission system;
- Running diagnostic and condition monitoring systems that optimize locomotive performance.

Aside from the application of electronic controls to new locomotives, the two major locomotive manufacturers and the aftermarket suppliers and rebuilders have also developed various after-market control systems that can be fitted to older locomotives to upgrade performance and reduce fuel consumption. An example is a microprocessor control system for EMD 38 and 40-series locomotives. The resulting improved locomotive appears in fleet lists as a -3 model (e.g., GP 38-3 or SD 40-3).

CONTINUING DIESEL ENGINE DEVELOPMENTS

Both manufacturers have followed a policy of incremental development of their basic engine models, EMD's 710 two-stroke engine and GE's FDL series. Development has generally followed those in other sectors of the diesel engine industry and included refinements to injector design and controls, improvements to the combustion chamber, valves (on four-stroke engines), and the use of more durable materials throughout the engine. In addition, there has been continuous development in turbochargers, inlet air cooling, and controlling engine cooling systems to improve efficiency and durability. In general, mechanical improvements in engine systems (e.g., fuel injectors, combustion chamber design or turbocharger design) have been linked to sensors and control systems to optimize engine performance. As with electronic controls, the improvements yield multiple benefits in fuel economy, increased power, reduced emissions, and reliability. The balance between the benefits is adjusted to achieve a mix that best meets the needs of locomotive operators.

The railroad diesel engine manufacturers (and other firms in the internal combustion engine industry) engage specialist engine development firms, like Ricardo in the UK and AVL in Austria, to help them keep up with the state of the art in rail engine engineering. Recent developments have focused on meeting EPA emissions requirements, while minimizing the potential adverse impact on fuel consumption. GE claims that its Evolution Tier 2 locomotive with the new 12-cylinder GEVO[9] engine has 3% lower fuel consumption at full throttle than the Tier 1 locomotive with the 16-cylinder FDL engine.

AC TRACTION SYSTEMS

AC traction systems replace the traditional DC series-wound traction motor and associated motor controls with a three-phase asynchronous AC traction motor. The AC motor is supplied with variable voltage, variable frequency AC power from a three-phase inverter. Practical high-power inverters became possible with the development of gate turn-off (GTO) thyristors in the 1980s. GTO thyristors are solid-state high-power, high-speed switching devices. Multiple GTO thyristors are used in solid-state inverters to create AC power for the motors from a steady DC input. A later development in power electronics was the insulated gate bipolar transistor (IGBT), which has now replaced the GTO thyristor in rail traction invertors for rail mass transit as well as locomotives. The advantages of AC traction for freight locomotives are:

- Very fine and responsive control of motor torque is possible to maximize useable adhesion. Studies show more than 25% improvement in adhesion and low-speed tractive effort over equivalent DC motors. This enables fewer locomotives to be used wherever locomotive assignment is based on tractive force, resulting in substantial fuel savings. Exhibit 2-6 summarizes the tractive effort difference between AC and DC motors in current (2006) locomotive models from EMD and GE;
- Modest reduction in electrical losses through the motor controls and the motor itself, especially when IGBT inverters are used;
- The motor itself is significantly smaller and lighter for a given power and torque, enabling higher power motors to be accommodated in practical truck designs. The practical limit for DC motors in on the order of 800 hp for a heavy freight locomotive whereas the limit for AC motors is over 1,000 hp;
- AC motors are more reliable and have lower maintenance costs than equivalent DC motors. There is no high-maintenance commutator, and electrical faults are less frequent due to the ingress of less dirt and moisture;
- The speed range for dynamic braking is expanded. The motor is used as a generator in dynamic braking, reducing brake wear especially on long downgrades. In a diesel-electric locomotive, the power generated is dissipated in resistor banks and is not conserved.

[9] GE Evolution Series.

However, the approaching development of hybrid locomotives with on-board power storage will enable fuel conservation.

Exhibit 2-6. Tractive Effort Comparison Between AC and DC Traction Motors

Manufacturer	AC Motors		DC Motors	
	Model	Tractive Effort (lb)*	Model	Tractive Effort (lb)*
EMD	SD70MACe	157,000	SD70M-2	113,000
GE	ES44AC	166,000	ES44	109,000

*Continuous rating

Source: Manufacturers product information

In summary, the fuel efficiency benefits of AC traction systems derive from the following features:

- Use of fewer locomotives with lower total horsepower where locomotive assignment is based on tractive effort and where the tractive effort advantage of AC locomotives can be exploited;
- Lower electrical losses in the electrical transmission, especially where IGBT invertors are used;
- Higher electrical (dynamic) braking capability. At present this benefit is not used, as energy from using motors as generators is dissipated in resistor banks. However, GE has built a demonstrator hybrid line-haul locomotive where braking energy can be conserved, yielding significant fuel efficiency benefits.

GE and EMD have taken somewhat different approaches to AC traction. GE developed their invertors from their rail mass transit experience, using one inverter per axle, thus enabling very fine control of each motor. EMD’s systems are derived from European electric locomotive technology from Siemens AG, and use one inverter per truck (three motors). This inverter installation has fewer components, but control is a little less precise and the wheels on one truck require closely matched diameters. Both manufacturers now use IGBT inverters, which are simpler and have lower electrical power losses.

The primary drawback of AC traction systems is the cost. Although truly comparable costs are hard to obtain, available data suggest that the premium over a DC locomotive was on the order of 40% when AC was first introduced in 1994 but has declined to about 10% in recent years. Since AC became available, sales have been equally divided between DC and AC motor models, as each railroad considered costs and benefits in light of planned applications and their requirements for a return on capital investments.

LOCOMOTIVE TRUCK AND BRAKE IMPROVEMENTS

The two key truck developments were radial trucks and wheel spin/slide protection systems. Radial trucks have a mechanism linking the outer axles of the three-axle truck so that they can assume a near radial position on curves, instead of being constrained by the truck frame to stay parallel. The benefits of radial trucks are a reduction in wheel and rail wear and higher adhesion available for traction. The improvements derive from the fact that a rigid truck negotiating a curve generates significant longitudinal and lateral forces between wheel and rail which are reacted by the wheel flange and by friction at wheel rail interface. Allowing axles to move into the radial position reduces these forces, thereby reducing wear and the portion of available friction used up by curving. Rolling resistance in curves is also reduced, resulting in fuel savings.

Spin/slide systems prevent wheel spinning from the application of excess traction torque by the motors or sliding due to excessive brake force. Either will damage the wheel, and spin sharply reduces tractive effort and can cause a train to stall on a steep upward grade. The systems compare locomotive speed over the ground with wheel rotational speed and reduce either traction or braking effort to control spin or slide. The latest traction control systems are very precise, especially with AC motors, allowing the limited speed difference between wheel and rail that maximizes traction, without allowing the wheel to “break away” and spin.

The fuel efficiency savings from these improvements derive from:

- Higher adhesion;
- Reduction in the number of locomotives assigned to trains where assignment is related to tractive effort rather than power;
- Reduction in rolling resistance from radial trucks.

OPERATOR’S CAB IMPROVEMENTS

The working environment for train crew in the locomotive cab has changed dramatically. At the beginning of the review period (1990), railroads were just beginning to acquire locomotives equipped with a “comfort cab” with improved noise and vibration insulation and a console control desk instead of the traditional control stand. Further developments have added better HVAC systems, electronic instruments and displays, digital communications with the control center, and diagnostic information on locomotive performance. While the improved cab environment and the more detailed information available to the operator do not reduce fuel consumption per se, the capabilities of integrated control and information displays provide a platform for the implementation of systems to aid the engineer in applying fuel conservation strategies. These systems are being offered by the manufacturers as an optional feature. When Global Positioning System (GPS) and Positive Train Control (PTC) systems become available (see Section 2.1.4), train operations can be further refined to reduce consumption while meeting operations and service requirements.

DEVELOPMENT OF 6,000 HP LOCOMOTIVES

When AC drives and motors had become accepted, both leading manufacturers initiated the development of a 6,000 hp locomotive. The lower weight and size of the AC motor permitted

1,000 hp per axle, an increase from the maximum of about 800 hp/axle that is achievable with DC motors. EMD developed a new four-stroke engine, the 265H, reported as providing a 16% reduction in fuel consumption compared with mid 1990s version of the 710 two-stroke model. GE also developed a new 6,000 hp engine in collaboration with an overseas manufacturer. Both manufacturers delivered numerous locomotives to the railroads, but further orders failed to materialize and the 6,000 hp models were discontinued. In EMD's case, the 710 two-stroke engine continued to be the prime mover for the North American market, while locomotives with the 265H engine have been produced for overseas customers (most notably in China).

The fuel efficiency benefits from the 6,000 hp locomotive derive primarily from the fact that fewer locomotives are necessary to pull a train, reducing total train weight, rolling resistance and aerodynamic losses. There would be little change in diesel engine efficiency for GE locomotives as the 6,000 hp diesel engine would employ the same engine technologies as the current 4,400 hp models. In EMD's case, the four-stroke 6,000 hp engine would displace the less efficient two-stroke engine.

In retrospect, the lack of acceptance of the 6,000 hp seemed to reflect the fact that railroads could not make productive use of a much higher power locomotive. All the large Class I railroads at the time were coping with merger-related operations and other problems and would also have been concerned about possible reliability problems from newly-designed engines and a large power increase. Given the undoubted technical benefits if they can be used productively, it is possible that both 6,000 hp locomotives and EMD's 265H engine will be revived in the future. A large order of 6,000 hp locomotives from one of the major Class I railroads would be needed to anchor the revival.

HYBRID AND GENSET LOCOMOTIVES

RailPower Technologies, a Canadian firm, was a pioneer in the development of hybrid locomotives, launching a 2,000 hp switcher with a 300 hp diesel-alternator set and a 1,200 amp-hour bank of batteries. Switching locomotives are an attractive application for a hybrid locomotive, given that full power is only needed intermittently and for relatively short periods. The first hybrid locomotive, the "Green Goat", was delivered in 2001 and approximately 150 are currently in service. In most cases, locomotive purchases have been financed in part by state air quality improvement grants, notably in California and Texas. As with all hybrid and Genset locomotives, the Green Goats are EPA Tier 2 compliant, and show substantial reductions in emissions compared with previous switching locomotives. Fuel consumption improvements of up to 50% in switching and local freight service are claimed. Note that these hybrid locomotives do not use the traction motors as brakes (dynamic braking in railroad terminology) and cannot return regenerated power to the batteries.

A second related development has been the Genset locomotive. Instead of a battery bank, a Genset locomotive is equipped with two or three independent diesel-alternator sets. One set is kept running on a rotating basis to provide basic locomotive functions, and the second and third sets are started as necessary when higher power is needed. The initial development was sponsored by Union Pacific in partnership with National Railway Equipment, with the first locomotive being delivered in 2005. While fuel efficiency gains are not quite as substantial as with the hybrid locomotive, Gensets have proved successful in service and about 250 had been ordered or delivered by early 2007, with every prospect of further growth.

The final development has been a true hybrid line-haul locomotive by GE. Based on the Evolution Series ES44AC, this 4,400 hp unit adds a battery pack to the basic locomotive and redirects dynamic braking power to the battery instead of resistor banks. The control system optimizes power management on the locomotive to minimize overall fuel consumption. A test and demonstration locomotive was unveiled in June 2007, and GE's intent is to complete trials and offer a production version in 2010.

Despite fuel efficiency improvements, the economics behind hybrid and Genset developments remain uncertain. Most purchases of such locomotives to date have been financed in part with air quality improvement grants, and it may be hard to compete with existing four-axle locomotives on the second-hand market.

2.1.3. Non-locomotive Technology Improvements

The primary area of improvement related to non-locomotive technology is in freight car design and related operating practices. Most freight car developments from 1990 to 2006 period have been evolutionary in nature, with ongoing development of established car types. Development has concentrated on intermodal and coal cars for two reasons:

- Intermodal and coal have been the fastest growing market sectors, resulting in a strong demand for new cars;
- Utilization of both car types has been very high (up to 100,000 miles/year), making incremental improvements in fuel consumption relatively valuable, and encouraging investment in improved designs.

In contrast, cars used for other freight commodities have comparatively low utilization and demand is growing more slowly, thus there is much less incentive for investment. These are also the car types that are used for non-intermodal truck-competitive commodities.

The specific developments of interest are:

- 286,000 lb gross weight cars;
- Lightweight car construction;
- Electronically controlled pneumatic brakes;
- Specialized car types;
- Use of distributed power;
- Reduction of rolling resistance through rail lubrication;
- Steerable or radial trucks;
- Low-friction bearings.

286,000 lb Gross Weight Cars

Approximately a decade ago (mid 1990s), the railroad industry approved the use of 286,000 lb (gross weight) cars on the general railroad network. This followed the use of such cars on selected routes by specific agreement among the railroads involved. These "286k" cars can carry significantly more freight compared with the previous standard of 263,000 lb gross weight.

The net effect of adding 286k cars to the fleet was a reduction in the ratio of RTM to GTM, leading to direct savings in fuel consumption. The nationwide reduction in this ratio, as shown in Section 2.1.1, is partially due to the increased use of 286k cars.

Almost all new cars offered by freight car manufacturers are 286k, with the notable exception of pressure tank cars. Most commodities carried in pressure tank cars are highly hazardous and the safety authorities have yet to fully consider the safety implications of heavier cars and finalize applicable safety regulations.

The broadest use of 286k cars has been in coal unit-trains where there is an immediate and substantial benefit from the higher capacity and reduction in gross to revenue ton-mile ratio. Some designs of double-stack intermodal cars also use 286k-equivalent trucks[10] (i.e., up to 143,000 lb on one two-axle freight car truck). Such designs reduce constraints on carrying heavier container combinations. Penetration of 286k cars for mixed freight has been much slower for the following reasons:

- As mentioned earlier in this section, the low utilization of cars and lower traffic growth reduces the incentive to invest in new cars;
- Many of the low-density branch lines used to access railroad customers for this kind of freight have yet to upgrade their track and structures to accommodate 286k cars.

Lightweight Car Construction

The primary objective of building lightweight cars is to increase the weight of freight that can be hauled within the permitted gross car weight, currently 286k. As with many other technical developments, the most attractive application for lightweight designs has been the coal car and other high-productivity bulk-commodity cars. Almost all new coal cars have aluminum bodies, and hopper cars have used composites in the underside hopper doors that are used to unload the cars. In addition, there has been a shift to using the high-side gondola car in place of hopper cars. These cars are unloaded by rotating up-side-down at the destination, saving the weight of hoppers and hopper doors.

More broadly, cars have generally become lighter as a result of the general application of relevant technology developments in mechanical engineering. These developments include a more precise structural design technique using advanced software, higher strength materials, simulation analysis methods for dynamic performance, and improvements in welding technology.

The final development that contributes to lowering the GTM/RTM ratio is higher cubic capacity cars for low-density commodities. By increasing capacity, total weight of freight can be increased with a proportionately lower percentage increase in empty car weight. The end result is a lower GTM/RTM ratio.

Electronically-Controlled Pneumatic (ECP) Brakes

Conventional freight train brakes are purely pneumatic, relying on pressure changes in a compressed air pipe running the length of the train to both apply and release brakes. Brake response times are slow, especially when releasing the brakes, and the level of precision is very

[10] A freight car truck supports the freight car on the track. It consists of a pair of wheel sets (a pair of wheels attached to a transverse axle) and an H-shaped frame with a pivot at the center of the cross member that supports the car body.

limited. There is a risk of causing excessive compression and tension forces in the train, leading to derailments and damaged couplings. Engineers thus have to be very cautious in applying and releasing brakes. This slows down the operation, reduces line capacity, and can lead to unnecessary stop-and-go operation.

The remedy to these problems is to control brakes electronically so that brake application and release can be near-simultaneous on all cars in the train. Also, application force can be graduated to the weight of the car to give uniform deceleration in a train having a mixture of loaded and empty cars. In the past, the railroad industry has been unable to overcome the technical, cost, and institutional barriers to ECP brakes. However, over the last several years, and after several experiments and demonstration projects, a technically and economically workable system has been developed, and industry and safety standards have been developed. The FRA recently (October 16, 2008) published comprehensive regulations for the installation and operation of ECP brakes, including inspection intervals, which will remove any uncertainty regarding their application. The first applications have been on coal unit trains where all cars on a train are of one design and have one owner. In addition, ECP brake intermodal unit train operations have recently begun. In spite of these gains, application to mixed freight is likely to be delayed because all cars in the fleet have to be ECP brake-equipped before benefits are realized. In coal and intermodal unit trains, implementation can be incremental (one train set at a time).

The benefits of ECP brakes include a reduction in delays, increased capacity on lines used by ECP-equipped trains, reduced brake system wear, and safety benefits. Fuel savings would derive from more precise operations, and a reduction in stop-and-go operation related to brake controllability.

Specialized Car Types

Use of specialized car types designed for a specific type of freight has been growing at the expense of generic car types such as the standard box and flat car. Examples of specialized car types are center-spine cars for lumber and other forest products and steel coil cars. Both commodities were traditionally carried on plain flat cars. The principal effects of this evolution are:

- Generally, a higher car capacity, which is positive for fuel efficiency;
- Easier loading and unloading, thereby increasing utilization and thus increasing incentives to invest in new cars (which is indirectly positive for fuel efficiency). Where gondola cars are not used in coal unit trains, rapid discharge hopper cars are used to minimize unloading time and locomotive idling at the destination;
- Often, greater empty mileage due to a lack of backhauls, which is negative for fuel efficiency. However, where opportunities exist, the railroads collaborate in designing a sequence of moves that minimizes empty movements. A good example is the multilevel autorack cars used for new automobiles and light trucks, where circular routings are used to link assembly plants, import docks, and distribution centers;
- Another factor is that many specialized car types are owned or leased to the shipper and used exclusively by that shipper. First, shippers do not have the incentive to invest in fuel-saving features (the exception are coal unit train contracts, under which railroads agree to charge lower rates). Second, shipper-controlled cars are likely to incur more empty mileage situations because the shipper will make little effort to maximize car utilization.

The shipper's focus is on ensuring car availability and the timely delivery of freight to himself or to his customers. Even though there may be minor fuel efficiency penalties, shippers value the added control over their business operations, and the railroad avoids the need for capital investments in cars.

Use of Distributed Power

Distributed power is the practice of placing remotely-controlled locomotives between rail cars along a train. The primary benefit from distributed power is to be able to operate longer trains. Coal trains have been increased from 100 or 110 cars to 135 cars, reducing the number of trains needed to move a given volume of traffic. This effectively increases track capacity and saves train crew costs. Fuel efficiency benefits from distributed power are due to a slight reduction in aerodynamic drag relative to net tons carried and indirect benefits from congestion reduction.

Reduction of rolling resistance through rail lubrication

Trains rely on friction between the track and locomotive wheels in order to move. But when the railcar wheels rub against the sides of rails, as happens especially around curves, unwanted friction occurs, which slows the train and causes wheel wear and increased fuel consumption. To reduce this friction, lubricants are applied to the sides of the rails. However, if these lubricants are washed away or applied unevenly, train derailment may occur.

All major railroads currently use track lubrication to some extent. Wayside lubricators at track curves are quite common. Based on the 1991 Study, a survey found that the portion of locomotives installed with rail flange lubricators was approximately 40% at Conrail and Santa Fe, 22% at Union Pacific, and 10% at Norfolk Southern.

Several advances have been made in this area. Conrail installed a rail lubrication system that applies rail lubricant from the rear of a passing locomotive, thereby reducing track resistance for the following train. They estimated achieving system-wide fuel savings of 7.3% with 80% of their locomotive fleet outfitted with the devices.[11] More recently, Tranergy, working with Texaco, has invented a computerized top-of-rail lubrication system (called SENTRAEN 2000) that can reduce fuel use by an average of 15% (test ranges fell between 12 and 42%).[12] The system is currently being studied at Argonne National Laboratory in conjunction with laser glazing and other technologies.

Steerable or Radial Trucks

A typical rail car truck (or "bogie") features two axles held parallel to each other in an H-shaped truck frame. When the car moves along curved tracks, the axles remain parallel to each other creating an angle between the natural rolling direction of the wheels and the rail (i.e., angle of attack). This angle causes the wheel flange to grind into the side of the rail, producing a lateral force on the rail, increased rolling resistance, and wear of both wheel and rail. The lateral force is transferred to the ties through the rail-tie fasteners, contributing to tie degradation along curves.

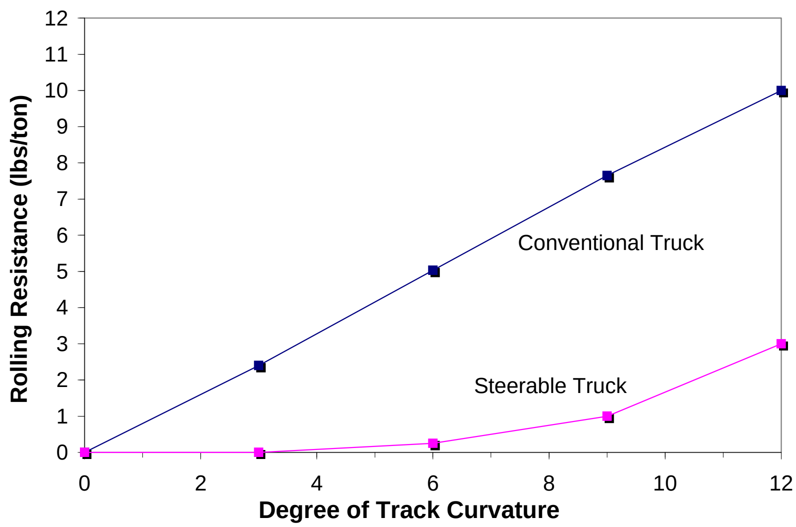
[11] Railway Track and Structures (1986): Conrail launches system-wide rail lubing. March 1986.

[12] Kumar, S. (1999): Top-of-Rail Lubrication System for Energy Reduction in Freight Transport by Rail. SAE Technical Paper 1999-01-2236.

If the wheelsets can move toward a radial position, the lateral forces, wear and resistance can be substantially reduced. Partial radial alignment can be achieved by using rubber pads between the bearing adapters and the truck side frame to allow wheelsets to assume a more radial position. A more effective (but more complex and costly) approach is to allow more longitudinal movement between the bearing housing and side frame, and to add a linkage between the bearing housings. This permits radial alignment but prevents relative parallel movement of one axle relative to the other. The linkage can be rigid rods that connect diagonally opposite bearing housings or a pair of connected Y-shaped yokes.

Radial trucks thus improve fuel economy by lowering rolling resistance, and reducing wear in wheels, rail, and possibly ties. Exhibit 2-7 illustrates the lower rolling resistance that can be gained through steerable trucks.[13]

Exhibit 2-7. Impact of Steerable Trucks on Rolling Resistance



Steerable trucks can improve fuel economy in all types of railroad operations, but their benefits are greatest in bulk commodities. They have less impact on intermodal trains, which often consist of articulated sets of five double-stack platforms that have much higher lateral stiffness and therefore generate less wheel and track wear.

Steerable trucks have clear economic benefits, but are not widely used today. Approximately 5% of rail cars in North American are estimated to include steerable trucks, but their use is confined mainly to Canada.[14] Canadian Pacific Railway has been the most aggressive adopter of this technology. More than 90% of new rail cars are purchased by independent car owners, not railroads. These include major shippers like utilities (coal), agricultural enterprises (grains), manufacturers (chemicals), and intermodal car owners. These car owners benefit only from reduced wheel wear and some of the weight savings. Savings due to reduced fuel use, rail

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[13] Kumar, S., Guowei, Y., Witte, A. (1995): Wheel-rail resistance and energy consumption analysis of cars ontangent track with different lubrication strategies. Proceedings of the 1995 IEEE/ASME Joint Railroad Conference.

[14] Based on conversation with Ken Rownd, TTCI.

wear, and tie wear all accrue to the railroads. Thus, the rail car owners and buyers have little incentive to invest in steerable trucks. Overcoming this barrier will probably require that railroads pass on a portion of the additional savings to the car owners.

Low-friction bearings

Bearing resistance is a significant component of train fuel use on level tangent track. Earlier in the 20th Century, all rail cars used friction bearings. The introduction of tapered roller bearings revolutionized this segment of the industry and substantially reduced rolling resistance. All rail cars now use roller bearings. Advances have been made in railroad axle bearings more recently, but rail car makers have been slow to adopt the new technologies.

Research in the 1980s suggested that the majority of bearing resistance today is caused by sliding friction at the bearing/seal interface.[15] In response, Burlington Northern Railway and the Timken Company developed a new low resistance bearing seal, marketed under the name "HDL Seal". Testing of the improved seal bearing has shown it to reduce total trailing resistance by 5% (at 50 mph) to 14% (at 10 mph) compared to a conventional lip-type bearing seal.

To estimate fuel savings of the improved seal bearings, Timken and Burlington Northern used test results with AAR's RECAP model, simulating loaded and unloaded coal trains on a typical route. The fuel economy gain was 1.6% for the loaded outbound route and 2.2% for the empty return route. Timken considers a 2% fuel savings to be typical for trains on routes with moderate curvature and grade.[16] Fuel savings, in percentage terms, would be larger on flat routes with less curvature, and smaller on mountainous or very curvy routes.

In 2001, Timken has started promotion of advanced low-torque bearings that lower rolling resistance even more. All aspects of these bearings differ from conventional bearings, including the geometry of the bearing itself and the seal. A range of fuel efficiency benefits can be obtained depending the level of investment. At the lower end, Timken estimates that the advanced bearings will yield an additional 2% fuel savings on top of the gain from the HDL Seal bearing, or 4% over conventional bearings.

The cost of the improved seal bearings is only marginally higher (4%) than conventional bearings. The improved seal bearings are currently used by a significant niche market, estimated to be 25% of U.S. rail ton-miles.[16] The cost for advanced low-torque bearings is considerably higher than conventional bearings. Because they have been released very recently, they have very low market penetration.

2.1.4. Operational and Train Control Improvements

Train Control Systems

The dominant method of train control used on North American freight railroad main lines is Centralized Traffic Control (CTC). CTC combines distributed safety controls with centralized management and train routing. The safety controls, called interlockings and block systems, prevent conflicting train movements if trains comply with signals and operating instructions. The central dispatcher offices can "see" the location of all trains in a given area, which can optimize

[15] See footnote 12.

[16] Based on conversation with Jim Mulder, The Timken Company.

train movements to either minimize fuel consumption or maximize capacity. Computer aided dispatching (CAD) systems are used to support the dispatcher's decision-making. Particularly, CAD systems can predict the consequences of various meet-and-pass strategies for operating a specific line segment and optimize operations. To date, the main focus has been on maximizing rail throughput and avoiding train delays. Avoiding delays will reduce fuel consumption, and further savings could result if CAD systems were programmed to consider fuel consumption effects.

Over the period 1990 – 2006, CTC and CAD have been implemented on most lines where they are economically justified, replacing older signal systems and signaling some formerly "dark" lines where trains were controlled by verbal train orders transmitted over voice radio. The next step will be to introduce positive train control (PTC) systems. In these systems, train movement instructions are transmitted directly to the locomotive over high-integrity digital radio links as opposed to line side visual signals, and train location is tracked by GPS and wayside transponders. Development of PTC systems has now reached the point where service applications appear technically and economically feasible.

CTC, CAD and PTC can all contribute to reduced fuel consumption by improving the precision of railroad operations, and by reducing wasteful stop-go or "hurry up and wait" events. PTC in particular can provide a communications and cab display platform for the implementation of automated systems that calculate and display to the operator optimized throttle and brake settings to meet service needs with minimum fuel consumption.

Communications and Management Information Systems

As in other industries, railroads have been developing and applying innovative communications and management information systems (MIS) to manage their operations more efficiently. Fuel saving per se is rarely the exclusive objective of such developments, but many have fuel saving as one of several benefits. Examples include:

- Freight car scheduling and tracking systems which help minimize empty freight car mileage. These systems are also linked to classification yard systems that manage activities that move cars to the correct outbound train. These systems optimize yard movements to reduce locomotive and crew hours and reduce car dwell time in the yard. They also serve to reduce errors inherent in manual systems and reduce the need to re-switch cars. Fuel consumption is reduced as well as other costly inputs;
- Remote monitoring of locomotive health. On-board sensors monitor the health of the engine and either store the data for download in the maintenance shop or directly transmit the data over a data link to the maintenance department. These sensors enable the maintenance staff to spot developing faults before they cause delay. Often maintenance services are now managed by the locomotive manufacturer who benefits from close monitoring of their product performance. This helps ensure engines are maintained in good condition, and situations that could lead to inefficient operation or cause an en-route failure are detected and corrected;
- Digital data links between control centers and locomotives and track maintenance crews. The data links are used to transmit operations data to the train and work crews. Examples include guiding track crews to where automated inspection systems have detected a possible fault or transmitting optimum freight car drop-off and pick-up schedules to local freight trains;

- Maintenance management systems that record and maintain a database of inspection and condition measurements on track, structures, locomotives, and freight cars. These systems collect inspection data, for example, from on-board diagnostics (for locomotives), automated rail flaw and track geometry inspection systems (for track), and wayside hot wheel and bearing detectors (for freight cars). Changes over time can be analyzed to predict the optimum time at which maintenance action is required. The systems improve the timeliness and effectiveness of maintenance operations and reduce in-service failures that can cause delays and accidents. Fuel saving is not a primary objective, but reducing delays and disruption to normal operations does yield fuel benefits;
- In parallel with improved maintenance management systems, new inspection systems are continually being developed. Examples include continuous track lateral strength measurements, in motion measurement of wheel and rail cross-section profiles for compliance with wear limits, machine vision inspection systems to detect displaced or damaged car components, and impact detectors to detect flat wheels.

Speed Reduction

Trains can increase fuel efficiency by operating at lower maximum line-haul speeds. Several major railroads have reduced operating speeds on one or more lines in an effort to cope with higher fuel prices. For example, BNSF began in January 2001 to operate eastbound intermodal trains between New Mexico and Chicago at a maximum speed of 60 mph rather than 70. In 1999, Canadian Pacific (CP) introduced an operating plan that reduced the maximum speed of many of its trains. Authorized speeds for CP intermodal and mixed freight trains are now 49 mph, instead of 55 to 60 mph. Bulk freight movements are limited to 45 mph. Several years ago, Conrail began limiting the speed of its intermodal trains to 60 mph, down from 70. The move reportedly saved the company $4 million annually in fuel costs, while lengthening Chicago-New Jersey transit times by about an hour.

2.1.5. Impediments to Implementation of Fuel-Saving Actions

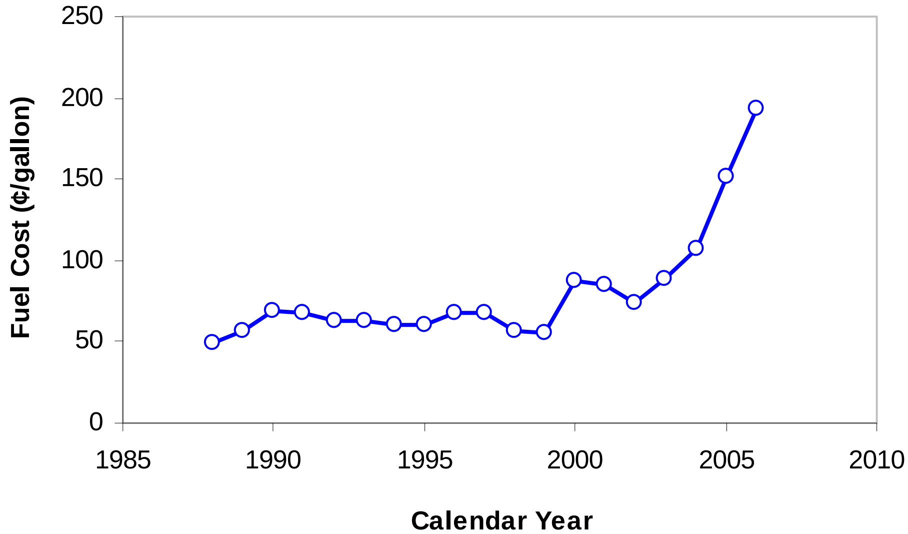
There have been two key and related impediments to the implementation of fuel saving technologies by railroads over the past 15 years. As previously indicated, railroad traffic has been growing rapidly throughout the study period. This growth and the associated increase in traffic density have both created congestion problems on the main line network and have dominated investment and management priorities.

Competing Priorities

Although railroads have made significant efficiency gains over the review period, fuel efficiency had not been a high priority. Fuel costs were reasonable prior to the sharp rise in 2005 and 2006 (Exhibit 2-8), and the value of fuel efficiency savings was limited.

Although fuel costs have always been a major railroad expense item, prices did not reach a level that would prompt high priority action until 2005, and any actions taken at that time have not yet had a measurable impact on the fuel efficiency trend. Instead, railroad resources have been concentrated on network and rolling stock maintenance, capacity expansion to meet demand, and implementing technologies that have multiple benefits, such as many of those mentioned in the previous sections. Technologies and operating methods that focused exclusively or principally on fuel saving were of lower priority. Now with the markedly higher fuel prices, it is likely that many of these potential improvements will be put into practice.

Exhibit 2-8. Cost of Diesel Fuel to Railroads

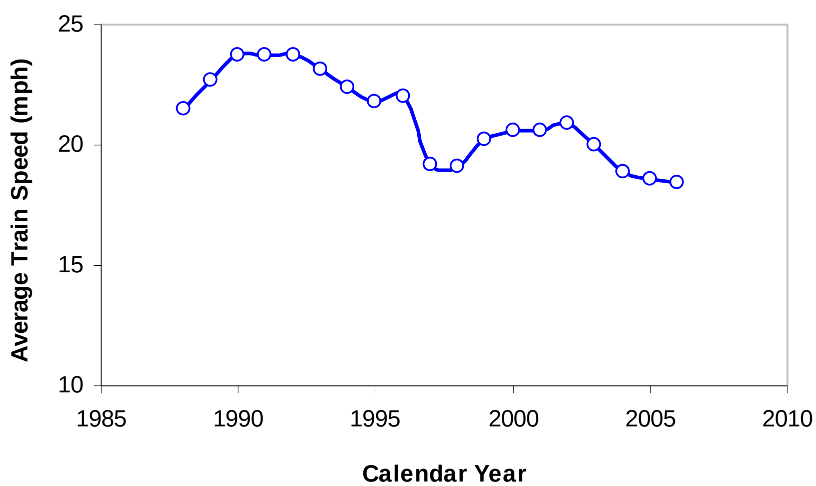


Source: Association of American Railroads

Increasing Rail Congestion

A key consequence of the rapid growth in rail traffic has been a parallel increase in traffic density. Average density on the Class I railroad network increased from 9.9 train-miles per route mile to 16.3 train-miles per route mile after adjusting for low-density tracks sold to short-line and regional railroads during this period. This represented an increase of 65%, which has not been fully matched by investments in additional route capacity. The result has been growing congestion, leading to a substantial reduction in average train speed, as illustrated in Exhibit 2-9.

Exhibit 2-9. Change in Average Train Speed (mph)



The chart also shows the sharp dip in average train speed in the late 1990s. This was due to significant operations problems following the major railroad mergers and acquisitions, most notably the merger of Southern Pacific with the Union Pacific in 1996 and CSX and Norfolk Southern's acquisition of Conrail in 1999. The railroads were unable to fully compensate for these problems in the face of rising traffic, and average train speed in 2006 was the lowest during the entire period.

Declining average train speed has had a significant adverse effect on fuel efficiency, as illustrated by two statistics. The first is GTM per hp-mile, a measure of the locomotive power assigned to trains. This measure has changed little. The second is a similar measure, GTM per hp-hour, which has declined from 12.36 to 10.38 (a change of 19%). The additional time would have been consumed in additional stops and starts and idling in sidings waiting for meets and passes, crew changes, and similar operations events. Our estimates indicate that fuel consumption could have increased by 2-4% from additional idling time, fuel consumption at idle, and the number of additional stops and starts.

Congestion has also had multiple adverse impacts apart from fuel efficiency. These include lower locomotive and crew productivity and reduced service quality for customers.

Implementation of Emissions Regulations for Locomotives

The U.S. EPA finalized emission standards for locomotives in April 1998, which took effect in 2000. These standards involve three tiers, based on the year of original locomotive engine manufacture. The Tier 0 emission standards apply to locomotives and engines originally manufactured from 1973 through 2001, any time the engine is manufactured or remanufactured. Tier 1 standards apply to original model years between 2002 through 2004. Tier 2 standards apply to original model years of 2005 and later. In July 1998, BNSF and UP signed a Memorandum of Understanding with the Air Resources Board (ARB) that requires early introduction of Tier 2 locomotives into the South Coast Air Basin, such that both railroads must achieve a fleet average Tier 2 standard in the basin by 2010.

EPA recently announced proposed new emission standards for locomotives.[17] The proposed emission standards include a retrofit of existing equipment as well as new engine emission standards (Tier 3 and Tier 4). Existing Tier 0, 1, and 2 engines will be subject to retrofit at the time of rebuild, so the engines will be rebuilt gradually throughout their remaining useful life.

The EPA regulations at some level apply to all locomotives in 2000 and after. A total of 5,552 new locomotives were put into service by Class I railroads over the period 2000-2006, plus 250 rebuilt locomotives for a total of 5,802. This is 25% of the fleet, but given the higher power and more intensive use of newer locomotives, they probably handled 35-40% of total GTM.

The imposition of more stringent emissions standards can have a negative effect on fuel efficiency if not implemented in conjunction with other engine design improvements. This is due to adjustments to engine functions to reduce emissions (e.g., injector timing, valve timing, turbocharger settings to change the air fuel mixture introduced into the engine, and the addition of systems to remove pollutants from the exhaust gases) can reduce either power output or engine efficiency.

[17] U.S. Environmental Protection Agency (2008): Regulatory Impact Analysis—Control of Emissions of Air Pollution from Locomotive Engines and Marine Compression Ignition Engines Less than 30 Liters per Cylinder. EPA420-R-08-001a. May 2008. Available online at http://www.epa.gov/otaq/regs/nonroad/420r08001a.pdf.

As well as the nationally-applicable EPA regulations, more stringent regulations in areas of poor air quality (most notable in the Los Angeles Basin and around Houston TX) also apply. In 2005 for example, the California Air Resources Board established a Rail Yard Agreement with UP and BNSF that obligates the railroads to significantly reduce diesel emissions in and around rail yards in California. Among other provisions, the agreement includes a statewide idling-reduction program and health risk assessments for all major rail yards.

Reduction of Locomotive Idling

Locomotive diesel engines do not use antifreeze in the engine coolant because antifreeze reduces the thermal capacity of the cooling fluid and would require larger radiators to adequately cool the engine. Fitting larger radiators in the limited space in a locomotive is difficult which supports the choice not to use antifreeze. Because of the lack of antifreeze, and because engine starts could be unreliable with older models, railroad practice has been to leave engines idling continuously, except when trains were at a locomotive terminal and the temperature was not expected to go below 40^{o}F. In recent years, railroads have tried to reduce unnecessary idling in warmer seasons, with partial success. Train crews and local managers can be resistant to changing established practice. In addition, newer locomotive models have lower idling fuel consumption, reducing the incentive to institute idling-reduction practices. Further reductions require more consistent application of no idling practices and/or the addition of a feature to restart the engine automatically when temperature falls below a preset value, or use of an auxiliary generator to heat and circulate engine fluids. Auxiliary diesel generator sets are often used in commuter passenger locomotives to save fuel and avoid community objections to overnight idling of locomotives but have not been widely applied in the freight community.

2.1.6. Summary of Findings

The overall gain in fuel efficiency on Class I U.S. railroads from 1990-2006 has been 21.5%, or a compound rate of 1.2% per year. The gain is the net effect of a mix of technical improvements in railroad plant, equipment, and operations. The principal contributors to the gain are:

- Introduction of new, more efficient locomotives. Over 13,000 new high-power locomotives were purchased in the period, replacing the majority of locomotives used for main line operations. The key technical improvements in locomotives responsible for the most of the fuel efficiency improvement since 1990 are more efficient diesel engines, extensive use of advanced electronic controls and sensors in all locomotive subsystems, improved truck designs, and the use of three-phase AC traction motors in about half of the new locomotives. At the same time, the locomotive builders bought their diesel engine designs into compliance with EPA Tier 2 emissions requirements by the due date of 1/1/2005, as described in the previous section;
- Technical improvements in railroad freight cars, most importantly the increase in allowed total car weight from 263,000 lb to 286,000 lbs over most of the U.S. railroad network. This increase in total car weight increases the ratio of payload to empty weight for all car types, leading to a direct reduction in the GTM/RTM ratio and, hence, power consumption for a given volume of revenue freight. Other freight car developments contributing to fuel efficiency gains include lightweight construction of cars, rail lubrication systems, distributed power and greater use of specialized car types for specific commodities that maximize the weight or volume of cargo carried in one car. Radial trucks, low-friction

bearings and electronically-controlled brakes will provide further reduction in fuel consumption as they are applied more widely;

- Improvements in operating efficiency, aided by extensive use of updated information and communications systems. Benefits include a reduction in freight car empty mileage and generally more efficient operations. These developments were supported by wider application of CTC and computer aided dispatching,

The principal barrier to larger fuel efficiency gains over the period has been operations and congestion problems. These problems have reduced the average speed of freight trains from 22-24 mph in the early 1990s to 17-19 mph at the end of the period, leading to longer delays at passing sidings and more stop-go operation. A secondary factor has been that diesel fuel prices remained moderate until the sharp rise after 2004, blunting incentives to introduce fuel-saving technologies and operating methods.

The gains in fuel efficiency have not been distributed evenly over the three principal traffic categories – coal, intermodal, and mixed freight. Coal and intermodal have been favored in freight car investments and in allocation of the newest locomotives, because these sectors are growing fastest and, as all-unit-train operations, can utilize new equipment very intensively. Exhibit 2-10 provides an indication of how fuel efficiency developments have impacted the traffic sectors (more stars represent a higher impact).

Exhibit 2-10. Application of Improvements to Railroad Traffic Sectors

Improvement Area	Improvement Category	Coal	Intermodal	Mixed Freight
Diesel Locomotives	AC Traction	★★★	★★	★
	Diesel Engine	★★★	★★★	★★★
	Electronic Controls	★★★	★★★	★★
	Trucks	★★★	★★★	★★★
	Auxiliary Systems	★★★	★★★	★★★
Freight cars	286k cars	★★★	★★	★
	Lightweight Construction	★★★	★★	★
	Electronic Brakes	★★	★	N/A at present
	Specialized Types	★	★★	★★★
Operations Management	CTC and CAD	★★	★★	★★★
	Info and Communications Systems	★	★★	★★★
Estimated Total Growth in Fuel Efficiency 1990-2006		24-26%	20-22%	18-20%
Estimated Annual Growth in Fuel Efficiency 1990-2006 (CAGR)		1.4%	1.2%	1.1%

2.2. Truck Fuel Efficiency

2.2.1. Overall Evolution of Truck Fuel Efficiency

There are two national data sources for truck fuel economy. The U.S. Federal Highway Administration (FHWA) Highway Statistics reports an aggregate estimate of truck fuel economy derived from state data on diesel fuel sales and miles traveled.[18] The U.S. Bureau of Census 1992 Truck Inventory and Use Survey (TIUS) and the 1997 and 2002 Vehicle Inventory and Use Surveys (VIUS) report truck fuel economy based on survey responses.[19] Due to these methodological differences, a direct comparison of truck fuel economy between these two sources is not recommended.

Although the FHWA data provide annual statistics (the VIUS data only provide three data points), there was a change in its methodology that caused a discontinuity between 1998 and 1999, when a substantial drop in truck fuel economy is observed (Exhibit 2-11). After fuel improvements between 1999 and 2004, it appears that fuel economy for combination trucks dropped in 2005 and 2006 (the two most recent years for which data are available). The reasons behind such decrease in fuel efficiency are not well understood. Besides the market demand for more powerful engines, the implementation of NO_x and PM control devices may also have compromised fuel efficiency.[20] Most engine manufacturers met the 2004 emission standards with a combination of combustion modifications, better turbo-charging, and exhaust gas recirculation (EGR). Truck manufacturers improved truck aerodynamics and reduced truck tare weight to compensate for emission controls, but the net result may have been a slight drop in fuel economy for most trucks.[21]

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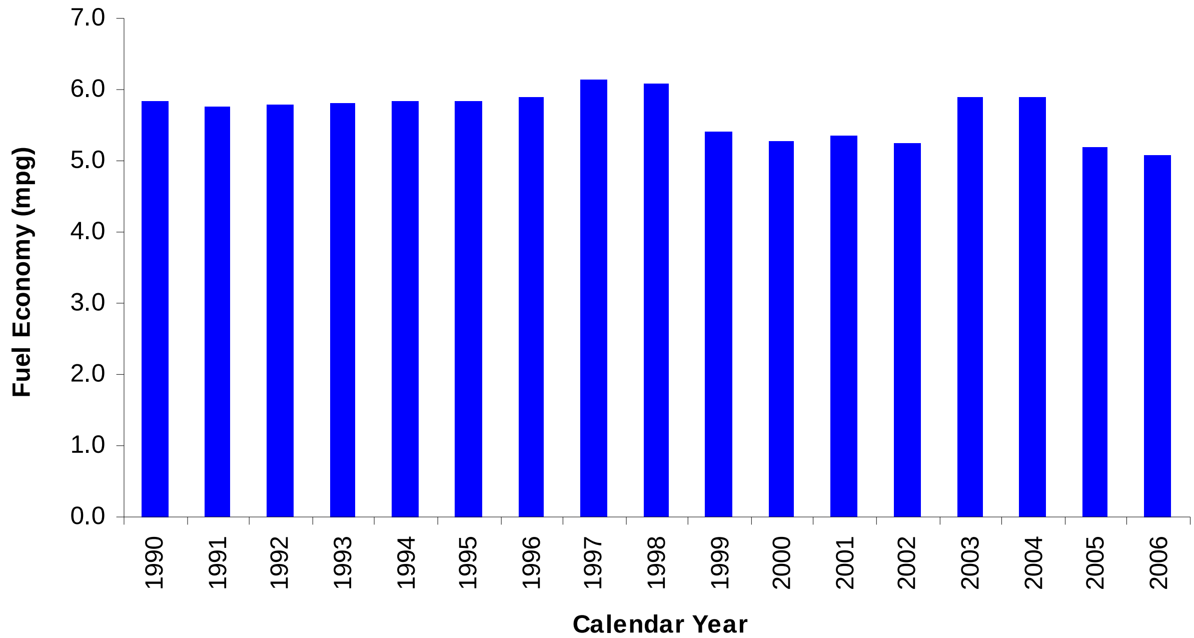
[18] Federal Highway Administration (1990-2006): Highway Statistics. Available online at http://www.fhwa.dot.gov/policy/ohpi/hss/hsspubs.htm

[19] U.S. Department of Census (1992, 1997, 2002): 1992 Truck Inventory and Use Survey (TIUS), and 1997/2002 Vehicle Inventory and Use Survey (VIUS).

[20] Because NO_x is normally reduced in a fuel rich environment (i.e., there is relatively more fuel than air in the combustion mixture than it is necessary for complete combustion) and diesel trucks usually operate in a fuel lean environment, extra fuel is needed to be injected into the after-treatment device to reduce NO_x emissions.

[21] ICF International (2003): Truck Fuel Economy Trends. Memorandum from Lou Browning and Larry O'Rourke to Matthew Payne (EPA).

Exhibit 2-11. Average Combination Truck Fuel Economy in miles per gallon (Highway Statistics)



VIUS data are generally thought as more reliable because it is based on surveys that collect fuel economy information directly from truck owners, rather than on aggregate data. However, the surveys that feed into VIUS are only performed at four-year intervals, and the latest dataset, based on 2002, is currently outdated.[22] Nonetheless, VIUS data enable the evaluation of trends in fuel economy of long and short-haul fleets separately, as opposed to the aggregate fuel economy depicted in Exhibit 2-11. Between 1992 and 2002, fuel economy for the long-haul and short-haul truck fleets improved by about 11 and 16%, respectively (Exhibit 2-12). The reasons for this increase are discussed in the following section.

Exhibit 2-12. Average Truck Fuel Economy (miles per gallon)[23]

Year	Long-haul	Short-haul
1992	5.5	4.9
1997	5.9	5.4
2002	6.1	5.7
Improvement 1992-2002	11%	16%
Compounded Annual Growth Rate (CAGR)	1%	1.5%

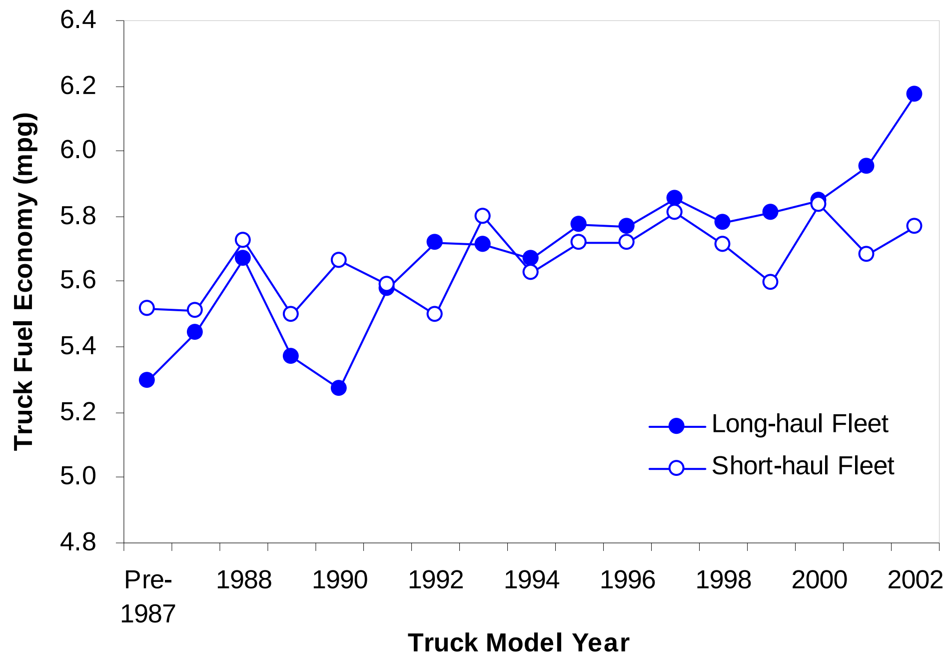
The 2002 VIUS was also used to estimate truck fuel economy by model year, as opposed to the average truck fuel economy included in Exhibits 2-11 and 2-12. In Exhibit 2-13, it is clear that, other than a reduction around 1990, long-haul truck fleet fuel economy has been improving,

[22] The 2007 VIUS was canceled due to lack of funding.

[23] See footnote 19.

especially in the latest model years (after 2000). The trends for the short-haul fleet are not as clear, but data also indicate an overall increase in fuel economy.

Exhibit 2-13. Truck Fuel Economy by Model Year (VIUS)



Truck efficiency can be measured in ton-miles per gallon of fuel. Using U.S. Bureau of Census 1992 TIUS and the 1997 and 2002 VIUS data[24], this analysis calculated diesel combination truck cargo efficiency. First the datasets were parsed to contain only Class 8 diesel heavy duty tractor trailers with a three axle tractor and a two axle trailer. Then datasets were split into a short-haul truck fleet (which travels 50 miles or less from its home base), and a long-haul truck fleet (which travels 200 miles or more from its home base). The short-haul truck fleet generally operates with more pickup and delivery stops, including transfers at cross-dock facilities. Drayage trucks that are responsible for the transfer of goods between shippers and rail yards tend to be short-haul trucks. The long-haul truck fleet represents those trucks that haul goods on intercity routes. Truck efficiency was determined by multiplying fuel economy by the average shipment weight.

Truck efficiency of the short-haul fleet improved about 11% while long-haul fleet truck efficiency improved about 8% from 1992 to 2002 as shown in Exhibit 2-14. Short-haul trucks tend to have lower truck efficiency than long-haul trucks due to a number of factors, such as shorter trips, more intermediate stops (sometimes to a cross-dock facility), and more idling time as well as an older fleet.

[24] See footnote 19.

Exhibit 2-14. Truck Efficiency in ton-miles per gallon

Year	Long-haul	Short-haul
1992	111.1	106.3
1997	111.2	107.7
2002	119.8	117.5
Improvement 1992-2002	8%	11%
Compounded Annual Growth Rate (CAGR)	0.76%	1%

The following sections describe how truck fuel economy has been affected by truck engine improvements and emission regulations (Section 2.2.2), non-engine technological improvements and changes in fleet composition (Section 2.2.3), and operational factors (Section 2.2.4). It is virtually impossible to quantify the individual impact of each of these factors on the average truck fuel economy due to: (1) data collection issues and uncertainty associated with fuel economy estimates, (2) the fact that different technologies apply to different types of truck fleets, (3) different penetration rates, and (4) uncertainty associated with the effect of certain factors on fuel economy, especially operational factors.

2.2.2. Truck Engine Improvements and Effects of Emission Regulations

U.S. emission standards for heavy duty engines are given in Exhibit 2-15. One of the largest improvements in truck engine fuel economy came in the early 1990s when most engines switched to electronic fuel injection, air-to-air aftercooling, and turbocharging. Turbocharging and air-to-air aftercooling increased engine power while reducing nitrogen oxides (NO_x) emissions by allowing a larger charge of air to enter the engine and also reduce peak combustion temperatures. It also allowed engines to run leaner (less fuel) which improved fuel economy. Electronic fuel injection allowed more precise control of fuel injection timing and the amount of fuel used, thereby enabling engine manufacturers to optimize fuel consumption while meeting emission standards. Electronic control also allowed manufacturers to utilize “defeat devices” which sensed when the truck engine was being emission tested and when it was on the road. Manufacturers used these defeat devices to optimize emissions when on an emissions test cycle, but optimize fuel consumption at the price of emissions when driving over the road. In many cases, NO_x emissions were two to three times the standard when operating over the road. In late 1997, the EPA, the Department of Justice (DOJ), and the California Air Resources Board (CARB) had meetings with seven heavy-duty engine manufacturers resulting in a consent decree issued in July 1999. The consent decree required manufacturers to stop building engines with the defeat device, to reprogram the engine controller upon engine rebuild, and to meet 2004 emissions standards for engines built after October 2002. The consent decree requirement to reprogram the engine controller had little short-term effect on truck fleet average fuel economy, because most heavy-duty engines last a million miles before needing to be rebuilt. However, the pull-ahead program (introducing 2004 engines in October 2002) had some impact on truck fleet average fuel economy. Most engines built to meet the 2004 standard use exhaust gas recirculation (EGR), a process in which some of the engine exhaust is rerouted to the engine intake to dilute the charge. While this process can dramatically reduce NO_x emissions, it also reduces fuel economy from 3 to 9%. As a result, many fleets bought their allotment of vehicles for 2002 and 2003 in the first nine months of 2002.[25] This has also been the case before the new emission standards on 2007 trucks (as explained below) were implemented.

Exhibit 2-15. U.S. Heavy Duty Engine Emission Standards in g/bhp-hr

Model Year	CO	HC	NO_x	PM
1974-1978[a]	40.0			
1979-1983[b]	25.0	1.5		
1984-1987	15.5	1.3	10.7	
1988-1989	15.5	1.3	10.7	0.6
1990	15.5	1.3	6.0	0.6
1991-1993	15.5	1.3	5.0	0.25
1994-1997	15.5	1.3	5.0	0.1
1998-2003	15.5	1.3	4.0	0.1
2004-2006[c,d]	15.5	0.5	2.0	0.1
2007-2009[e]	15.5	0.14	1.0	0.01
2010+[e]	*15.5*	*0.14*	*0.2*	0.01
Improvement	61%	91%	98%	98%

[a] Combined HC+NOx emission standard of 16 g/bhp-hr
[b] Combined HC+NOx emission standard of 10 g/bhp-hr
[c] Under a consent decree with U.S. EPA, engine makers implemented the 2004 standards in October 2002.
[d] Standards allow option of 2.4 g/bhp-hr NMHC+NOx or 2.5 g/bhp-hr NMHC+NOx with a 0.5 g/bhp-hr NMHC cap.
[e] 2007/2010 standards start in 2007 and have a three-year phase in for the 0.2 g/bhp-hr NOx standard.

The next change in emission standards occurred for the 2007 model year in which particulate matter (PM) emissions were reduced by 90% and NO_x emissions by 50%. In 2010, NO_x emissions are to be reduced to approximately 10% of the 2004 standard. The EPA estimated that the 2010 emission standard would reduce fuel economy from 5-20% when compared to engines meeting 2004 standards.[26] However, more recent estimates developed by ICF indicate a reduction from 5-10%.

2.2.3. Non-Engine Technology Improvements and Changes in Fleet Composition

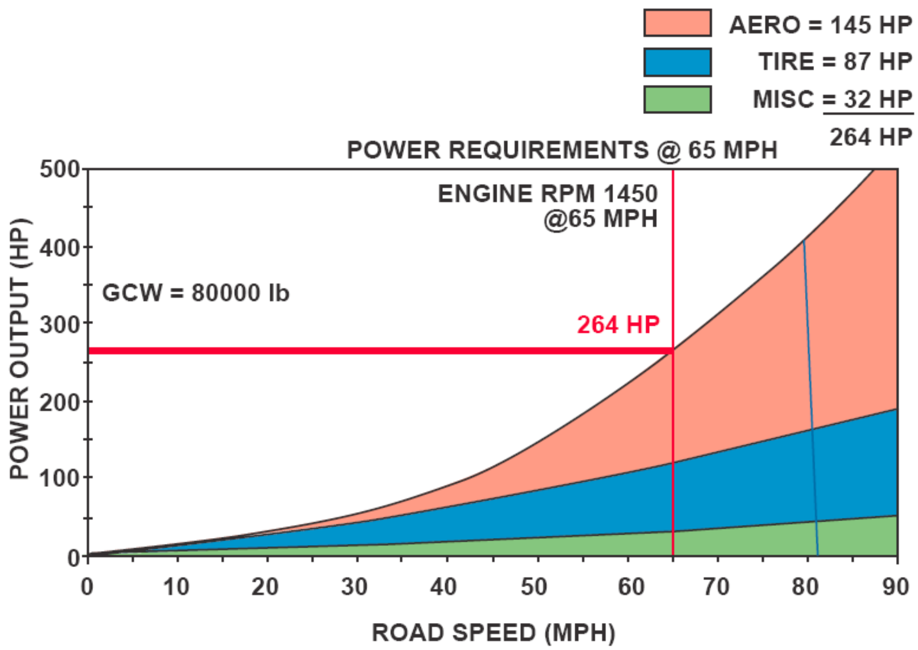
Several non-engine technologies can also increase truck fuel economy. These include aerodynamics, rolling resistance, tare weight reduction, on-board speed governors, improvements in transmissions and lubricants, and idle reduction technologies. In addition, fleet composition can change over time, having an effect on the overall fleet fuel economy.

[25] Merrion, David (2003): Heavy Duty Diesel Emission Regulations – Past, Present, and Future. SAE paper 2003-01-0040, March 2003.

[26] U.S. Environmental Protection Agency (2002): Highway Diesel Progress Review. EPA420-R-02-016.

The amount of power required to move a truck down the road is a factor of four forces (namely aerodynamic drag, grade resistance, tire rolling resistance, and engine accessory/drivetrain losses). Aside from grade resistance, the three forces that can be improved are shown in Exhibit 2-16. As illustrated in Exhibit 2-16, high speed loads are dominated by aerodynamic drag, while lower speed is dominated by rolling resistance. Typically tires make the biggest difference when speed falls below 50 mph, while aerodynamics become the predominant factor affecting fuel economy over 50 mph.

Exhibit 2-16. Level Road Power Requirements



Source: Cummins MPG Guide[27]

Aerodynamics

Aerodynamic drag can be reduced through the use of aerodynamic devices for tractors and trailers. Devices for truck tractors include roof deflectors, integrated cab-roof fairings with closed sides[28], cab extenders, front air dams and others (Exhibit 2-17). All of these devices are in wide use today, as discussed below. Trailer aerodynamic improvements are much less developed. Available devices include trailer side skirts and “boat tails” (Exhibit 2-18). To date, there is little interaction between tractor and trailer manufacturers, and as a result, there has been no effort to treat tractor-trailer aerodynamics as an integrated whole.

[27] Cummins Inc (2007): Cummins MPG Guide, The Secrets of Better Fuel Economy, The Physics of MPG. Available online at http://www.everytime.cummins.com/every/pdf/MPG_Secrets_Whitepaper.pdf

[28] A roof fairing that extends partially over the cab of the truck with enclosed sides.

Exhibit 2-17. Tractor Aerodynamic Devices

Classic profile conventional cab tractor (Peterbilt 379)

Aerodynamic conventional tractor with integrated cab-roof fairing. (Peterbilt 387)

Exhibit 2-18. Trailer Aerodynamic Devices

Full aerodynamic treatment on a truck can increase fuel economy by up to 15% compared with a truck with no aerodynamic devices.[29] As illustrated in Exhibit 2-19, aerodynamic devices are most effective for the long-haul fleet and much less effective for the short-haul fleet. Estimated penetration of aerodynamic devices has increased from 66% of VMT in 1992 to 78% in 2007 for the long-haul fleet and 24% of VMT in 1992 to 48% in 2007 for the short-haul fleet.

Tractor aerodynamic devices have achieved high market penetration among long-haul trucks because of their clear cost-effectiveness, though approximately 20% of these vehicles have the classic profile that reduces efficiency gains.

The 1997 VIUS identifies trucks that report having "aerodynamic features," which presumably means a roof fairing or roof deflector for combination trucks (the 2002 VIUS does not specifically ask which features trucks have). Among van trailer trucks, nearly 70% of the VMT is associated with vehicles with aerodynamic devices (45,100 out of 65,094 million miles). This finding is supported by the American Trucking Association (ATA), which conducted an informal roadside survey several years ago and found that 80 to 90% of van trailer trucks had full roof fairings. Among non-van trailer trucks, 34% of the VMT is associated with vehicles with aerodynamic devices according to the VIUS (12,030 out of 35,814 million miles).

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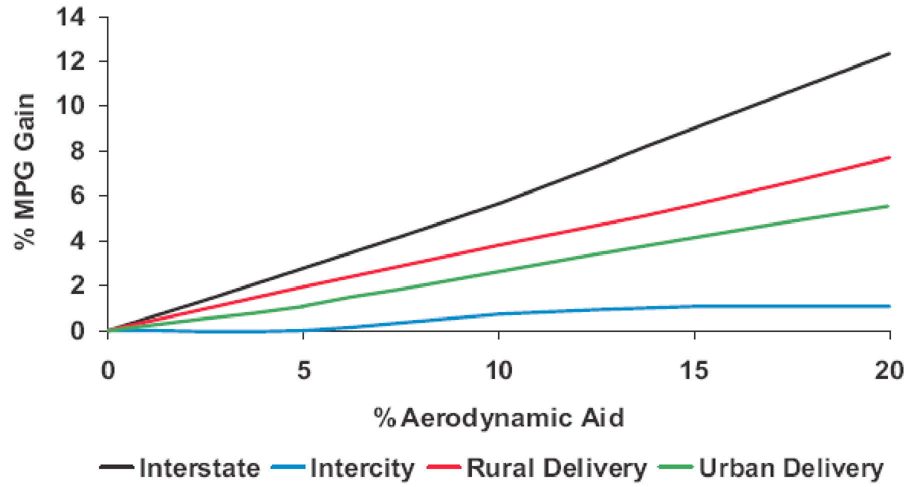
[29] Ang-Olson, Jeffrey and Will Schroeer (2002): Energy Efficiency Strategies for Freight Trucking, Potential Impact on Fuel Use and Greenhouse Gas Emissions. Transportation Research Record Paper No. 02-3877.

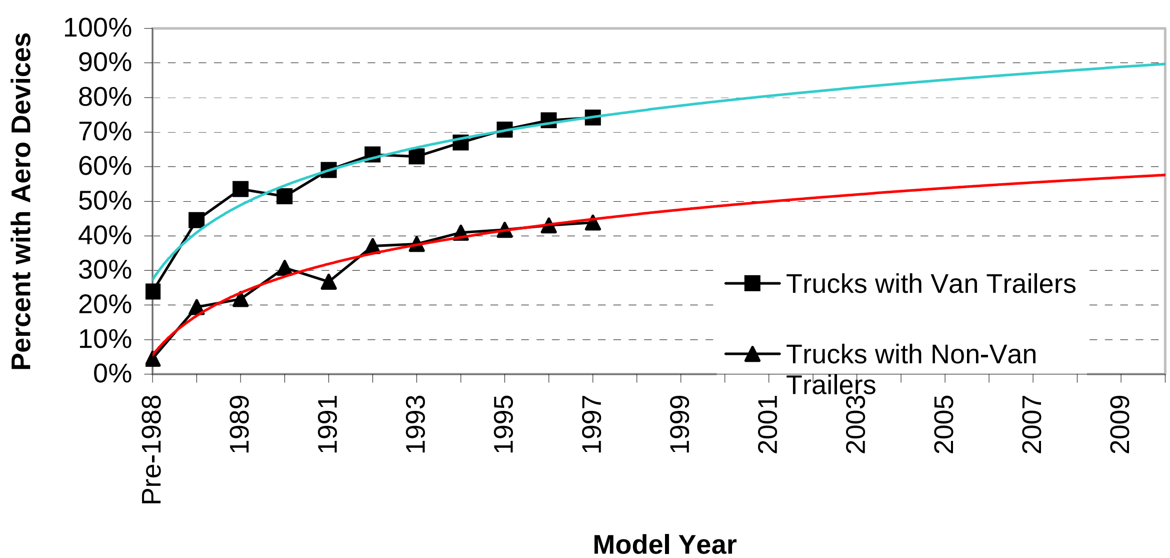
Exhibit 2-19. Aerodynamic Device Effectiveness



Source: Cummins MPG Guide (see footnote 27)

The market penetration of aerodynamic devices on combination trucks has been increasing steadily over the last decade. Exhibit 2-20 shows, for van and non-van trailer combination trucks, the percentage of vehicles that reported having aerodynamic devices by model year. Nearly 75% of model year 1997 van trailer trucks report having aerodynamic devices. (The actual percentage is likely higher because the non-respondents to this VIUS question are indistinguishable from those reporting no aerodynamic devices.) Among combination trucks with non-van trailers (mostly tanks and flatbeds), 44 percent of model year 1997 vehicles report aerodynamic devices. Exhibit 2-20 also shows logarithmic trend lines fitted to the historic data and extended to 2010. If past trends continue, at least 90% of model year 2010 van trailer trucks will have aerodynamic devices, as well as over 50% of the non-van trailer 2010 fleet.

Exhibit 2-20. Aerodynamic Devices by Model Year, with Projections



Rolling Resistance

Reducing tire rolling resistance is the second most significant factor in improving fuel economy of trucks. Rolling resistance results from the tire as it flexes during motion. Wide-based tires, which replace dual tires on a truck's drive and trailer axles, can also improve fuel economy by reducing rolling resistance and tare weight (Exhibit 2-21). Proper tire inflation also reduces rolling resistance and fuel consumption caused by tire under-inflation.

Single wide-based tires can reduce fuel consumption by up to 5% compared to dual tires, but some manufacturers are putting resources into developing double-tires with the same fuel benefits. Although single wide-based tires have been available since the 1980s, they have achieved very little market penetration among long-haul trucks. One reason for this is the concern about lack of redundancy. Because standard tires are mounted in pairs on the truck drive axles and trailers axles, the failure of one will not prevent a truck from driving to the next service station. Some drivers are concerned that failure of a wide-base tire will leave them immobilized. Tire manufacturers dispute this claim, noting that because most tractors and trailers have tandem axles, they can continue to operate with the failure of one wide-base tire. In addition, some states have laws that prevented the use of early models of single-wide based tires due to the higher force they exerted on roads. Although current models of single-wide tires are in compliance with such laws, some fleet managers still believe that they violate state pavement load restrictions.

Exhibit 2-21. Single Wide-based Tires

Proper tire inflation also has an effect on fuel consumption. Every 10 psi[30] of tire under-inflation reduces fuel economy by 1%. Tire inflation monitors are relatively new but could reduce the occurrence of under-inflation.[31] Automatic tire inflation systems are not widely used today. The technology is fairly new, and many fleets are reluctant to install a system without a proven track record. ATA reports that many fleets do not recognize them as cost effective, in part because they do not believe they have a serious problem with tire under-inflation.[32]

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30 Pounds per square inch.

31 See footnote 29.

32 Based on conversation with Robert Braswell, Technical Director, The Maintenance Council, ATA.

Tare Weight Reduction

The empty truck weight (tare weight) can be reduced by purchasing tractor or trailer components made of lightweight materials such as aluminum. Since the majority of long-haul trucks operate volume-limited (cube-out), tare weight reduction reduces gross-vehicle weight and fuel consumption. For trucks that operate weight limited (weigh-out), tare weight reduction allows for more cargo and a reduction in fuel consumption per ton-mile. It should be noted that the potential benefits of freight truck tare weight reduction are more limited than with passenger cars because their payload makes up a much larger portion of total vehicle weight. The payload to weight ratio is typically 65% for a combination truck, compared to 8% for an automobile.[33]

The tare weight of a typical combination truck can be reduced by as much as 10,000 pounds by using lightweight materials, even though most trucks will not be able to achieve reductions this large, in part because of the need for certain accessories or more durable components.[34]

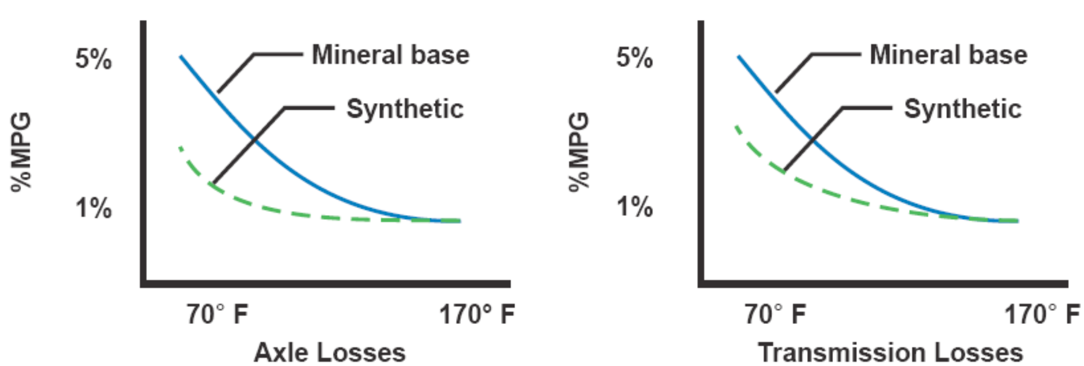
According to ATA, a 3,000-pound reduction in vehicle weight improves fuel economy by approximately 0.11 mpg at 65 mph. This would reduce fuel use by 296 gallons annually (1.8% savings) for a typical long-haul freight truck.

As mentioned, the potential benefits from tare weight reduction are fairly limited due to the high payload to vehicle weight ratio. Truck buyers recognize this and are often unwilling to spend more for small efficiency gains. A lengthy payback period also suggests that this strategy is not cost effective for many fleets. There is also a perception that aluminum components are less durable, particularly tractor frames.

Improvements in Transmissions and Lubricants

Friction losses in the drivetrain (transmission and differential) and engine can be lowered using lower viscosity lubricants. Low viscosity lubricants are usually synthetic and exhibit superior high temperature stability and low temperature fluidity. At normal operating temperatures, there is little difference between synthetics and mineral oils; however, at lower temperatures, frictional losses are reduced significantly with the use of synthetic oils (see Exhibit 2-22).

Exhibit 2-22. Lubrication versus Axle and Transmission Losses



33 Muster, Tobias (2000): Fuel Savings Potential and Costs Considerations for U.S. Class 8 Heavy Duty Trucks through Resistance Reductions and Improved Propulsion Technologies until 2020. Energy Laboratory, Massachusetts Institute of Technology, May 2000.

34 American Trucking Association (1998): The Fleet Manager's Guide to Fuel Economy, The Maintenance Council.

Source: Cummins MPG Guide[35]

Synthetic, low viscosity lubricants are becoming common for transmissions and axles. Eaton, one of the major truck transmission manufacturers, now recommends use of synthetic lubricants for nearly all of its products. Such lubricants have been less common in truck engines, in part because of fleet manager concerns over possible increased engine wear. In addition, the lubricant performance requirements specified by engine manufacturers might exclude (or appear to exclude) some synthetics. Because engine warranties may be voided by not following specified maintenance, fleet managers have been hesitant to try any products not clearly within the manufacturers' recommendations.

Idle Reduction Technology

Idle reduction technology, which includes direct-fired heaters, auxiliary power units (APUs), automatic engine idle systems, and truck stop electrification, can also play an important role in reducing truck fuel consumption. These technologies are particularly effective for the long-haul fleet that tends to idle overnight at rest stops. As shown in Exhibit 2-23, idling can use up to 1.5 gallons per hour. Every hour of idling is equivalent to a 1% decrease in fuel economy in long-haul operation. According to our calculations based on VIUS data, 2007 idle reduction technology penetration is estimated at 15% for the short-haul fleet and 25% for the long-haul fleet.

Exhibit 2-23. Idle Fuel Consumption

Engine Speed (rpm)	Fuel Consumption (gallons per hour)
650	~0.5
1,000	~1.0
1,200	~1.5

Source: Cummins MPG Guide[36]

All idling alternative options currently have low market share. Truck owners have identified safety concerns, retrofitting costs, and unknown reliability as reasons for their reluctance to install direct-fired heaters.[37] While direct-fired heaters have been available for many years in the U.S., their market penetration is limited to approximately 5% of combination trucks.[38] (By comparison, over 55% of European long-haul trucks are reportedly equipped with cab heaters.) APUs are a newer technology. Some truck manufacturers believe that certain APUs may not be compatible with the truck electrical system, possibly causing it to fail under high demand conditions, and that use of some types of APUs may void the truck's warranty.[38] Their current market penetration is very low.[38]

[35] Cummins Inc (2007): Cummins MPG Guide, The Secrets of Better Fuel Economy, The Physics of MPG. Available online at http://www.everytime.cummins.com/every/pdf/MPG_Secrets_Whitepaper.pdf

[36] See footnote 35.

[37] Based on conversations with Whiteside, D. (J.B. Hunt Trucking).

[38] Based on conversations with John Dennehy of Espar Heater Systems, Gary Rosso of Freightliner, Rex Greer of Pony Pack, Jeff Lasley of Detroit Diesel Corporation, and Cummins technical support staff.

Some drivers have been reluctant to use automatic engine idle systems because the starting engine can be disruptive when sleeping in the cab at night. Detroit Diesel first offered the Optimized Idle system in 1997 and reported in 2002 that approximately 20% of their engines included the option (62,000 total vehicles).[38] Cummins began offering their ICON system as an original equipment manufacturer (OEM) option in 2002 and also reported that approximately 20% of new long-haul trucks were choosing the option in that year.[38] This study assumes that the current market share is 20% of all trucks that idle for long periods (those with a majority of travel of at least 500 miles from home base, or 38% of all combination truck VMT). Thus, current market penetration is estimated to be 7.6% of combination truck VMT (20% of 38%).[39]

Truck stop electrification used to be quite rare, and most examples were part of government pilot projects. Currently IdleAire, a private company that provides truck stop electrification systems, has 130 locations throughout the country.[40] The U.S. EPA also provides an interactive map with the location of all electrified truck stops nationwide.[41]

Truck Average Age

Average fleet age for the long-haul fleet has tended to decrease between 1992 and 2002 while the short-haul fleet has tended to get older. Older trucks typically have lower fuel economy, but this could change in the future. Truck age was weighted by VMT. Exhibit 2-24 shows the average age of trucks in the two fleets.

Exhibit 2-24. Average Truck Age in years[42]

Year	Long-haul	Short-haul
1992	4.76	7.73
1997	4.32	8.69
2002	4.18	8.48

2.2.4. Operational Factors

Changes in operational characteristics of truck operations could also have had an effect on truck fuel economy since 1990. There are no studies in the literature that investigated the impacts of operational efficiency on truck fuel economy at the national level. Establishing a strong connection between operational efficiency and fuel economy is difficult because of uncertainties associated with data collection and the challenge of defining operational efficiency.

One measure of operational efficiency is truck utilization (i.e., the share of the truck capacity that is loaded with cargo, measured by weight or by volume). Anecdotal evidence shows that there has been a reduction in truck utilization due to the high growth in the number of small shipments, as well as just-in-time (JIT) systems that rely on frequent shipments that do not

39 VMT percentages based on 1997 VIUS.

40 IdleAire Technologies (2007): IdleAire Locations. Available online at http://www.idleaire.com/

41 U.S. Environmental Protection Agency (2007): Idling Reduction - National Transportation Idle-Free Corridors. Available online at http://www.epa.gov/smartway/idling.htm#iam

42 U.S. Department of Census (1992, 1997, 2002): 1992 Truck Inventory and Use Survey (TIUS), and 1997/2002 Vehicle Inventory and Use Survey (VIUS).

necessarily optimize truck capacity. In a JIT system, inventory is minimized and raw materials and parts arrive at the manufacturing facility as they are needed at the production line, sometimes within just a few hours. In order to fulfill the operational requirements of a JIT system, a given shipment frequency is first determined to match the production line schedule. Therefore, optimizing truck capacity is less of a priority than delivering the shipment at a specific time. The result is that trucks tend not to be as fully utilized as if they had been in other types of service.

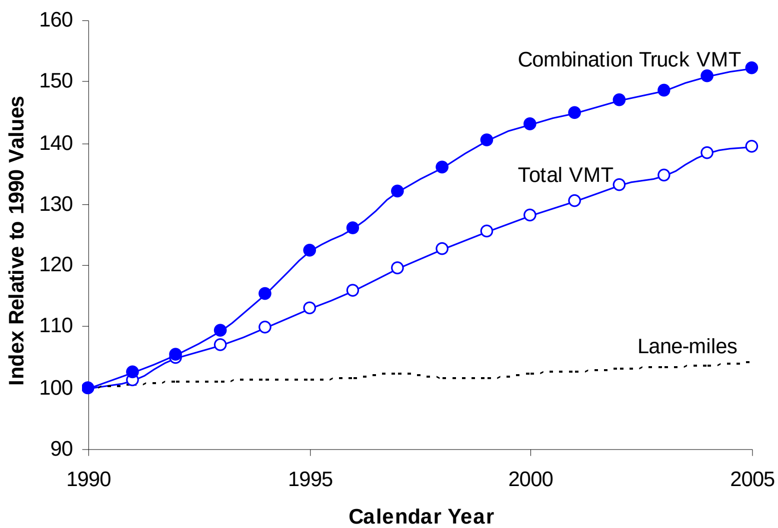
The share of empty miles for a given truck is another measure of operational efficiency. Although fuel consumption increases with truck weight, trucks that are not fully utilized or that are empty consume more fuel per ton-mile, leading to a drop in fuel efficiency. While the share of empty miles has remained relatively constant for the heaviest truck class (Class 8) between 1997 and 1992, it has increased since then (Exhibit 2-25).

Exhibit 2-25. Empty Miles

Year	Long-haul	Short-haul
1992	18.27%	38.72%
1997	17.81%	38.36%
2002	20.41%	42.34%

It might be speculative to imply a correlation between increasing congestion and a possible drop in truck fuel economy at the national level. Commercial trucks generally try to avoid peak traffic hours in urban areas, and state-of-the art information and communications technology can also be used to route drivers around problems due to accidents or weather. However, it is reasonable to expect some effect, given that total VMT (and truck VMT) have been increasing at a significantly faster pace than have roads, measured in lane-miles (Exhibit 2-26).

Exhibit 2-26. Growth in VMT and Lane-Miles (1990-2005)[43]



43 Bureau of Transportation Statistics (2006): National Transportation Statistics Tables 3-8 and 3-9.

Speed Reduction

Truck fuel economy can be improved by reducing highway driving speeds. As speed increases, aerodynamic drag and tire rolling resistance increases thereby reducing fuel economy. For each 1 mph over 55 mph, fuel economy is reduced by 0.1 mpg.[44] Many motor carriers have adopted a maximum speed policy for their drivers as a way to save fuel expenses and to promote safety. These policies can be implemented through electronic engine controls (e.g., on-board speed governors), driver training programs, or incentive programs that monitor truck engine speed and reward drivers for staying within set limits.

Use of on-board speed governors is more effective on long-haul trucks than short-haul trucks because the latter usually never reach high speeds. On-board governor penetration increased from about 50% in 1992 to an estimated 80% in 2007 in the long-haul fleet. The short-haul fleet penetration went from 36% in 1992 to about 49% in 2007.

The elimination of mandatory speed limits may also have marginally reduced truck fuel efficiency since the mid 1990s. In 1995, Congress repealed the national speed limit which dictated a 65 mph limit on interstates and a 55 mph limit on other highways. The law, originally passed in 1974, capped all travel at 55 mph and was modified in 1987 to increase the interstate highway limit. The elimination of this law, which was originally passed as a fuel conservation measure, allowed each state to set its own speed limits. In some cases, states set split speed limits, requiring trucks to travel slightly slower than passenger vehicles. The repeal of this law did not affect many freight trucks, since many were (and continue to be) equipped with on-board speed governors.

2.2.5. Other Factors Affecting Fuel-Saving Strategies

Fuel Costs

One of the factors affecting the implementation of fuel-saving strategies in the trucking industry has been the change in diesel fuel costs. Between 1990 and 2005, there have been two contrasting periods. As illustrated in Exhibit 2-27, diesel fuel costs decreased until the late 1990s, as opposed to the cost of other basic commodities such as food, shelter, and apparel, which have gradually increased in the same time period. After 2001 however, diesel fuel costs have increased exponentially due to strong worldwide demand for oil amongst other factors.

Fuel economy of Class 8 trucks has been increasing from 1992 to 2002, despite a relative drop in diesel costs compared to other commodities. The trucking industry generally operates with extremely low profit margins, which is possibly the main driver behind the increasing truck fuel economy.

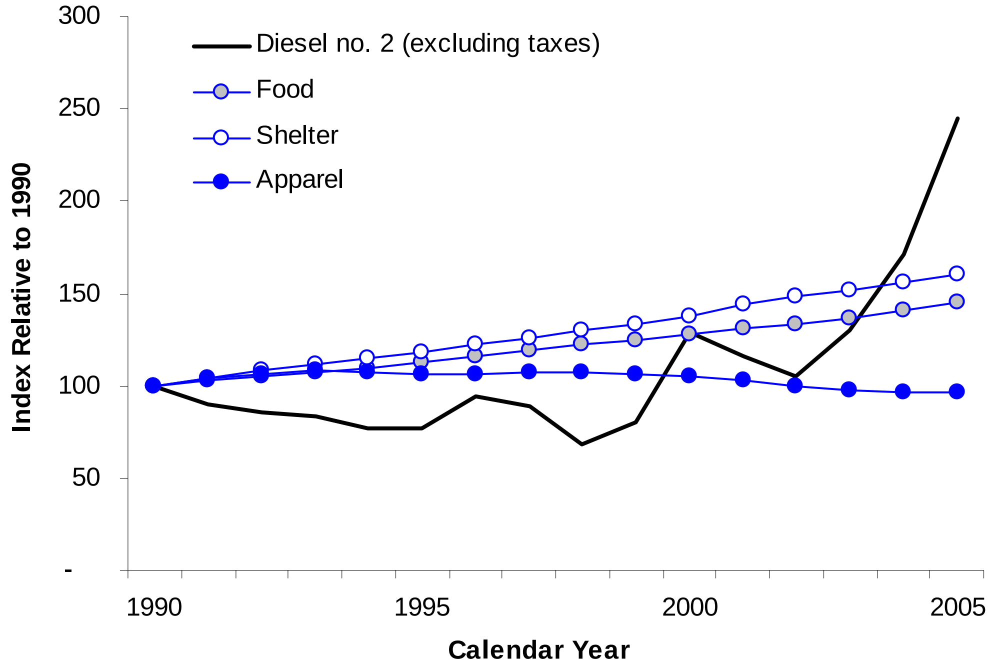
Because the 2007 VIUS will not be issued, it will not be not possible to evaluate the effects of recent fuel price increases (after 2002) on truck fuel economy. As previously described, tracking fuel economy from FHWA's statistics is not ideal due to their aggregate nature.

Fuel costs account for a large portion of truck operating costs. Based on an evaluation by the ATA, fuel costs represent from 16 to 32% of trucking costs, with the variance depending on

[44] Ang-Olson, Jeffrey and Will Schroeer (2002): Energy Efficiency Strategies for Freight Trucking, Potential Impact on Fuel Use and Greenhouse Gas Emissions. Transportation Research Record Paper No. 02-3877.

whether the total includes driver benefits and represents purchased transportation (when a carrier hires an independent carrier to handle a load).[45] Only labor costs (41%) and purchased transportation (23%) tend to be more important cost categories than fuel costs.[46,47] It should be noted, however, that most trucking companies today have fuel price surcharges in their contracts, and therefore are able to pass on the cost of higher fuel prices to shippers.

Exhibit 2-27. Growth in Diesel Fuel Costs Relative to Other Commodities (1990-2005)[48]



Anti-Idling Policies

Through the SmartWay Transport Partnership, the U.S. EPA has developed a national anti-idling program to address environmental and transportation issues associated with long-duration engine idling. About 15 states and many local counties have passed anti-idling policies that are applicable to different vehicle classes.[49] In California, for example, operators of diesel-fueled

45 American Trucking Association (2003): American Trucking Trends 2003

46 U.S. Department of Labor (2007): Occupational Employment and Wage Estimates (1998-2006). Available online at http://www.bls.gov/oes/oes_dl.htm

47 U.S. Department of Labor (2007): Producer Price Indexes. Available online at http://www.bls.gov/ppi/

48 See footnote 43.

49 U.S. Environmental Protection Agency (2007): Idling Reduction – State and Local Laws. Available online at http://www.epa.gov/otaq/smartway/idle-state.htm

trucks, with a gross vehicle weight rating over 10,000 pounds, cannot idle for more than five minutes.[50]

2.2.6. Summary of Findings

Generally, truck efficiency has increased in both the long-haul and short-haul fleet from 1990. The short-haul fleet in particular has shown approximately a 10% increase in truck efficiency while the long-haul fleet has shown about an 8% increase. These improvements were due to more advanced engine technologies (e.g., electronic fuel injection, air-to-air aftercooling, and turbocharging), as well as non-engine technologies and operational improvements. A previous study estimated fuel savings benefits and market penetration for many of the non-engine technologies and operational strategies included in this chapter (Exhibit 2-28).

Exhibit 2-28. Fuel Savings Benefits and Market Penetration[51]

Strategy	Fuel Savings per Participating Truck	2002 Market Penetration (% VMT)*	2002 Maximum Market Penetration (% VMT)
Tractor Aero Features (Non-van Trailer)	3.5%	18%	35%
Tractor Aero Profile (Van Trailer)	3.6%	52%	65%
Improved Trailer Aerodynamics	3.8%	0%	65%
Wide-Base Tires	2.6%	5%	100%
Automatic Tire Inflation Systems	0.6%	5%	100%
Tare Weight Reduction	1.8%	14%	64%
Low-Friction Engine Lubricants	1.5%	10%	100%
Low-Friction Drive Train Lubricants	1.5%	70%	100%
Speed Reduction (70 to 65 mph)	6.0%	49%	63%
Speed Reduction (65 to 60 mph)	7.6%	10%	63%
Idling Reduction (Direct-Fire Heater)	4.3%	5%	38%
Idling Reduction (Auxiliary Power Unit)	8.1%	0%	38%
Idling Reduction (Automatic Engine Idle)	5.6%	8%	38%

*VMT = Vehicle-miles Traveled

50 California Air Resources Board (2007): Heavy-Duty Vehicle Idling Emission Reduction Program. Available online at http://www.arb.ca.gov/msprog/truck-idling/truck-idling.htm

51 Ang-Olson, Jeffrey and Will Schroeer (2002): Energy Efficiency Strategies for Freight Trucking, Potential Impact on Fuel Use and Greenhouse Gas Emissions. Transportation Research Record Paper No. 02-3877.

Chapter 3. Identification of Competing Services and Commodities

This chapter identifies services and commodities in which rail and trucks compete. Competitive movements are defined as those carrying the same commodity and having the same (or proximate) origin and destination (O-D) pairs.

Mode fuel intensity, measured in gallons of fuel per ton-mile, often varies considerably depending on the transportation corridor and on the commodity being hauled. A transportation corridor, here defined as an origin-destination (O-D) pair, is associated with one or more possible routes, each with different levels of circuity and different grade and curvature patterns along railways and highways. Fuel intensity also varies depending on the level of congestion at a given time on a given route. The number of intermodal connections, as well as drayage distances, is also corridor-specific and affects fuel intensity. Commodities move in specific types of equipment, which affect train consist and weight, rolling resistance, and aerodynamic drag factors, which determine, in part, fuel intensity. The same is true for truck configuration and weight.

Each movement identified is associated with a transportation corridor, a commodity, and a service offering, from which a typical equipment configuration is determined. Selection of movements is based on ICF's analysis of the data, and the results were validated by rail industry experts.

This chapter starts with a formal definition of a competitive movement, which is followed by a list of selection criteria. To develop a list of competitive movements, a preliminary list was first created and then refined to obtain the final list. The preliminary list of movements was based on data with states as O-D pairs. Commodities at the 2 or 3-digit level (Appendix I) were used for both the preliminary and final lists.[52] After receiving feedback from key industry stakeholders, a more detailed analysis followed to develop a final list of movements with O-D pairs defined by metropolitan regions. Finally, this chapter presents a comparison of the final list with the movements identified in the 1991 study. This reflects changes in freight movement since 1991.

3.1. Definition of a Competitive Movement

Relative fuel efficiency should be evaluated in movements where rail and trucks are reasonably competitive. In some markets, one mode or the other is so dominant that comparisons between the two would be meaningless. Carriage of bulk commodities (e.g., coal) relies almost entirely on rail, while carriage of high-value and very time-sensitive commodities is dominated by truck or aviation. The focus of this study is on commodities and corridors where rail and trucks compete to a significant degree.

Many criteria affect mode choice, including cost, transit time, reliability, and loss and damage. A competitive movement is here defined as one where mode share is comparable between rail and trucks, and competitive movements do not imply equivalent levels of service. The term

[52] In the CFS and FAF2 databases, we used 2-digit SCTG commodity groups. In the Rail Waybill Sample, we used either the 2-digit or the 3-digit STCC commodity group, depending on the commodity.

"competitive" is here used in an economic sense, meaning that cost and level of service, taken together, are close economic equivalents for shippers in a given market.

3.2. Selection Criteria

The criteria for final selection of movements are shown below. Only criteria 1, 2, and 3 are considered in the preliminary list of competitive movements (Appendix I), which contained more movements than could be realistically analyzed. Additional criteria are used for the final selection (criteria 4 and 5).

1. Movements that had comparable rail and truck mode shares;
2. Movements that were representative in terms of freight activity (measured in ton-miles);
3. A mix of short, medium, and long-distance movements;
4. A mix of different commodities (and thus different types of equipment);
5. A mix of geographic regions.

3.3. Final List of Competitive Movements

As noted above, the final list of movements is based on O-D pairs with metropolitan regions as the end points. The choice of metropolitan regions for O-D pairs was done with FAF2 data (where rail was not intermodal), and Waybill data (where rail was intermodal). For each movement first identified on a state basis, these data were used to identify the metropolitan-region pairs with the highest traffic volumes.

In order to reduce the pool of movements, only those with the highest rankings (95-100) were considered.[53] A few movements were also eliminated because they were not served by the two participating railroads. Exhibit 3-1 includes the final list of movements, accounting for both intermodal and non-intermodal movements. The assignment of rail and truck equipment is described later in this section.

These movements have comparable rail and truck mode shares, are typical in terms of freight activity, and include a mix of short, medium, and long-distance movements. They also reflect differing mixes of rail and truck equipment and geographic regions. Exhibit 3-2 shows the mix of these characteristics for the chosen movements. The Eastern and Western regions were selected to match the participating railroads' networks. Because the Western region is much larger than the Eastern region, short-distance routes were not covered in the Western region, and long-distance routes were not covered in the Eastern region.

[53] An explanation of this ranking system is included in Appendix I.

Exhibit 3-1. Final List of Movements

Movement Number	Geographic Location	Ranking	Origin	Destination	Commodity Group
1	East	95.0	Fort Valley, GA	Jacksonville, FL	Newsprint/paper
2	East	95.5	Columbus, GA	Savannah, GA	Intermodal
3	East	98.7	Detroit, MI	Fort Wayne, IN	Waste/scrap
4	East	97.7	Arcadia, OH	Jacksonville, FL	Intermodal
5	East	95.1	Atlanta, GA	Huntsville, AL	Waste/scrap
6	East	99.2	Chicago, IL	Atlanta, GA	Intermodal
7	East	90.0	Chicago, IL	Atlanta, GA	Other foodstuffs
8	East	97.7	Decatur, IL	Frank, OH	Intermodal
9	East	96.0	Decatur, IL	Frank, OH	Other foodstuffs
10	East	99.0	Detroit, MI	Decatur, IL	Motorized vehicles
11	East	96.0	Dayton, OH	St Louis, MO	Motorized vehicles
12	East	95.8	Toledo, OH	Memphis, TN	Base metals
13	East	95.7	Memphis, TN	Atlanta, GA	Intermodal
14	West	95.8	Chicago, IL	Fargo, MD	Intermodal
15	West	100.0	Oakland, CA	Clovis, NM	Intermodal
16	West	100.0	Chicago, IL	Los Angeles, CA	Intermodal
17	West	N/A	Kansas City, MO	Chicago, IL	Motorized Vehicles
18	West	95.3	Houston, TX	Los Angeles, CA	Intermodal
19	West	97.4	Memphis, TN	Los Angeles, CA	Intermodal
20	West	95.7	Clovis, NM	Memphis, TN	Intermodal
21	West	98.9	Seattle, WA	Chicago, IL	Intermodal
22	West	N/A	Clovis, NM	Atlanta, GA	Intermodal
23	West	N/A	Kansas City, MO	Los Angeles, CA	Fuel

Exhibit 3-2. Mix of Movements

Equipment Type		Eastern Routes		Western Routes	
		Short	Medium	Medium	Long
Rail Equipment	Double Stack	✓	✓	✓	✓
	TOFC		✓		
	Box Car	✓	✓		
	Auto Rack		✓	✓	
	Flat Car				
	Covered Hopper		✓		
	Gondola	✓	✓		
	Tank				✓
Truck Equipment	Container	✓	✓	✓	
	Van Trailer	✓	✓		✓
	Auto Haul		✓	✓	
	Tank		✓		✓
	Flatbed with Sides		✓		
	Dump Trailer	✓	✓		

*Short-distance Movements: < 300 miles; Medium-distance Movements: > 300 and < 1,000; Long-distance Movements: > 1,000 miles

There is reasonable consistency between the commodities analyzed in this study and those included in the 1991 Study. Exhibit 3-3 provides a comparison of the commodity groups selected for both studies. At the 2-digit STCC code, the only difference was in waste and scrap materials, which were excluded from the 1991 Study, but included in this current study. At the 3-digit STCC code, the differences are more apparent. For example, within food and kindred products (STCC 20), canned/preserved fruits, vegetables and seafood were included in the 1991 Study, but not in this study. On the other hand, confectionery products are included in this study but not on the 1991 Study.

Exhibit 3-3. Comparison of Selected Commodity Groups

STCC Number	Commodity Group	1991 Study	This Study
203	Canned/Preserved Fruits, Vegetables or Seafood	✓	✗
204	Grain Mill Products	✓	✓
207	Confectionery or Related Products	✗	✓
208	Beverages or Flavoring Extracts	✓	✓
209	Miscellaneous Food Rations and Kindred Products	✓	✓
242	Sawmill or Planing Mill Products	✓	✓
243	Millwork or Prefabricated Wood Products	✓	✗
26	Pulp, paper, or allied products	✓	✓
281	Industrial Inorganic or Organic Chemicals	✓	✓
282	Plastic Materials or Synthetic Fibers, resins, or rubber	✓	✓
287	Agricultural Chemicals	✗	✓
289	Miscellaneous Chemical Products	✓	✗
402	Waste & Scrap	✗	✓
331	Steel Works, Rolling Mill Products	✓	✓
371	Motor vehicles or equipment	✓	✓
41-47	Containerized Freight	✓	✓

Rail and truck equipment were selected based on the commodity group for each movement. Equipment selection is important because it affects fuel efficiency in two ways. First, the ratio between payload and tare weight affects fuel consumption. Second, rail and truck equipment have different aerodynamic features, which also drive fuel consumption. Appendix J includes both rail and truck equipment for each commodity group.

Chapter 4. Calculation of Rail and Truck Fuel Efficiency

This chapter characterizes rail and truck movements and provides a comparative analysis of rail and truck fuel efficiency. Because freight moved by rail needs to be either trucked in or moved into a terminal area from a rail siding, rail fuel consumption includes the movement between shipper/consignee and the rail yard, which is assumed to be done by rail in the case of mixed freight and by truck (drayage movement) in the case of intermodal shipments. These movements are assumed on both ends of the trip. In the case of truck movements, it is assumed that freight moves directly from shipper to consignee. Fuel consumption associated with truck idling, either during loading/unloading operations, breaks or overnight idling, is also considered.

Rail and truck fuel consumption are compared in 23 movements, which represent lanes and service offerings in which rail and truck compete. The calculation of line-haul fuel consumption for both modes takes into consideration distance, grade profile, speed profile, vehicle characteristics, vehicle weight, and vehicle aerodynamic profile, amongst other parameters.

4.1. Fuel Efficiency Metrics

Rail and truck fuel efficiency are measured and compared in terms of *lading ton-miles per gallon*, which represents the number of tons of freight (excluding equipment tare weight) and the distance (in miles) that can be moved with one gallon of fuel. The calculation is as follows:

$$\text{Ton-miles per Gallon} = \frac{\text{Payload (tons) x Distance (miles)}}{\text{Fuel (gallons)}}$$

Since the main goal of the study is to compare rail and truck fuel efficiency, the *rail-truck fuel efficiency ratio* is the ratio between rail and truck fuel efficiency, both measured in lading ton-miles per gallon as follows:

$$\text{Rail-Truck Fuel Efficiency Ratio} = \frac{\text{Rail Fuel Efficiency (ton-miles/gallon)}}{\text{Truck Fuel Efficiency (ton-miles/gallon)}}$$

Two additional metrics are also considered to evaluate modal efficiency individually (Exhibit 4-1). The first, which applies to rail only, is *trailing ton-miles per gallon*. In contrast to ton-miles per gallon, trailing ton-miles per gallon considers a train's trailing weight (train's gross weight excluding the weight of locomotives), distance traveled, and the fuel consumed by the entire train. *Miles per gallon*, which applies to truck only, is a typical measure of fuel efficiency for on-road vehicles, thus justifying its inclusion in this study. This metric does not take truck payload into account, and consequently cannot be used to compare truck and rail fuel efficiency.

Exhibit 4-1. Fuel Efficiency Metrics

Metric	Applies to Rail	Applies to Truck	Used in Rail Vs Truck Comparison
Ton-Miles per Gallon	✓	✓	Yes
Rail-truck Fuel Efficiency Ratio	✓	✓	Yes
Trailing Ton-Miles per Gallon	✓	✗	No
Miles per Gallon	✗	✓	No

4.2. Rail Fuel Consumption

Rail fuel consumption includes the following elements:

- **Line-haul rail movements:** the line-haul rail movement includes the long-distance segment between origin and destination, and excludes local movements between shippers/consignees and rail yards, as well as rail terminal operations;
- **Truck drayage (for intermodal movements):** truck drayage is required for intermodal shipments of containers and trailers, so two additional truck trips (one on each end of the trip) are included between the shipper/consignee and the intermodal terminal;
- **Intermodal terminal operations (for intermodal movements):** this includes the fuel consumed by yard tractors used by the railroads to move intermodal containers and trailers from the point where they are dropped by an inbound drayage truck to the track location where they are to be loaded onto the rail flatcar. The reverse process occurs at the other end of the trip. Intermodal terminals generally use mobile lifts or side loaders to place containers and trailers directly on the flatcars that are designated to their final destination, so there is no further classification of rail cars after loading;
- **Short branchline rail movements (for non-intermodal movements):** to better represent actual rail movements, this study considers two short branchline rail movements (one on each end of the trip) that transport rail cars between the shipper/consignee and the rail classification yard;
- **Rail switching operations (for non-intermodal movements):** trains that are neither intermodal nor unit trains require further classification of rail cars, and rail switching operations consist of railroad switch movements to classify mixed trains.

Line-haul rail fuel consumption was calculated by two participating railroads with in-house train simulators. Fuel consumed in truck drayage, intermodal terminal operations, short branchline rail movements, and rail car switching was added separately to the line-haul rail fuel consumption. Section 4.2.1 characterizes the rail movements, including all of the above-mentioned elements, and Section 4.2.2 provides the methodology to calculate rail fuel efficiency.

4.2.1. Characterization of Rail Movements

Rail movements are characterized based on the following elements:

- Line-haul route characteristics;
- Locomotive characteristics;
- Consist characteristics;
- Load characteristics;
- Short branchline and switching characteristics;
- Drayage and intermodal terminal characteristics.

Line-Haul Route Characteristics

The train simulators used by the participating railroads use actual rail routes with their grade profile, curvature, and speed limit changes. The following items describe the distance, grade severity, and operational constraints of line-haul rail routes. It was not possible to obtain a measure of curvature severity or the frequency of speed limit changes from all participating railroads, so this study does not consider these two factors explicitly in the analysis of rail fuel efficiency.

- **Distance:** rail routes range from 133 to 2,232 miles, with four short routes (less than 300 miles), ten medium routes (between 300 and 1,000 miles), and nine long routes (over 1,000 miles);
- **Grade severity:** a numeric rating system is used to describe the level of grade severity. The rating numbers range from 1 (low) to 5 (high), and do not represent actual grades. Instead, they are intended to provide a qualitative scale to describe route severity. Grade severity ranges from 1.29 to 2.55, with seven routes between 1 and 1.5, seven routes between 1.5 and 2, five routes between 2 and 2.5, and four routes above 2.5. Some routes cross mountainous areas, but their grade is somewhat offset by longer flat segments. Appendix C provides the methodology to calculate grade severity;
- **Operational constraints:** the simulation of rail line-haul movements was done with consideration to average traffic levels along rail corridors, so train speeds, acceleration and deceleration profiles, and delay reflected actual train operations.

Locomotive Characteristics

The type and number of locomotives were chosen to reflect actual rail operations. The locomotives in this analysis include General Motors 4,000 hp locomotives (D9-40C, SD70) and General Electric 4,380 hp locomotives (C44-9). From two to four locomotives are used in all rail movements, with the majority of movements running with three locomotives. Appendix A lists the specific locomotives assumed for each rail movement.

Consist Characteristics

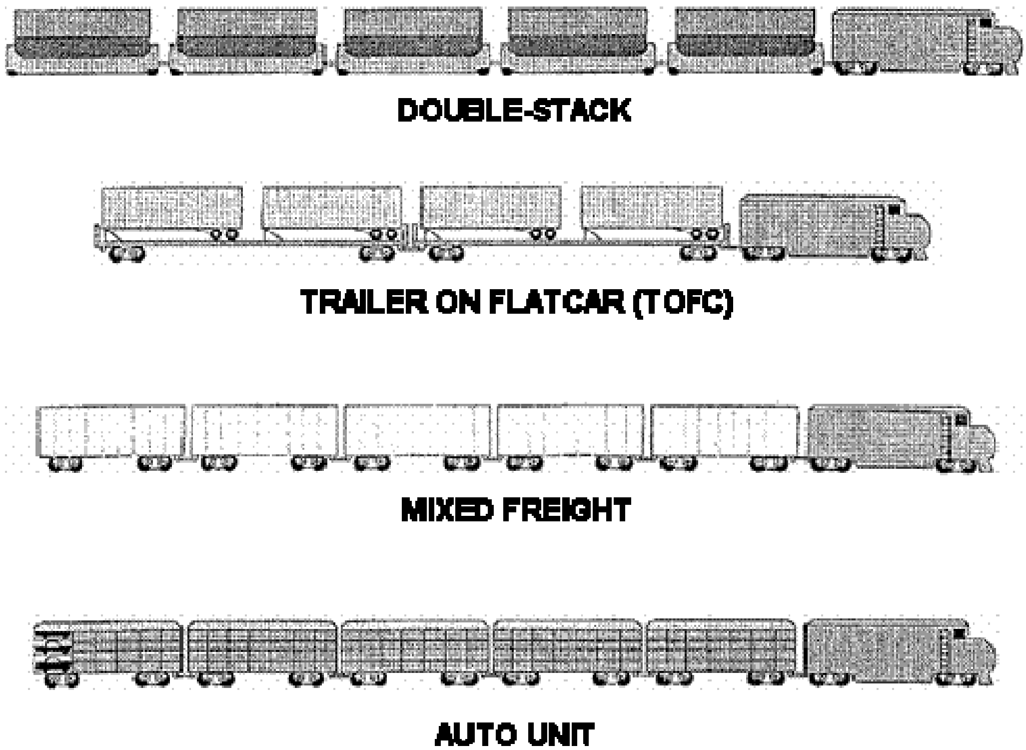
The consists of rail movements are characterized by the type of train, the number and position of cars, and the train's trailing weight (Exhibit 4-2):

- **Type of train:** the 23 movements consist of 12 intermodal movements, eight mixed train movements, and three auto train movements. The disproportionate number of double-stack movements in comparison with TOFC movements reflect the actual operations of the participating railroads on the lanes modeled, but it is not an indication that TOFC movements are less competitive with trucks than double-stack movements. Exhibit 4-3 illustrates the different types of trains considered in this study;
- **Consist size:** The number of cars per train ranges from 27 to 105 cars, with about half of the trains carrying more than 70 cars. Mixed trains are slightly longer than intermodal trains, and with the exception of one train, all mixed trains haul more than 70 cars in this study;
- **Trailing weight:** Trailing weight range from 3,132 to 8,107 tons. Auto trains tended to be the lightest trains, with trailing weights below 4,300 tons.

Exhibit 4-2. Consist Characteristics

Train Type	Number of Movements	Number of Cars	Trailing Weight (tons)
Double-Stack	11	27 - 85	4,243 – 8,107
TOFC	1	39	4,854
Mixed	8	36 - 105	4,026 – 7,695
Auto	3	45 - 65	3,132 – 4,281
Total	23	27 - 105	3,132 – 8,107

Exhibit 4-3. Train Types[54]



Load Characteristics

The rail movements include commodities that have comparable mode shares with truck movements on the routes identified in Chapter 3. The participating railroads assisted in the configuration of trains in which the commodities identified in Chapter 3 are typically transported. The types of commodities and car types assumed in this study are as follows, broken down by train type:

- **Intermodal trains (double-stack and TOFC):** intermodal trains carry a wide variety of commodities, including beverages, food products, electronics, and miscellaneous merchandise freight. These commodities are carried in containers (in double-stack trains) and trailers (on TOFC trains);
- **Mixed trains:** the commodities carried by mixed trains in this study include paper products, waste and scrap, food products, grain products, metal products, and fuel. These commodities are carried in box cars, covered hoppers, gondolas, and tank cars;
- **Auto trains:** this study assumes the transport of motorized vehicles on bi-level and tri-level auto rack cars.

[54] Abacus Technology Corporation (1991): Rail Vs. Truck Fuel Efficiency: The Relative Fuel Efficiency of Truck Competitive Rail Freight and Truck Operations Compared in a Range of Corridors. Report Prepared to the Federal Railroad Administration. DOT/FRA/.RRP-91/2.

Car type is important in the calculation of train fuel consumption because it affects the train's aerodynamic profile. The commodity type is also important because its density affects the ratio between payload and car tare weight, which is an important factor in the determination of rail fuel efficiency at the car level. The specific car types and commodities assumed in each movement are described in Appendix A.

Short Branchline and Switching Characteristics

Because the simulation of line-haul rail movements does not account for short branchline movements or yard switching operations from mixed train movements, their associated fuel consumption needs to be calculated separately. Appendix D includes the specific assumptions involved in these calculations.

Drayage and Intermodal Terminal Characteristics

Since the calculation of line-haul rail movements does not account for truck drayage or intermodal terminal operations at each end of the trip, their associated fuel consumption is calculated separately. Appendix D includes the specific assumptions used for these calculations.

4.2.2. Rail Fuel Efficiency Calculation

Rail fuel consumption is initially calculated at the train level. Because the goal of the study is to compare rail and truck fuel consumption for specific commodities on specific lanes, the train fuel consumption is then allocated to the carload. The steps used in the calculation of rail fuel efficiency are as follows, assuming the example of the 910-mile trip:

- **Step 1 – Calculate train fuel consumption:** outputs from the train simulations include total fuel used, total distance, train trailing weight, total horsepower, and average speed, amongst other variables necessary for subsequent steps. Fuel consumed in short branchline movements, yard switching operations, truck drayage movements, and intermodal terminal operations are added to the rail line-haul fuel consumption. In the 910-mile example, the train consumed 9,063 gallons to move 6,386 tons of train trailing weight over 910 miles.
- **Step 2 – Determine share of train trailing weight for the loaded car:** this is done by dividing the loaded car weight (including the equipment tare weight) by the train trailing weight, according to the formula below. The example assumes a payload of 91 tons and an equipment tare weight of 38 tons.

$$\text{Loaded Car Share of Train Trailing Weight} = \frac{\text{Loaded Car Weight}}{\text{Train Trailing Weight}} = \frac{129 \text{ tons}}{6{,}386 \text{ tons}} = 2.02\ \%$$

- **Step 3 – Calculate fuel consumed to move loaded car:** the amount of fuel allocated to the loaded car is the following:

$$\text{Fuel Consumed by Loaded Car} = 9{,}063 \text{ gallons} \times 2.02\% = 183.1 \text{ gallons}$$

- **Step 4 – Calculate ton-miles per gallon to move commodity:** this is done by multiplying the loaded car payload by the route distance and dividing the product by the fuel allocated to the loaded car.

$$\text{Ton-Miles per Gallon} = \frac{\text{Payload x Distance}}{\text{Fuel Consumed by Loaded Car}} = \frac{\text{91 tons x 910 miles}}{\text{183.1 gallons}} = \text{452 ton-miles/gallon}$$

The energy needed to move a car is the combination of rolling resistance (e.g., friction in bearings, at the wheel/rail interface), which is weight-related, and aerodynamic resistance, which is related to car size and shape rather than weight. For speeds lower than 40 mph, the energy necessary to move the train is spent mostly to overcome rolling resistance. However, at higher speeds (over 45 mph), rail car aerodynamics start having a substantial effect on the energy needed to move a car, and the ideal allocation of fuel to the loaded car should account for car weight, size, shape, and position within the train. Because the rail simulation outputs did not include information at the carload level, this analysis simplified the fuel allocation to consider only car weight. This adds uncertainties with the allocation of fuel, since some intermodal movements had average speeds over 45 mph.

4.3. Truck Fuel Consumption

Truck fuel consumption includes the following elements:

- **Line-haul truck movements:** because truck movements consider a direct movement between shipper and consignee, only one segment is considered in the calculation of line-haul truck fuel consumption. To ensure consistency with the calculation of rail fuel consumption, the simulation of truck movements accounts for actual truck routes, with their associated grade profiles, speed limits, and a driving cycle that is consistent with truck interstate travel. Truck movements also consider the equipment type to transport the identified commodities in Chapter 3;
- **Truck idling:** truck idling during loading/unloading operations, breaks and overnight stays is added separately.

Line-haul truck fuel consumption was calculated by ICF with MOVES/PERE, a model designed by the U.S. EPA to estimate vehicle emissions and fuel consumption. Section 4.3.1 includes a discussion of the different steps to model truck fuel consumption in MOVES/PERE. Section 4.3.2 characterizes the truck movements, and Section 4.3.3 provides the methodology to calculate truck fuel efficiency.

4.3.1. Truck Simulation Models

To fulfill the objectives of this study, a truck simulation model needs to provide this basic functionality:

- Route truck movements based on O-D pairs;
- Obtain route information (e.g., distance, circuity factor, road grade, speed limits);

- Consider driving cycles that reflect different patterns of truck travel;
- Enable the simulation of different truck types (e.g., tractor type, trailer type, vehicle weight, aerodynamic profile, tire type);
- Calculate fuel consumption based on pre-defined parameters, including vehicle configuration, route configuration, and driving cycle.

Micro modal models use a parameterized physical approach that breaks down the entire combustion process into different components that correspond to physical phenomena associated with the vehicle operation.[55] They generally measure fuel and emissions rates on a second by second basis according to a set of input parameters that describe the vehicle, the driving cycle, and the road facility. Micro modal models have the advantage that they take into account all factors that have a strong influence on fuel consumption, including vehicle technology, fuel type, operating modes, accessory use, aerodynamic devices, and road grade. Additionally, transient operations can be properly modeled, including the time dependence of fuel consumption to vehicle operation.

The micro-modal model PERE (Physical Emission Rate Estimator), designed by U.S. EPA to assist in the development of MOVES, was chosen to estimate truck fuel consumption in this analysis. [56] The EPA team has simulated the instantaneous fuel consumption in a number of actual heavy duty trucks to calibrate their model, so the model predicts actual truck fuel consumption with a reasonable degree of accuracy.

Because micro modal models typically consider a theoretical road segment, route information was compiled prior to running the model, as summarized in the following steps:

- **Determine truck route:** based on an O-D pair, the path with the lowest driving time was considered. Routes included speed limits;
- **Determine route elevation profile:** route elevation profiles were determined based on USGS data (Appendix E);
- **Determine driving cycle:** a driving cycle typical of interstate truck travel was selected for this study. This driving cycle was superimposed with the route elevation profile to provide instantaneous speed and road grade on a second-by-second basis. Truck speeds were adjusted for road grade from truck performance curves (Appendix F);
- **Configure vehicle:** the vehicle associated with each movement was configured, including tractor weight, trailer weight, fuel type, aerodynamic coefficient, rolling resistance coefficient, engine power characteristics, accessory loads, and gear ratios;
- **Run simulations:** after the route and the vehicle were configured, the simulation runs were completed for each movement.

[55] An example of a micro modal model is the Comprehensive Modal Emissions Model (CMEM) developed by U.C. Riverside.

[56] EPA (2005): Fuel Consumption Modeling of Conventional and Advanced Technology Vehicles in the Physical Emission Rate Estimator (PERE). Draft Version. EPA420-P-05-001.

4.3.2. Characterization of Truck Movements

The previous section summarized the necessary inputs for the calculation of truck fuel consumption. This section provides the details of such input parameters, organized in the following topics:

- Route characteristics;
- Engine and drivetrain characteristics;
- Speed characteristics;
- Vehicle characteristics;
- Load characteristics;
- Idling characteristics.

Route Characteristics

The calculation of truck fuel consumption is based on actual truck routes with their grade profile, speed limits, and driving cycles that are consistent with interstate truck travel. The following items describe the distance, grade severity, speed limits, and operational constraints:

- **Distance:** truck routes range from 197 to 2,046 miles, with two short routes (less than 300 miles), 13 medium routes (between 300 and 1,000 miles), and eight long routes (over 1,000 miles);
- **Grade severity:** consistent with the rail analysis, a numeric rating system to describe the level of grade severity is used for truck movements. Grade severity ranges from 1.7 to 3.5, and is typically higher for truck movements than for rail movements. Three routes had grades below 2, six routes have grades between 2 and 2.5, 11 routes have grades between 2.5 and 3, and the remaining three routes have grades above 3. Appendix C provides the methodology to determine grade severity;
- **Frequency of speed limit changes:** typically most of the routes are predominantly on interstate highways where truck speed limit is 55 mph, occasionally dropping to lower speeds in smaller roads and urban areas. Appendix F provides detailed information on the development of driving cycles, which take speed limit changes into account;
- **Operational constraints:** the simulation of truck movements is done with consideration to average traffic levels along truck corridors during off-peak travel, which is generally the time that long-distance truck drivers operate.

Engine and Drivetrain Characteristics

Engine and drivetrain configurations are important since they have a direct effect on truck power and torque. Most parameters that describe truck engines and drivetrains were taken directly from PERE documentation, and reflect standard long-haul trucks. Those include engine efficiency, engine friction, engine power, engine torque, engine displacement, number of gears, and gear ratios. Engine displacement, assumed to be 12 liters for all tractors, has a direct influence on engine power and torque. PERE assumes a 13-gear manual transmission for heavy-duty trucks.

Speed Characteristics

Because the simulation of rail movements is based on actual train data that considers train acceleration and deceleration patterns caused by changes in grade and congestion levels, a consistent approach is taken for the calculation of truck fuel consumption. Therefore, the simulation of truck movements considers a driving cycle that reflects truck travel along interstate highways. A baseline driving cycle assumes mostly constant speed at 55 mph, with some slight speed variations to account for regular interstate traffic during off-peak times. Road grade is not considered in the baseline cycle, which is adjusted for each truck movement to account for the fact that trucks need to slow down significantly during steep grades. Route speed limits are also considered in the customization of the baseline cycle to individual routes. Appendix F includes the methodology used to develop the specific driving cycles used in the truck movements.

Vehicle Characteristics

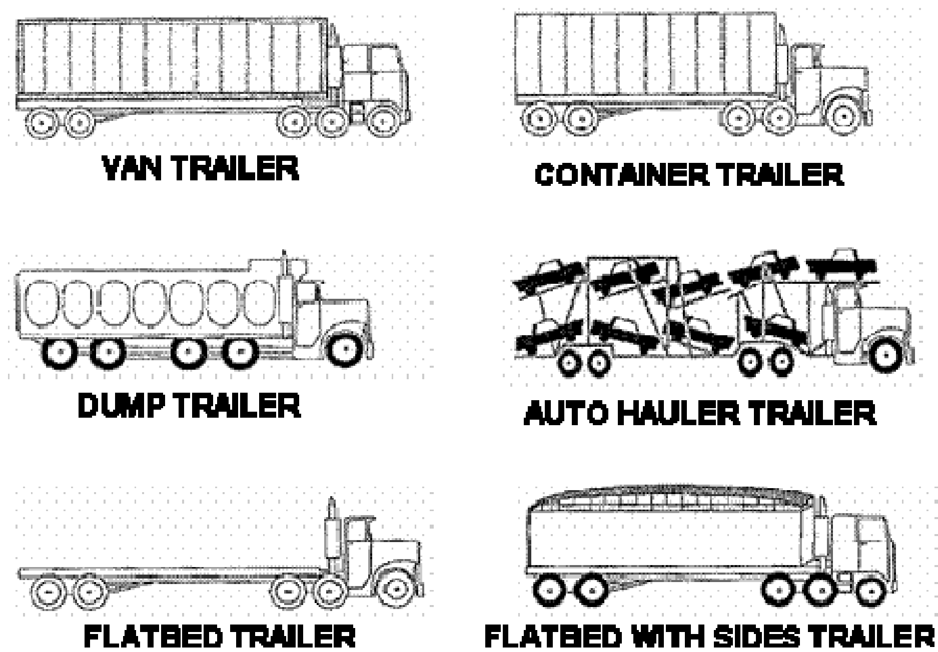
Vehicles are configured based on tractor type, trailer type, tires, and accessories.

- **Tractor type:** a conventional cab, where the engine compartment is located under the hood in front of the driver, is assumed for the truck movements. As indicated in Chapter 2, aerodynamic devices for tractors are widely implemented, so roof deflectors, integrated cab-roof fairings with closed sides, cab extenders, and front air dams are assumed in all truck movements;
- **Trailer type:** different trailer types are used in the truck movements, as indicated in Exhibit 4-4. The most common type of trailer in this study is the dry van, which is used in 12 movements. No trailer aerodynamic devices are considered since they have not been widely implemented to date. Illustrations of truck trailer types are included in Exhibit 4-5;
- **Tires:** because high-efficiency dual tires or single-wide tires have not been widely implemented, this analysis assumes standard dual tires for all truck movements. A rolling resistance coefficient of 0.0067 is used (See footnote 56);
- **Accessories:** an accessory load of 0.75 kilowatt (kW) is assumed for all truck movements to account for additional power necessary to supply driver comfort.

Exhibit 4-4. Number of Movements by Truck Trailer Type

Truck Trailer Type	Number of Movements	Truck Loaded Weight (tons)
Dry Van	12	29 - 31
Container	3	23 – 31
Auto Hauler	3	30
Dump	2	37
Flatbed with sides	1	37
Tank	2	23 - 37
Total	23	23 - 37

Exhibit 4-5. Truck Trailer Types[57]



Load Characteristics

The truck movements include commodities that have comparable mode shares with rail movements on the routes identified in Chapter 3. The types of commodities and car types assumed in this study are as follows, broken down by trailer type:

- **Dry van and container trailers:** these two trailer types compete directly with double-stack and TOFC trains, so they carry the same types of commodities, including beverages, food products, electronics, and miscellaneous merchandise freight;
- **Auto hauler trailers:** carry automobiles and light-duty trucks;
- **Dump and flatbed with sides trailers:** carry bulk commodities. In this study, waste/scrap and base metals are assumed to be transported in dump trailers and flatbed with sides trailers, respectively;
- **Tank trailers:** carry liquid commodities. In this study, ethanol is assumed to be transported in tank trailers.

Trailer type is important in the calculation of truck fuel consumption because it affects the truck's aerodynamic drag, which is the predominant parameter during high vehicle speeds. The commodity type is also important because its density affects the ratio between payload and

[57] S Abacus Technology Corporation (1991): Rail Vs. Truck Fuel Efficiency: The Relative Fuel Efficiency of Truck Competitive Rail Freight and Truck Operations Compared in a Range of Corridors. Report Prepared to the Federal Railroad Administration. DOT/FRA/.RRP-91/2.

truck tare weight, which is an important factor in the determination of truck fuel efficiency. The specific trailer types and commodities assumed in each movement are described in Appendix B.

Idling Characteristics

All truck movements are associated with some level of truck idling during loading/unloading operations, breaks, and overnight stays. Appendix D includes the specific assumptions involved in these calculations.

4.3.3. Truck Fuel Efficiency Calculation

Truck fuel efficiency is calculated in lading ton-miles per gallon to enable a comparison with rail movements. The steps used in the calculation of truck fuel efficiency are as follows, assuming the example of the 302-mile trip:

- **Step 1 – Calculate truck fuel consumption:** outputs from PERE include total fuel used, amongst other variables. In the 302-mile example, the truck consumes 47 gallons to move 31.1 tons (including a payload of 16.6 tons) over 302 miles. In addition, the truck consumes 1 gallon during idling.

- **Step 2 – Calculate ton-miles per gallon to move commodity:** this is done by multiplying the payload by the route distance and dividing the product by the fuel consumed by the truck.

$$\text{Ton-Miles per Gallon} = \frac{\text{Payload x Distance}}{\text{Fuel Consumed}} = \frac{\text{16.6 tons x 302 miles}}{\text{48 gallons}} = \text{104 ton-miles/gallon}$$

- **Step 3 – Calculate truck fuel efficiency in miles per gallon:** this is done by dividing the total truck mileage by the fuel consumed by the truck.

$$\text{Miles per Gallon} = \frac{\text{Distance}}{\text{Fuel Consumed}} = \frac{\text{302 miles}}{\text{48 gallons}} = \text{6.3 miles/gallon}$$

4.4. Consideration of Empty Miles

Empty miles refer to the fact that empty equipment needs to be relocated to places where it is needed. Additional fuel is consumed in the movement of empty rail and truck equipment. To ensure transparency in the analysis of fuel efficiency, and because of the high uncertainty associated with the estimation of empty miles, the inclusion of empty miles in the calculation of rail and truck fuel efficiency is considered separately. This section provides the methodology used to develop correction factors to account for empty mileage.

Logistics of Empty Movements

The logistics of empty equipment is a highly complex issue, which depends on the commodity, equipment, lane, and sometimes individual shippers. Commodities hauled in specialized rail cars, which are often owned by or leased to the shipper, almost always return empty to the point of origin. This is the case of tank, box, and hopper cars that are shipper-owned and move in dedicated cycled service. To the extent that such rail cars move strictly in one corridor, it is possible to estimate the share of empty movements by examining the composition of the train consists.

For most commodities that are rail-truck competitive however, it is quite difficult to establish the geographic boundaries within which rail equipment is used. Whether cars are owned by the railroad or a private car firm, car managers work to minimize empty mileage, by routing the car to the nearest shipper that needs a car of that type. This can be a purely dynamic process based on short-term needs, or car managers will set up a sequence of moves that make a regular circuit, which is common practice with autorack cars. In the case of intermodal traffic, the railcars are almost always owned by TTX Corporation, which is co-owned by all the Class I railroads, and whose aim is to pool flatcars to avoid the inefficiencies associated with having cars tied to specific routes or shippers.

In the truckload market, large carriers also minimize empty miles by planning operations based on predicted demand, as well as routing trucks to the nearest locations. Small carriers and independent operators generally have less flexibility to minimize empty miles due to the small number of trucks.

Consideration of Empty Miles in Fuel Consumption

There are two key points to consider when accounting for fuel consumption associated with empty miles: (1) the method must be applicable to both rail and truck movements, and (2) the method must be transparent. In other words, the impact of empty miles on fuel consumption should be measured separately from the loaded movements.

The approach taken in this study is to first calculate the fuel consumed by the loaded equipment, and then to apply a correction factor to account for empty miles. The correction factor accounts for the fact that it takes less fuel to move empty than loaded equipment.

In the rail movements, the consists also include empty rail cars (as configured by the participating railroads), but the fuel consumed by a given load does not include the fuel consumed by the empty equipment in the same consist. This is the case because the empty and loaded equipment in the same consist are not always “related.”

There is obviously a trade-off between accuracy and precision. The higher the precision (i.e., by choosing specific O-D pairs and commodities), the lower the accuracy due to data availability and the inherit uncertainty and variation in movements. Conversely, the lower the precision (i.e., by choosing an equipment type nationwide), the higher the accuracy.

The balance between accuracy and precision is driven by data availability. Public data sources with aggregate information about empty miles exist. AAR’s *Analysis of Class I Railroads* (compilation of individual Class I Railroad Annual Report(s) R-1 to the Surface Transportation Board), published annually, contains full and empty mileage by car type and railroad, which enables the derivation of empty factors by equipment type. Similarly, the Vehicle Inventory and

Use Survey (VIUS) provides data on empty mileage for different truck types.[58] More precise empty factors for specific lanes and commodities could be obtained directly from the railroads and trucking companies, but that would be unlikely due to confidentiality issues. It is possible that transportation rates could reflect empty miles, but it is difficult to disaggregate the impacts of empty miles from other factors such as supply and demand, labor markets, and equipment availability.

The use of aggregate data is chosen to provide transparency and to ensure consistency in the approach taken for rail and truck movements. It is important to note that a railcar can be loaded with empty containers and still be a revenue move for the railroads. There are similar nuances in the trucking industry, since the movement of empty containers might still be considered a revenue movement for truck carriers, and thus not being "reported" as empty. The analysis did not consider such nuances.

Estimation of Rail Empty Ratios

The *Analysis of Class I Railroads* report provides data on loaded car miles and empty car miles, disaggregated by equipment type and geographic region. Exhibit 4-6 provides the share of empty miles out of total car miles. Because empty ratio is defined as the ratio between empty miles and loaded miles, the empty shares in Exhibit 4-6 (ratio between empty mileage and total mileage) need to be converted into empty ratios.

Exhibit 4-6. Rail Empty Mileage by Region and Equipment Type

Equipment Type	East			West		
	Total Car Miles	Empty Car Miles	Share of Empty Miles	Total Car Miles	Empty Car Miles	Share of Empty Miles
Box Car – Plain 50"	126,463	53,419	42%	202,479	64,279	32%
Gondola – Plain	1,031,131	496,772	48%	5,187,676	2,775,568	54%
Covered Hopper	2,251,736	1,121,408	50%	4,779,419	2,389,218	50%
TOFC/COFC	1,096,520	140,226	13%	3,310,253	471,962	14%
Flat – Multi-level	996,591	349,578	35%	1,313,823	332,313	25%
Tank Car	1,354,155	682,821	50%	2,025,939	1,035,160	51%

Estimation of Truck Empty Ratios

The 2002 Vehicle Inventory and Use Survey (VIUS) provides data on empty miles, the most relevant to this analysis being disaggregated by equipment type and distance range (Exhibit 4-7). Because empty ratio is defined as the ratio between empty miles and loaded miles, the empty shares in Exhibit 4-7 (ratio between empty mileage and total mileage) need to be converted into empty ratios.

[58] Other than a truck's home base state and the share of miles driven within and outside of the home base state, there is no information in the VIUS that could indicate empty mileage in specific corridors.

Exhibit 4-7. Truck Empty Mileage by Equipment Type and Distance Range

Equipment Type (VIUS)	Trailer Type Assumed in this Study	Share of Empty Miles				
		< 50 miles	50 – 100 miles	100 – 200 miles	200 – 500 miles	> 500 miles
Dump	Dump	41%	39%	40%	41%	38%
Flatbed	Container	36%	31%	31%	29%	28%
Tank, liquid	Tank	30%	30%	37%	43%	31%
Van, all types	Dry Van	21%	21%	23%	26%	19%
Van, open top	Flatbed with sides	46%	43%	47%	31%	44%

Calculation of Correction Factors

For the development of correction factors, fuel consumption is assumed to be proportional to vehicle loaded weight. The correction factor is applied to the fuel consumed by the loaded truck in the line-haul movement as follows:

$$\text{Corrected Fuel} = FL + FE = FL + FL \times ER \times (TW / LW) = FL \times [1 + ER \times TW / LW]$$

, where: FL = Fuel consumed in loaded movement (gallons)
FE = Fuel consumed in empty movement (gallons)
TW = Equipment Tare Weight (tons)
LW = Equipment Loaded Weight (tons)
ER = Empty Ratio (ratio between empty and loaded miles)

4.5. Simulation Results

This section presents the results of rail and truck movement simulations, and provides a comparative analysis of rail and truck fuel efficiency. This section is structured according to the main findings of this analysis, starting with (1) a broad comparison of rail and truck fuel efficiency, and following up with (2) the influence of specific parameters on rail and truck fuel efficiency. Finally, this analysis provides a comparison with the 1991 Study.

Because the rail and truck movements reflect individual operational characteristics, conclusions should not be generalized for all freight movements. For this reason, this analysis does not average results across movements, but presents ranges of results.

All findings are developed without the consideration of empty mileage in order to provide transparency to this study. Finding 7 addresses the influence of empty mileage on rail and truck fuel efficiency separately.

4.5.1. General Comparison of Rail and Truck Fuel Efficiency

Finding 1: Rail is more fuel efficient than truck on all 23 movements.

Exhibits 4-8 and 4-9 summarize rail and truck movement characteristics and fuel efficiency findings. For all 23 competitive movements, rail fuel efficiency was higher than truck fuel efficiency, both measured in lading ton-miles per gallon. The rail-truck fuel efficiency ratio is a ratio between rail and truck fuel efficiency, and it is an indicator of how much more fuel efficient rail is in comparison to truck. More detailed information on rail and truck movements is included in Appendices A and B, respectively.

Exhibit 4-8. Summary of Rail Movement Characteristics and Results

Movement	Equipment Type*	Distance (miles)	Grade Severity	HP per Trailing Ton	Average Speed (mph)	Payload (tons)**	Fuel Efficiency (ton-miles/ gallon)	Rail-Truck FE Ratio
1	BC	280	1.7	1.1	14	66	406	3.9
2	DS	294	1.8	1.5	31	38	384	5.5
3	G	133	1.3	1.9	31	73	301	2.3
4	BC	1,083	1.9	1.2	21	74	469	3.6
5	G	242	2.2	2.0	17	96	278	2.8
6	TOFC	790	2.0	1.6	27	15	273	3.2
7	CH	790	2.0	1.3	21	98	487	5.3
8	DS	352	1.4	1.4	31	30	373	5.5
9	CH	352	1.4	1.4	21	95	475	4.3
10	A	367	1.4	1.4	27	18	156	1.9
11	A	561	1.8	1.4	20	18	157	2.0
12	G	910	2.1	1.3	21	91	452	4.0
13	DS	450	2.2	1.9	31	30	226	2.7
14	DS	673	1.5	2.1	50	54	348	3.5
15	DS	1,415	2.0	2.7	45	69	361	3.9
16	DS	2,232	2.6	2.2	46	65	426	4.8
17	A	445	1.5	2.0	51	20	164	2.2
18	DS	1,805	2.0	1.7	39	70	449	4.6
19	DS	2,090	2.6	2.5	44	48	358	4.0
20	DS	1,034	1.5	1.6	41	50	512	5.1
21	DS	2,150	2.6	2.1	48	54	409	4.5
22	DS	1,484	1.7	1.7	37	39	490	5.2
23	TC	1,788	2.6	2.3	43	47	370	5.3

* A = Auto Rack; BC = Box Car; CH = Covered Hopper; DS = Double-stack; G = Gondola; TC = Tank Car; TOFC = Trailer on Flat Car

** Rail and truck payloads are different due to different equipment capacities. Rail payload for intermodal movements are based on two stacked containers.

Exhibit 4-9. Summary of Truck Movement Characteristics and Results

Movement	Equipment Type*	Distance (miles)	Grade Severity	Payload (tons)**	Fuel Efficiency (ton-miles/ gallon)	Rail-Truck FE Ratio
1	DV	302	2.2	17	104	3.9
2	C	330	3.1	11	70	5.5
3	D	197	1.7	24	129	2.3
4	T	1,039	2.7	25	132	3.6
5	D	239	3.5	24	98	2.8
6	DV	704	2.6	15	85	3.2
7	FS	704	2.6	24	133	3.7
8	C	439	1.7	9	68	5.5
9	DV	439	1.7	17	110	4.3
10	A	326	2.0	15	81	1.9
11	A	350	2.4	15	77	2.0
12	FS	595	2.9	24	112	4.0
13	DV	447	3.2	15	82	2.7
14	C	636	2.4	17	100	3.5
15	DV	1,303	2.6	17	93	3.9
16	DV	1,983	2.9	17	88	4.8
17	A	518	2.7	15	74	2.2
18	DV	1,531	2.4	17	98	4.6
19	DV	1,771	2.9	17	90	4.0
20	DV	780	2.5	17	101	5.1
21	DV	2,046	2.9	17	90	4.5
22	DV	1,226	2.7	17	94	5.2
23	T	1,591	2.9	11	70	5.3

* A = Auto Rack; C = Container; DV = Dry Van; FS = Flat Bed with Sides; T = Tank
** Rail and truck payloads are different due to different equipment capacities.

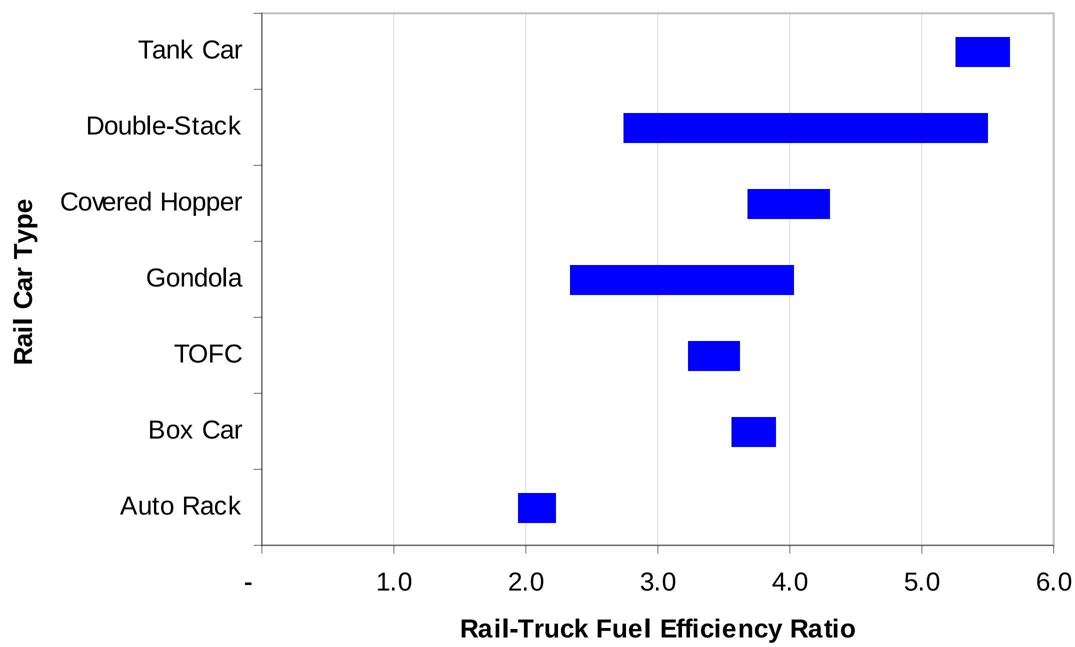
Finding 2: There is a strong correlation between rail-truck fuel efficiency ratio and equipment type.

Exhibit 4-10 provides the range of rail-truck fuel efficiency ratio by rail equipment type, and it illustrates the strong correlation between the two variables. Two factors influence such correlation, namely the ratio between payload and total car weight (payload plus tare weight), and train aerodynamic resistance.

As previously indicated, train fuel consumption is first allocated to each car as a proportion of the car total weight to the total trailing weight. Subsequently, lading ton-miles per gallon is determined by multiplying the payload by the distance and dividing the product by the fuel allocated to that car. Therefore, cars with a low ratio between payload and total car weight will have lower fuel efficiency. This explains why auto haulers, with ratios between payload and total car weight ranging between 25 and 30%, have relatively poor fuel efficiency in comparison with the remaining equipment types. In contrast, tank cars and covered hoppers have ratios above 75%, which explains higher rail-truck fuel efficiency ratios in comparison with other equipment types.

The second factor that has a strong influence in the rail-truck fuel efficiency ratio is the aerodynamic resistance, which increases with both equipment aerodynamic coefficient and train speed. Although rail movements with higher average speeds tend to have lower rail-truck fuel efficiency ratios, this is not the case in the movements analyzed because higher speed movements over long distances tended to have higher payload to total car weight ratios, which offset the fuel penalties from higher speeds.

Exhibit 4-10. Range of Rail-Truck Fuel Efficiency Ratio by Rail Car Type

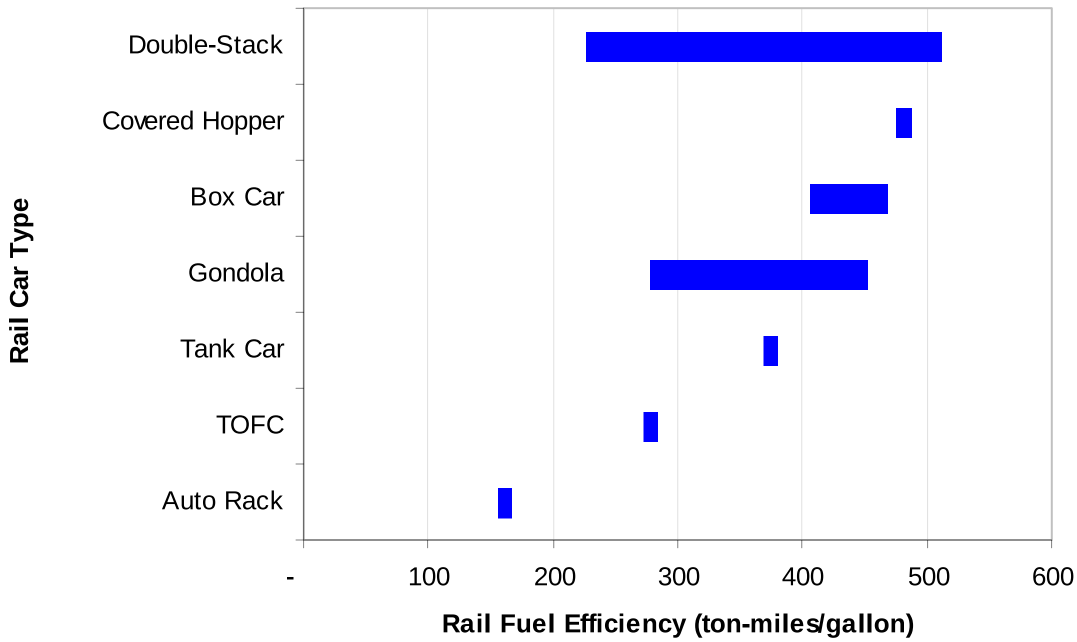


Finding 3: The range of rail fuel efficiency is wider than the range of truck fuel efficiency.

Exhibits 4-11 and 4-12 provide the range of rail and truck fuel efficiency across all movements included in this study. Rail fuel efficiency has a much wider range, varying from 156 to 512 ton-miles/gallon, with the movement with the highest fuel efficiency being over four times more fuel efficient than the movement with the lowest fuel efficiency. In contrast, truck fuel efficiency ranged from 68 to 133 ton-miles/gallon, with the highest fuel efficiency being about twice more fuel efficient than the lowest fuel efficiency. The rail fuel efficiency variation stems from the fact that rail movements have a wider range of horsepower per trailing weight than truck movements do. In addition, rail movements have a wider range of train configuration options than those seen in truck movements.

Although double-stack and gondola rail movements appear to have a wider range of fuel efficiency than other rail equipment types, this is more of a reflection of the higher number of movements of double-stack (11) and gondola (3), as opposed to other types of rail equipment.

Exhibit 4-11. Range of Rail and Truck Fuel Efficiency (ton-miles/gallon)



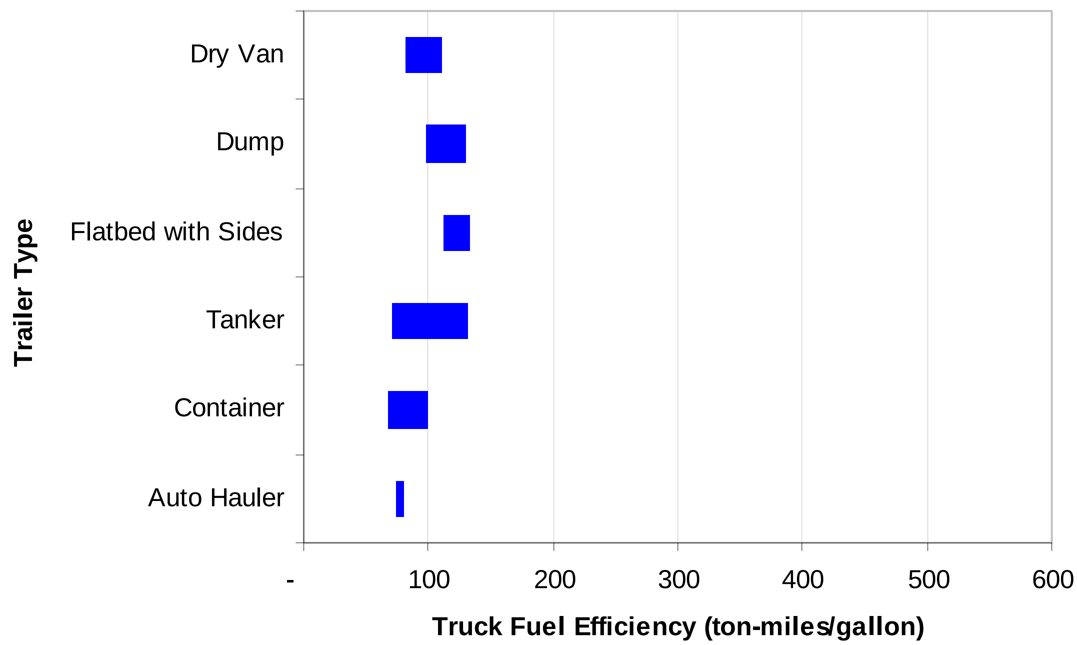


Exhibit 4-12. Range of Rail and Truck Fuel Efficiency (ton-miles/gallon)

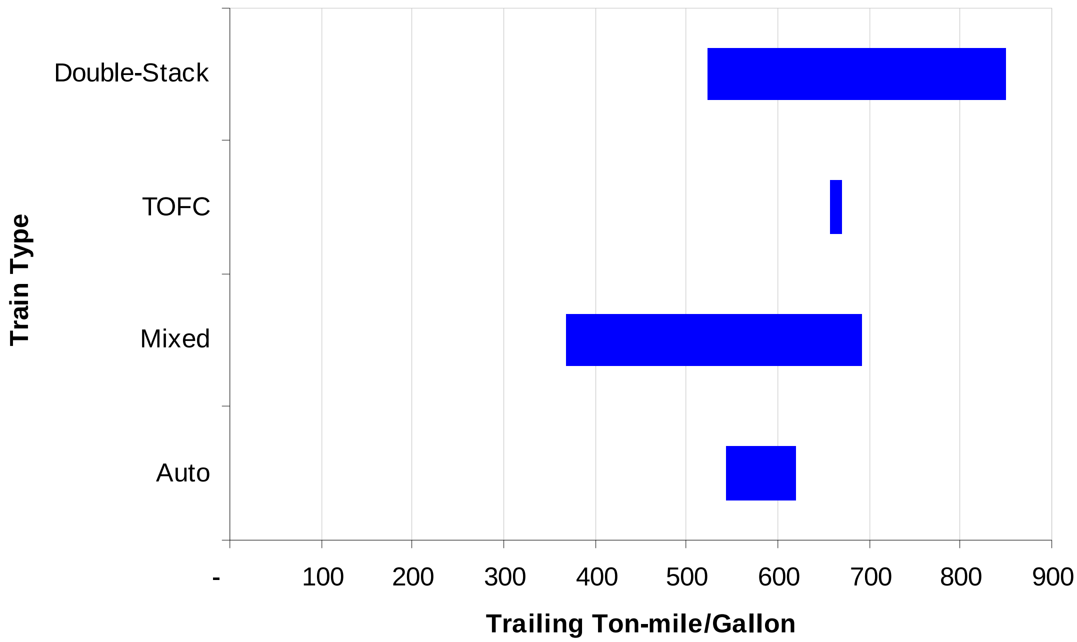
Rail Equipment	Min	Max	Truck Equipment	Min	Max
Double-Stack	226	512	Dry Van	82	110
Covered Hopper	475	487	Dump	98	129
Box Car	406	469	Flatbed with Sides	112	133
Gondola	278	452	Tank	70	132
Tank Car	370	370	Container	68	100
TOFC	273	273	Auto Hauler	74	81
Auto Rack	156	164			

Finding 4: The variation in rail fuel efficiency is narrower if analyzed in terms of trailing ton-mile per gallon.

As previously indicated, the share of payload to total car weight has a strong influence on rail fuel efficiency when measured in ton-miles/gallon. To eliminate this issue from consideration, rail fuel efficiency can be analyzed at the train level instead of at the car level. This is done by evaluating train fuel efficiency in terms of trailing ton-miles per gallon.

Even without considering the ratio between payload and train tare weight, variations in train fuel efficiency (measured in trailing ton-miles per gallon) still occur due to terrain difficulty (grade and curvature), frequency of speed limit changes, number of locomotives, average speed, and train composition (which influence both rolling and aerodynamic resistance). Exhibit 4-13 provides the range of trailing ton-miles per gallon for different types of trains. Double-stack trains tend to be more fuel efficient than mixed trains (despite their higher average speeds) because they do not require consecutive switching operations to classify rail cars. The wide variation in fuel efficiency of double-stack and mixed trains as opposed to auto and TOFC trains is justified by the smaller number of movements analyzed in the latter trains.

Exhibit 4-13. Train Fuel Efficiency by Train Type



Finding 5: Short branchline movements, switching operations, truck drayage, terminal operations and truck idling have very different impacts depending on the movement analyzed.

The total fuel consumed in rail and truck movements are associated with the actual line-haul movements and other operations. The latter refer to (1) truck drayage and intermodal terminal operations for intermodal rail movements, (2) short branchline movements and yard switching operations for mixed rail movements, and (3) truck idling for truck movements. Exhibit 4-14 provides the range of the share of total fuel associated with each of these operations. While truck idling accounted for a relatively low share of total truck fuel consumption (less than 7%), the same was not true for rail movements. Truck drayage and intermodal terminal operations accounted for 7-27% of total fuel consumed by intermodal trains, with the wide range justified by the fact that the analysis assumed a fixed distance for all drayage movements independently of the route distance. Therefore, the fuel share allocated to truck drayage was higher for shorter routes and lower for longer routes. Similar conclusions can be drawn for short branchline movements and yard switching operations, which combined make up 6-45% of fuel consumed by mixed trains.

Exhibit 4-14. Operations Included in Rail and Truck Movements

Movement	Short Branchline Movements & Yard Switching Operations	Truck Drayage & Intermodal Terminal Operations	Truck Idling
Rail Intermodal		7-27%	
Rail Mixed/Auto	6-45%		
Truck			1-7%

Finding 6: As a consequence of rail being more fuel efficient than truck on all 23 movements, fuel savings when examining gallons of fuel consumed under each scenario can be significant.

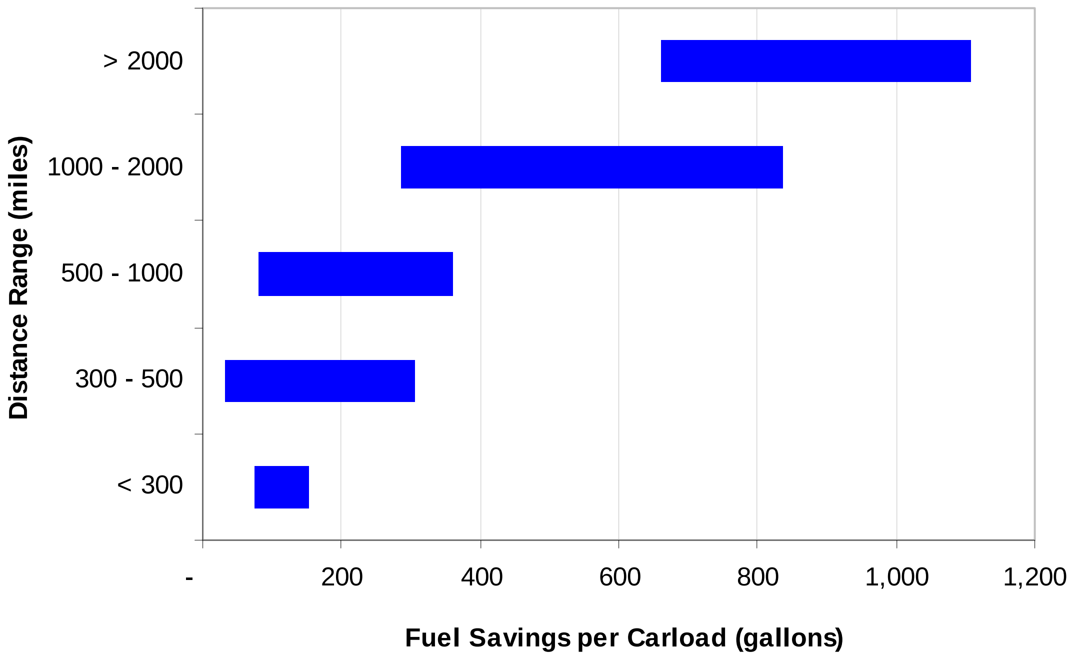
With the exception of one movement, rail results in fuel savings when compared to their counterpart truck movement (Exhibit 4-15). Fuel savings are calculated by comparing the fuel consumed by one carload with the fuel consumed by the equivalent number of trucks needed to transport the same payload.

The fuel savings from using rail ranged from 18 to 1,108 gallons per carload. Section 4.5.2 addresses the influence of route circuity on fuel consumption. Because the range of variation in fuel savings is more dependent on route distance than equipment type, Exhibit 4-16 illustrates the range of savings by distance segments.

Exhibit 4-15. Fuel Savings from Using Rail by Movement

Movement	Rail Payload (tons)	Rail Fuel Consumption (gallons)	Truck Payload (tons)	Number Equivalent Trucks	Truck Fuel Consumption (gallons)	Fuel Saved Using Rail (gallons)
1	66	46	17	4.0	191	146
2	38	29	11	3.3	178	149
3	73	32	24	3.1	111	79
4	74	171	25	2.9	583	413
5	96	84	24	4.0	235	151
6	15	43	15	1.0	124	81
7	98	159	24	4.1	520	361
8	30	28	9	3.3	194	166
9	95	71	17	5.7	378	307
10	18	42	15	1.2	73	30
11	18	64	15	1.2	82	18
12	91	183	24	3.8	482	299
13	30	60	15	2.0	163	103
14	54	104	17	3.2	345	240
15	69	270	17	4.2	962	691
16	65	338	17	3.9	1,446	1,108
17	20	54	15	1.3	140	86
18	70	281	17	4.2	1,096	815
19	48	280	17	2.9	941	661
20	50	101	17	3.0	386	285
21	54	284	17	3.3	1,227	943
22	39	119	17	2.4	511	392
23	47	227	11	4.2	1,064	837

Exhibit 4-16. Rail Vs Truck Fuel Savings by Distance Segment



The analysis of fuel savings can also be developed at the train level. For example, if trucks were to carry the equivalent payload included in the double-stack rail movements, the fuel savings would evidently be much greater. Exhibit 4-17 summarizes the fuel savings for such movements, which range from 1,549 to over 80,000 gallons per train.

Exhibit 4-17. Rail Vs Truck Fuel Savings for Double-Stack Trains

Movement	Rail Route Distance (miles)	Number of Loaded Cars	Train Payload (tons)	Rail Fuel (gallons)	Truck Load (tons)	Truck Fuel (gallons)	Number of Trucks Required	Adjusted Truck Fuel (gallons)	Fuel Saved (gallons)
2	294	35	665	509	11	53	59	3,113	2,604
8	352	27	405	383	9	58	45	2,620	2,237
13	450	30	450	896	15	81	30	2,445	1,549
14	673	64	3,468	6,711	17	108	204	22,135	15,424
15	1,415	56	3,893	15,254	17	231	234	54,259	39,005
16	2,232	74	4,758	24,920	17	372	287	106,667	81,747
18	1,805	65	4,557	18,304	17	260	274	71,343	53,039
19	2,090	58	2,791	16,304	17	326	168	54,735	38,432
20	1,034	60	2,994	6,053	17	128	180	23,133	17,080
21	2,150	64	3,468	18,212	17	377	209	78,799	60,587
22	1,484	52	2,048	6,205	17	216	123	26,576	20,371

Finding 7: The effects of empty mileage associated with rail and truck movements can be significant.

Because many analyses of rail and truck fuel efficiency do not account for empty mileage, this study considers those effects separately to provide a transparent comparison. Additionally, the issue of empty logistics is highly complex, and the empty mileage associated with individual movements can vary quite dramatically. Moreover, data on empty mileage is typically regarded as highly confidential by railroads and trucking firms, so this study relied instead on more aggregate data from public sources.

By applying the methodology described in Section 4.4, Exhibit 4-18 provides a comparison of rail and truck fuel efficiency for all movements before and after accounting for empty mileage. Positive variations indicate that rail is more efficient when compared to truck when accounting for empty miles. All intermodal movements (double-stack and TOFC) have positive variations ranging from 3 to 15%, indicating that, in those cases, rail is even more efficient than truck when accounting for empty miles. The opposite is true for box car movements, which show negative variations. In those cases, rail is still more fuel efficient than trucks, but the gap between rail and truck narrows with the inclusion of empty miles. Conclusions are somewhat less clear with auto and covered hopper movements (-9% to +5%).

Exhibit 4-18. Effects of Empty Mileage on Rail-Truck Fuel Efficiency Ratios

Movement	Rail Equipment*	Rail-Truck Fuel Efficiency Ratio		
		Without Empty Miles	With Empty Miles	Variation (%)
1	BC	3.9	3.6	-7%
2	DS	5.5	6.2	15%
3	G	2.3	2.4	5%
4	BC	3.6	3.3	-7%
5	G	2.8	2.9	4%
6	TOFC	3.2	3.3	3%
7	CH	3.7	3.8	5%
8	DS	5.5	6.3	15%
9	CH	4.3	3.9	-8%
10	A	1.9	1.9	0%
11	A	2.0	2.0	-2%
12	G	4.0	4.1	1%
13	DS	2.7	2.8	3%
14	DS	3.5	3.9	12%
15	DS	3.9	4.1	5%
16	DS	4.8	5.1	5%
17	A	2.2	2.3	3%
18	DS	4.6	4.8	5%
19	DS	4.0	4.1	4%
20	DS	5.1	5.3	5%
21	DS	4.5	4.7	4%
22	DS	5.2	5.4	4%
23	TC	5.3	4.5	-14%

A = Auto Rack; BC = Box Car; CH = Covered Hopper; DS = Double-stack; G = Gondola; TC = Tank Car; TOFC = Trailer on Flat Car

4.5.2. Effects of Individual Parameters on Fuel Efficiency

This section provides an analysis of the effects of individual parameters on rail and truck fuel efficiency. Because many variables influence fuel efficiency concurrently, it is challenging to isolate the effects of individual parameters, so this analysis includes both quantitative and qualitative components.

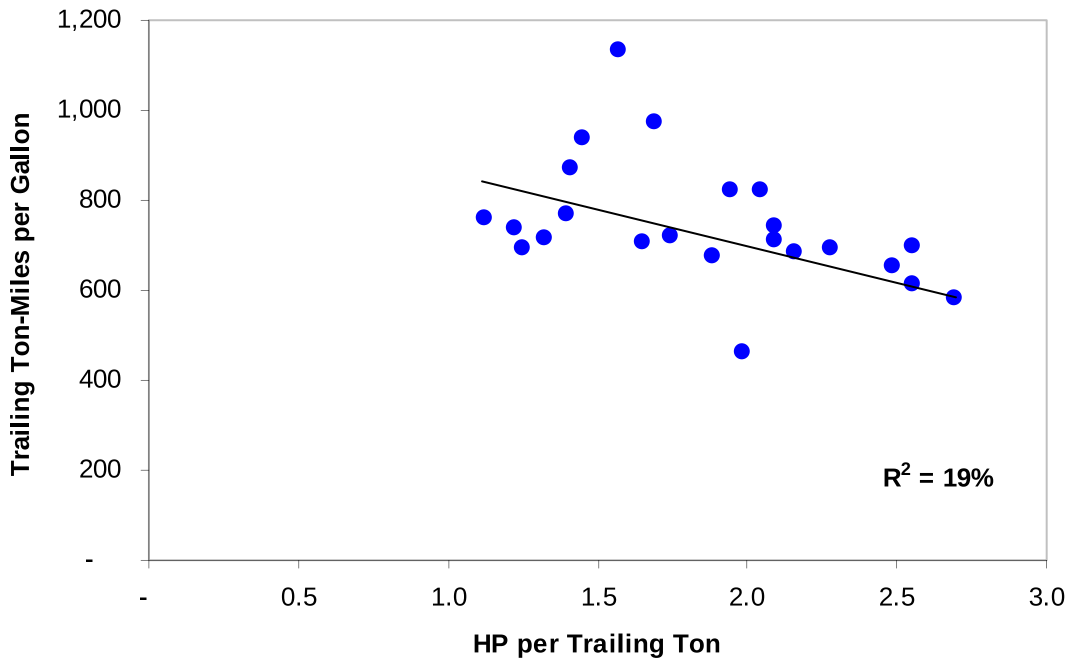
Effects of HP per Trailing Ton

Horsepower per trailing ton is calculated as follows:

$$\text{HP per Trailing Ton} = \frac{\text{Number of Locomotives x Locomotive HP}}{\text{Trailing Weight (tons)}}$$

It is somewhat intuitive to assume there is a strong correlation between horsepower per trailing ton and rail fuel efficiency. Exhibit 4-19 illustrates the correlation between horsepower per trailing weight and rail fuel efficiency at the train level (trailing ton-miles/gallon). For this specific analysis, only the fuel associated with line-haul movements was considered to minimize the “noise” that could possibly be created by adding fuel consumed in short branchline movements, yard switching, truck drayage, and intermodal terminal operations. A linear regression returns an R-squared of 19%. Because there are many other variables that also affect rail fuel efficiency (e.g., train aerodynamics, grade profile, average speed), the correlation between horsepower per trailing ton and rail fuel efficiency is not as clear as it would have been should those other parameters had remained constant. However, Exhibit 4-19 still shows a somewhat clear relationship between train fuel efficiency and horsepower per trailing ton.

Exhibit 4-19. Effects of Horsepower per Trailing Ton on Train Fuel Efficiency



Effects of Circuity

Circuity refers to the fact that the distance between two points by rail and over the road is not a straight line. Typically, distances by rail are greater than those over the road, but truck distance is longer in some movements due to the fact that truck routing minimized travel time rather than travel distance. Therefore, in some movements truck routes are longer to make use of faster interstate routes.

Because the comparisons of rail and truck fuel efficiency are done in lading ton-miles per gallon, the effect of circuity is not taken into account. Therefore, the actual fuel savings from using rail versus truck are not proportional to the ratio between rail and truck fuel efficiency. For example, if rail is four times more fuel efficient than truck on a given movement, the fuel consumed by rail would only be four times lower than the fuel consumed by truck if the distances were equal.

Exhibit 4-20 provides route distances by rail and over the road, as well as the ratio between rail and truck fuel efficiency with and without consideration of circuity. Truck routes are shorter than rail routes in 17 out of 23 movements, and in those cases the rail-truck fuel efficiency ratios decrease when considering the effects of circuity.

The difference between the rail-truck fuel efficiency ratios with and without consideration of circuity is typically twice as large as the difference between truck and rail route distances. This is the case since the consideration of circuity affects rail and truck fuel efficiency in opposite ways, thus magnifying the difference between rail-truck fuel efficiency ratios.

Exhibit 4-20. Effects of Circuity on Rail-Truck Fuel Efficiency Ratios

Movement	Route Distance			Rail-Truck FE Ratio		
	Rail (miles)	Truck (miles)	Difference (%)	Without Circuity	With Circuity	Difference (%)
1	280	302	8%	3.9	4.5	16%
2	294	330	12%	5.5	6.9	26%
3	133	197	48%	2.3	5.1	119%
4	1,083	1,039	-4%	3.6	3.3	-8%
5	242	239	-1%	2.8	2.8	-2%
6	790	704	-11%	3.2	2.6	-21%
7	790	704	-11%	3.7	2.9	-21%
8	352	439	24%	5.5	8.5	55%
9	352	439	24%	4.3	6.7	55%
10	367	326	-11%	1.9	1.5	-21%
11	561	350	-38%	2.0	0.8	-61%
12	910	595	-35%	4.0	1.7	-57%
13	450	447	-1%	2.7	2.7	-1%
14	673	636	-5%	3.5	3.1	-11%
15	1,415	1,303	-8%	3.9	3.3	-15%
16	2,232	1,983	-11%	4.8	3.8	-21%
17	445	518	17%	2.2	3.0	36%
18	1,805	1,531	-15%	4.6	3.3	-28%
19	2,090	1,771	-15%	4.0	2.8	-28%
20	1,034	780	-25%	5.1	2.9	-43%
21	2,150	2,046	-5%	4.5	4.1	-9%
22	1,484	1,226	-17%	5.2	3.5	-32%
23	1,788	1,591	-11%	5.3	4.2	-21%

Effects of Grade

Grade is a direct input in the calculation of rail and truck fuel consumption. In the train resistance formula used in rail simulations, the effects of grade depend on vehicle weight, while in the truck power demand formula its effects depend on both vehicle weight and speed.

The effects of grade on rail movements could not be isolated because rail movements were simulated on actual networks taking into account current rail traffic levels. As such, the simulations of rail movements without grade resulted in unrealistic travel patterns, especially on busy segments. The effects of road grade on truck movements could be specifically modeled by running the simulations on flat terrain. As a result of grades, fuel consumption is increased between 10-35%.

Effects of Congestion

Congestion can affect rail and truck fuel consumption to the extent that it requires vehicles to accelerate and decelerate more often to adapt to network traffic levels. Because fuel consumption is significantly higher in acceleration mode than when traveling at constant speed, fuel consumption is typically higher in congested scenarios.

A large share of rail movements was modeled with and without consideration of current traffic levels on the rail segments traveled, and the fuel consumption between the opposed (with rail traffic) and unopposed (without rail traffic) simulations ranged from 0.7 to 3.6%.

All truck movements were modeled with consideration to average traffic levels on interstate highways during off-peak times, so congestion on roadways was not accounted for in the analysis. A previous analysis have indicated that truck fuel consumption can be reduced quite dramatically as road level of service degrades.[59, 60] For example, truck fuel economy was reduced by 6% as level of service degraded from A to D. If level of service degraded to E or F, truck fuel economy was reduced by about 20% and 40%, respectively. However, because heavy-duty trucks that typically compete with rail travel along interstate during off-peak hours, the analysis did not account for congestion on truck movements.

4.6. Evolution of Rail and Truck Fuel Efficiency

The 1991 Study provided a similar comparative analysis of rail and truck fuel efficiency on competitive corridors, and this study was designed to enable a comparison with those results. After almost 20 years, it is reasonable to expect differences from both studies, since it is likely that shifts might have occurred in mode shares, thus affecting the selection of competitive corridors.

Exhibit 4-21 provides a comparison of the ranges of rail fuel efficiency in the 1991 Study and in this study. Exhibit 4-22 provides the same comparison for truck fuel efficiency. Double-stack trains appear to have become more fuel efficient, with a similar lower-bound in both studies, but a much higher upper-bound in the current study. At the same time, dry vans and container on chassis are somewhat less fuel efficient in this study, possibly because of the more realistic representation of truck movements.[61] These two factors explain why the rail-truck fuel efficiency ratios increased for commodities moved in double-stack trains. The current study includes only one TOFC train, but its associated rail fuel efficiency is consistent with the results from the 1991 Study. The rail-truck fuel efficiency ratio increase for TOFC trains because the fuel efficiency of dry vans is lower in the current study. The most striking difference between the studies relates to mixed trains, where the current study estimates much lower rail fuel efficiencies, possibly because of the inclusion of more fuel used in short branchline movements and switching operations. This is offset by lower truck fuel efficiencies due to the more rigorous approach taken in the simulation of truck movements. As a consequence, the rail-truck fuel efficiency ratio for mixed trains stayed relatively the same. Auto movements have lower rail and truck fuel efficiencies in the current study, and rail-truck fuel efficiency ratios are also lower, which shows

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59 Level of Service (LOS) is the primary measurement used to determine the operating quality of a roadway segment or intersection. According to methods described in the Highway Capacity Manual, there are typically six designations for LOS: A (free flow), B (stable flow, operating speed is beginning to be restricted by other traffic), C (stable flow, volume and density levels are beginning to restrict drivers in their maneuverability), D (stable flow, speeds and maneuverability closely controlled due to higher volumes), E (approaching unstable flow), and F (forced traffic flow, long delays with stop and go traffic).

60 Facanha, C. (2009): Effects of Congestion and Road Level of Service on Vehicle Fuel Economy. Presented at the 2009 Transportation Research Board Conference.

61 Truck fuel consumption is measured with micro modal simulation models, which account for specific route elevation profiles as well as driving cycles that are consistent with long-distance truck movements. As explained in Appendix F, standard driving cycles were also adjusted for the fact that heavy-duty trucks need to decelerate during uphill road segments. The fuel consumption from idling operations is also included.

that rail fuel efficiency became comparatively worse over time when compared to truck fuel efficiency.

Exhibit 4-21. Evolution of Rail Fuel Efficiency (ton-miles/gallon)

Train Type	Rail Fuel Efficiency Range		Rail-Truck Fuel Efficiency Ratio Range	
	1991 Study	Current	1991 Study	Current
Double-Stack	243 - 350	226 - 512	2.5 – 3.4	2.7 – 5.5
TOFC	196 - 327	273	1.4 – 2.1	3.2
Mixed	414 - 843	278 - 487	2.8 – 5.5	2.3 – 5.3
Unit Auto	206	156 - 164	2.4	1.9 – 2.2

Exhibit 4-22. Evolution of Truck Fuel Efficiency (ton-miles/gallon)

Trailer Type	Truck Fuel Efficiency Range	
	1991 Study	Current
Dry Van	131 - 163	82 – 110
Container	97 - 132	68 – 100
Dump	N/A	98 – 129
Flatbed with Sides	147	112 – 133
Tank	N/A	70 – 132
Auto Hauler	86	74 – 81

Chapter 5. Future Trends in Rail and Truck Fuel Efficiency

This chapter provides an analysis of anticipated future trends in rail and truck fuel efficiency over approximately the next 20 years. It builds on Chapter 2, which includes an analysis of past trends in rail and truck fuel efficiency from 1990 to 2006. There is some overlap between these chapters, since some technologies have had little market penetration to date, and therefore have not had much impact on fuel efficiency since 1990. Because some technologies and trends have had an impact on past fuel efficiency and will likely have an impact on future fuel efficiency, they were also included in this chapter.

The approaches to future trends in fuel efficiency are slightly different for rail and trucks. Some rail technologies can be implemented incrementally one unit at a time with benefits being realized immediately, and others can only provide benefits when introduced on a wider scale. The larger the required scale, the longer the implementation time. The analysis is divided into short-term, medium-term, and long-term actions to improve rail fuel efficiency. In each of these time categories, fuel-saving strategies are addressed as either technological or operational strategies, and whether they are single-unit developments, complete train or route segment developments, or system-wide developments. Because most fuel-saving strategies for the trucking industry can be implemented individually one truck at a time, the implementation time frame tends to depend on the state of the technology and R&D efforts. Therefore, developments for the trucking industry are classified as engine improvements, non-engine improvements, and operational strategies. Both the rail and truck sections start with an analysis of external factors affecting fuel efficiency.

5.1. Diesel Fuel and Energy Prices

Recent high prices of oil and diesel fuel have stimulated industry interest in reducing fuel consumption. The price of diesel fuel has risen 673% since 1990, with much of the increase coming since 2002, and accelerating thereafter.[62] Fuel costs, which are typically the second largest expense after labor for most large trucking companies, became the largest cost for many companies. The subsequent collapse in prices of crude oil and diesel fuel illustrate the difficult choices managers face in choosing investments.

Many transportation investments have long lives, 20 years or more, especially in the railroad industry. Where that investment is justified, in part, on fuel savings, railroads and trucking companies need to consider carefully the likely trends in future oil prices in their investment decisions. Decision-makers have to consider both the long term trend in oil prices and the likely volatility. Transportation investment analysts must review the best available forecasts of prices for both crude oil and diesel fuel.

[62] Association of American Railroads (2008): Monthly Railroad Fuel Price Indexes July 2008.

Expert analysts[63,64] suggest that crude oil prices exceeding $100-120/barrel will prompt significant conservation efforts by individuals, business, and government to the degree that further substantial and sustained price increases beyond that range would be unlikely. Both sources also agree that a future period of very low oil prices as was seen in the 1980s and 1990s is also very unlikely. The higher prices have very solid underpinnings in the continued growth of world demand and the increasing costs of exploration, production, and refining. All this means that even conservative investment analysts will be able to support some fuel and energy efficiency investments in response to higher oil prices.

Because of the uncertainty regarding the size of future benefits, railroads and trucking companies will favor more limited investments in efficiency, which require little up-front capital and pay for themselves in the short term. This is the best way to obtain a secure return from fuel-efficiency investments. Railroads will be very cautious about large investments with system-wide effects, because the long-term payback is unclear.

5.2. Rail Fuel Efficiency

Between 1990 and 2006, rail fuel efficiency[65] improved by about 20%, or 1.1% per year.[66] These figures represent the overall industry average for U.S. Class I railroads and are the net outcome of multiple changes in railroad traffic mix, technological improvements, and operating practices. Most of this improvement took place without the strong incentive of rising diesel fuel prices after 2004. The principal factors behind rail fuel efficiency improvements were:

- Changes in traffic mix, especially the steady growth of unit-train traffic and in particular, coal and intermodal traffic;
- Technological improvements in locomotives, freight cars, signals, train control and dispatching systems, and track systems;
- Changes in operating practices that lowered fuel consumption, such as the optimization of train meets and passes at sidings, crew training in fuel-saving operating techniques, and improved scheduling to avoid delays.

There is every indication that development and implementation of these changes will continue, maintaining or accelerating the pace of fuel efficiency improvement over the next 15 to 20 years. The primary driving force will be increasing cost of diesel fuel, which has shifted management attention and investment priorities toward fuel-saving developments. However, railroads are subject to a variety of external factors that can influence their ability to improve fuel efficiency. These factors include the overall economic outlook, shifts in the demand for rail services and the mix of traffic deriving from that demand, rail network congestion and the ability of the railroad industry to fund the needed capacity investments, federal and state legislation affecting railroads, and overall U.S. transportation policy.

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63 Yergin, Daniel (2008): Oil at the Break Point. Testimony to the US Congress Joint Economic Committee, June 25, 2008.

64 New Zealand Transport Agency (2008): Managing transport challenges when oil prices rise. New Zealand Transport Agency Report 357 April 2008.

65 Measured in gallons per million revenue ton-miles.

66 Association of American Railroads (2006): Railroad Facts – 2006 Edition.

The following sections address both the external factors affecting railroad fuel efficiency and the developments in railroad operations and technology that may be implemented to improve efficiency. Section 5.2.1 describes the external factors that may affect fuel efficiency and the railroad industry's investment and operating priorities. Section 5.2.2 describes short term measures to improve efficiency being implemented in response to the recent fuel price spike. Section 5.2.3 describes medium term fuel efficiency improvement that will likely result from the broad implementation of proven technologies and operating methods, and the ongoing process of replacing older locomotives, cars and train control systems with new equipment and systems. Section 5.2.4 describes long term and more speculative changes, such as electrification of main line freight railroads and use of alternative fuels and power plants. Section 5.2.5 is a summary of the findings.

In considering new railroad technologies and operating methods it should be noted that railroad technology and operations developments fall into three groups, which face very different barriers to successful application. Some technologies can be introduced in small increments, e.g., one locomotive at a time with benefits being realized right away; others do not provide benefits unless implemented on a broader scale. The principal groups are:

- **Single-Unit Developments:** this category includes most locomotive and freight car developments, such as more fuel-efficient locomotives, higher capacity freight cars, and freight cars with reduced rolling resistance. Each such unit that is put into service provides an immediate benefit. Achieving these benefits does not require changes in any other area of railroad operations and technology, nor does it depend on regional or system-wide application. The benefits are usually easy to estimate and can be confirmed with short operating tests. Thus, railroads find it relatively easy to justify such investments;
- **Complete Train or Line-segment Developments:** the best example of a complete train development is the unit train that carries trainload quantities of freight from origin to destination with no intermediate switching. Unit trains also serve as a platform for other technologies and operating methods, such as electrically controlled pneumatic (ECP) brakes, which have to be fitted throughout the train to be effective, and distributed, remotely controlled locomotive power. Line segment developments include upgraded signal systems, such as Centralized Train Control (CTC). Most of the large systems still have territory without CTC;
- **System-Wide Developments:** these are developments whose benefits are only realized when applied to a whole railroad network or to a significant fraction of that network. Examples are Positive Train Control (PTC), which requires equipment at both trackside and on locomotives, and that will only provide its safety and operations benefits if all trains and routes in an area are equipped; or ECP brakes on freight cars used in mixed freight (not in unit trains). System developments are much more difficult to implement because (1) benefits will often lag investments by several years, (2) investments can be large, requiring a consistent financial commitment over a long period, and (3) in some cases, implementation may require industry-wide agreement on new technical standards.

5.2.1. External Factors Affecting Railroad Fuel Efficiency

External factors that will influence rail fuel efficiency are organized in three groups:

- Mix of commodities and equipment;
- Traffic volume relative to capacity;
- Environmental regulations.

Mix of Commodities and Equipment

The mix of commodities and equipment is important because it affects both type of train and equipment. Further, type of train—unit train or mixed train—drives mode of operation. Unit train service, typically 100 cars or more, is loaded at the origin point with one commodity and all cars of the same type. The train follows a direct route to the destination point where it is unloaded. It does not pass through yards or terminals on the way and remains intact. Unit trains are used for intermodal service and bulk commodities. Most unit trains are either intermodal or coal trains, and grain also moves in unit trains.[67]

Mixed trains, also referred to as merchandise trains or manifest trains, move many shipments, each consisting of one or a few carloads. This type of operation is often referred to as carload service. A particular shipment does not move in the same train from origin to destination. It moves in a series of trains from one intermediate terminal to another. The typical carload move starts when a local train picks up the shipment (a few cars or one car) at the shipper's facility and moves it to a terminal. The shipment is placed with other shipments, enough to make up a full train, and the mixed train moves to another terminal where it is broken up, with the individual shipments placed in new trains for on-movement towards their destinations. When a shipment reaches the final terminal in its route, it is placed in a local train for delivery to the consignee's facility. Compared to unit trains, this is a fuel-intensive operation because of the need for switch engines in breaking up trains and making new ones in every terminal through which the shipment passes. Further, the fact that all the cars in a unit train are identical creates a potential for aerodynamic improvement that is not present in a mixed train.

Until a few decades ago, virtually all rail traffic was carload traffic. In recent years, there has been a strong trend towards unit trains—partly due to the growth of intermodal traffic from West-coast ports and coal traffic from the Powder River Basin. Carload service still accounts for a significant fraction of all traffic, but the preponderance of ton-miles are now in unit-train service. As noted in Exhibit 2-1 in Chapter 2, the combined share of coal and intermodal traffic rose from 52% of ton-miles in 1990 to 57% in 2006. Part of the remaining 43% was grain and other traffic moving in unit trains. A continually decreasing share of carload service would be a positive factor for rail fuel efficiency.

[67] Grain trains may be made up of smaller blocks of cars that are loaded at a few origins and combined into one train before going to destination; they do not go through yards or terminals.

Traffic Volume and Capacity

There is general agreement among economists and other analysts observing the freight industry, that the next several decades will see continued strong growth in freight traffic. As an example, a recent study sponsored by the Association of American Railroads (AAR) cited a USDOT forecast of traffic growth from 2005 to 2035 of 88%, measured in tonnage.[68] That is an annual growth rate of 2.1%. The same study estimated that for today's traffic, 12% of primary corridor mileage is at or above capacity and that, in 2035, 55% of mileage would be at or above capacity, if there were no expansion from today's capacity.

Clearly, any estimate of traffic growth 30 years into the future is open to challenge and debate. But the central point is valid. Traffic will grow, and if capacity is not increased in proportion as traffic grows, congestion will increase. Increasing congestion is necessarily a negative factor for fuel efficiency as trains are forced to operate below optimum speeds and spend more time idling on sidings while waiting for an available slot in the flow of trains.

To what degree railroads' investment in capacity keeps pace with traffic growth depends on many factors. Of greatest importance is railroads' return on investment (ROI) in increased capacity. Railroads are private firms, and they cannot invest in increased capacity unless they see the prospect of adequate returns on their capital.

With rising demand for rail service, one might expect that rail carriers could earn a return sufficient for some investment in capacity increase. Quite aside from the future level of demand, there is uncertainty about railroads' ability to profit from it. A major cause of uncertainty is future federal policy regarding railroad rate regulation. The Staggers Act of 1980, and subsequent ICC decisions, substantially reduced regulatory restraint on rail pricing and laid the groundwork for the subsequent return of the industry to profitability and financial strength. There is now some prospect for significant revision of the regulatory regime that has been in place since Staggers. This is likely to be an issue before Congress over the next year or two. The likely result of increased regulatory restraint would be reduction in railroads' return on capital below what it would otherwise have been. There is no way at the present time to predict the outcome of the political struggle on this issue. If federal rate policy remains unchanged, that will be a positive factor for future railroad investment in capacity.

It must be noted, however, that the level of investment that maximizes railroads' ROI is not necessarily the level of investment that maximizes fuel efficiency. Many factors besides fuel costs drive rail profit levels. Nonetheless, it is reasonable to suppose that any significant restraint on rail earnings would be a negative factor for fuel efficiency.

A related issue is whether there would be any public funds for investment in railroads that might make up for inadequate ROI. There has been a great deal of discussion of this issue. It will continue to be a matter debated in the political arena, and there is no reliable way of predicting the outcome of that debate. The upshot of this discussion is that market forces might provide the railroads with sufficient funds for capacity investment. There are also major public-policy issues driving future level of investment in rail, and the final decisions on those issues may not be known for some time.

[68] Cambridge Systematics (2007): National Rail Freight Infrastructure Capacity and Investment Study, September 2007, sponsored by AAR, Executive Summary.

EPA Emissions Regulations

The EPA has steadily tightened the emission limits for locomotive engines. These limits will be met with new technology to control emissions in diesel locomotive engines. EPA regulations do not directly address fuel economy, and have a mixed impact on efficiency. Some technologies, especially engine improvements, reduce emissions while boosting fuel economy. However, many after-treatment technologies scrub pollutants from engine exhaust at the expense of efficiency. In addition, new fuels or blends may reduce emissions with varying efficiency impacts. This section examines EPA emission caps, the technology which will be used to meet these caps, and the impacts of this technology on fuel economy.

EPA Locomotive Regulations

The EPA has set emission caps for diesel engines in on-road and off-road applications. These regulations limit the amount of criteria pollutants produced in each hour of operation. In 1998, EPA adopted targets for locomotive emissions, to be reduced over time. These targets are denoted as tiers 0, 1, and 2, which apply to locomotives of different ages. The emission caps are applied to locomotives upon their remanufacture after 2010. In 2008, EPA introduced tiers 3 and 4 which limit emissions in newly manufactured locomotives. Tier 3 applies to locomotives manufactured after 2012, while tier 4 applies to locomotives manufactured after 2015. Exhibit 5-1 details EPA's emission caps. Note that these standards apply to line-haul locomotives; the standards for switcher locomotives are less restrictive. [69]

Exhibit 5-1. EPA Emission Standards for Line-Haul Locomotives (g/bhp·hr)

Tier	MY	Date	HC	CO	NO_x	PM
Tier 0[a]	1973-1992	2010[b]	1.00	5.0	8.0	0.22
Tier 1	1993-2004[c]	2010	0.55	2.2	7.4	0.22
Tier 2	2005-2011	2010	0.0	1.5	5.5	0.20[e]
Tier 3[d]	2012-2014	2012	0.30	1.5	5.5	0.10
Tier 4	2015 or later	2015	0.14[f]	1.5	1.3[f]	0.03

a. Tier 0-2 line-haul locomotives must also meet switch standards of the same tier.
b. As early as 2008 if approved engine upgrade kits become available.
c. 1993-2001 locomotives not equipped with an intake air coolant systems are subject to Tier 0 rather than Tier 1 standards.
d. Tier 3 line-haul locomotives must also meet Tier 2 switch standards.
e. Starting in 2013, PM standard drops to 0.10 g/bhp·hr.
f. Manufacturers may elect to meet a combined NOx+HC standard of 1.4 g/bhp-hr.
Source: EPA (2008): 40 CFR parts 85, 89, 92. Available online at http://www.epa.gov/fedrgstr/EPA-AIR/2008/May/Day-06/a7999a.pdf

The Class I railroads have been working to improve their fleet in order to meet EPA standards. Current EPA restrictions (tiers 0, 1, and 2) can be met by upgrading old locomotives with current engine technology. Currently, the most effective method for meeting EPA Tier 2 requirements is by replacing or rebuilding non-compliant locomotives. In 2007, railroads introduced 902 new

[69] A summary of new loco standards can be found at DieselNet: http://www.dieselnet.com/standards/us/loco.php.

locomotives into the fleet of 24,143 locomotives.[70] An additional 167 locomotives were rebuilt with new engines to meet requirements.

While changes up to now have reduced both emissions and fuel consumption, future improvements will reduce emissions at the expense of fuel economy. Future goals (tiers 3 and 4) will require further engine improvements and new technologies. In practical terms, this means that some of the improvements in fuel economy will be offset by the negative effects of adding emissions controls. Specifically, tier 4 requirements for NO_x and PM will be met with exhaust after-treatment technologies which are expected to have a negative effect on fuel efficiency.

5.2.2. Short-Term Actions to Improve Fuel Efficiency

In response to high fuel prices, railroads will seek efficiency strategies that can be implemented promptly and at low cost. These strategies will quickly lower operating costs to improve financial results. Because of their fast payback, these projects are not affected by future changes in external forces, as described above. For the purposes of this report, short-term improvements occur in less than five years.

Overall, the short-term strategies fall into three categories: employee training, operational improvements, and incremental technological improvements. Many of these strategies have been tested in pilot projects and small-scale implementations, and their costs and benefits are well defined. Due to the fast payback and established costs, these strategies can be implemented with a high degree of confidence in their effectiveness.

Employee Training

To reduce operating costs, Class I railroads are training engineers to operate locomotives in a more efficient manner. These programs can quickly lower fuel consumption with low investment or capital costs. Employee programs include one or more of the following elements: training in best practices for locomotive operation; monitoring of engineer performance; and providing incentives to employees for saving fuel.

Training programs, such as the CSX Process Improvement Program, educate engineers on efficient techniques for operating locomotives. Employees learn to employ operations techniques to reduce fuel consumption, such as reducing idling and lowering top speed. Locomotive simulators are frequently used as a training aid. These training programs provide operators with tools and techniques to save fuel and reduce costs.

In addition, many programs combine training with performance monitoring and bonus structures, in order to encourage and reward employee efforts to save fuel. Both UP's Fuel Masters program and BNSF's Fuel MVP program provide small rewards to the most efficient engineers.

Operator performance can be difficult to measure, as fuel consumption depends not only on operating techniques but also on factors outside of the engineer's control, including train weight and track grade. However, railroads find different methods for comparing performance. BNSF compares the efficiency of each engineer against his or her past performance, using several methods such as ton-miles per gallon and horsepower per ton. A combination of metrics allows BNSF to compare an engineer's current operation against past performance. UP eliminates

[70] Association of American Railroads (2007): Class I Railroad Statistics. Available online at http://www.aar.org/

external variables by evaluating the performance of engineers in the same territory. This allows a comparison of operator efficiency for similar track conditions.

Employee training programs have been successful in quickly reducing operating costs. The UP program, which started in 2004, has reduced fuel consumption by 5%, and has been expanded to 95% of operators within four years. The BNSF program, which started in 2007, was also implemented quickly and will be expanded to all railroad engineers.

The success of these programs shows that training employees in fuel efficiency can lower operating costs within a few years after implementation. Employee training requires little up-front capital.

Operational Improvements

Railroads can quickly reduce fuel consumption by improving operating practices both on trains and on the rail network as a whole. These techniques save fuel by improving train efficiency, reducing idling, and coordinating classification yard activities. Examples of suitable practices are listed below.

- **Scheduled operations:** typically train operations over a route segment are not scheduled and trains are simply dispatched from each end with little advanced planning. This leads to delays, stop-go operation and excessive idling time as trains wait in passing sidings. Moving toward a more scheduled operation reduces delays, and stop-go operation. Trains can be advised of the planned arrival time at the next passing siding and may be able to travel at a lower, more economical speed to arrive at the right time, instead of operating at full speed and having to wait. This process is known as "pacing" trains. CN's Precision Railroading program includes efforts to schedule train operations in a more efficient manner;
- **Train composition for improved aerodynamics:** keeping cars of similar size or lading together in the train minimizes the gaps and changes in cross-section that produce aerodynamic drag. Examples are loading all trailers and all containers together on an intermodal train instead of alternating them, or placing similar cars together in a mixed freight train. Efficiency gains may be limited, as a railroad will not implement this practice at the cost of complicating terminal and switching activities;
- **Enforcing no-idling policies:** diesel engines are shut down whenever ambient temperature exceeds a preset threshold to minimize fuel consumption during idling. The addition of automatic systems that monitor the temperature of engine fluids and restart the engine when necessary allows the expansion of no-idling practices. CSX's policy of requiring that engines be shut down if they are expected to idle for more than 15 minutes and ambient temperature is above a specified threshold is an example of a typical no-idle policy;
- **Speed limits on trains:** UP is testing a maximum speed of 50 mph. The goal is to both save fuel while a train is in motion and reduce waiting time after a train arrives at destination. Analysis has shown that this program does not decrease overall transit time.

Technology Improvements

Railroads can boost returns of training and operations programs by supplementing them with new technologies, many of which have been in development or pilot stages for several years. These technologies provide more information to operators on train performance, helping them to make informed decisions on how to reduce fuel consumption. In addition, they can be installed on existing equipment quickly with small capital investments, and create viable opportunities for reducing fuel consumption in the short term. These technologies include:

- **Train simulation programs**. In a stationary train simulator, engineers can practice techniques for fuel reduction, with real-time feedback on performance. Instructors can coach engineers in a classroom setting. This technology is currently in use by all Class I railroads;
- **On-board information technology** provides real-time data to engineers, as well as recommendations for reducing fuel consumption. Developed by New York Air Brake, NS is deploying the locomotive engineer assist display and event recorder (LEADER) information system, further described in the following section, which tracks train position and track conditions to determine optimal use of engine and brakes to conserve fuel;
- **Automatic shutdown devices** operate in concert with idling procedures to save fuel when not in motion. Such devices are currently implemented by BNSF, CN and UP (e.g., “Smart Start” system developed by ZTR Control Systems).

5.2.3. Medium-Term Evolutionary Fuel Efficiency Improvement Opportunities

This section discusses medium term developments in railroad plant, equipment and operating practices that will lead to improvements in fuel efficiency. For the purpose of this discussion, medium term refers to 20-25 years, which is about the operating life of new railroad locomotives, freight cars and other systems that are entering service today. Most of these developments are technically proven, in that they have been applied in test or demonstration service and the technical performance is fully understood. However, broad implementation can only take place over several years at a minimum, and can be as much as the full life-cycle of the plant or equipment.

Locomotives

A major part of the gain in fuel efficiency over the next 20 years, as in past years, will derive from regular replacement of old, less efficient locomotives with more efficient current models. The Class I railroads operate about 12,000 line haul locomotives, with typical operating life of around 20 years. Even if there were no further improvement in efficiency over current models, an improvement in fuel efficiency of line-haul locomotives operated by the Class I railroads of approximately 8-10% over 20 years can be expected. If the locomotive manufacturers continue to improve fuel efficiency at the same rate as in the past, as seems likely, this improvement will approximately double, to 15-20%.

While the expected evolution of the Class I line haul fleet is in line with past practice, more sweeping changes are to be expected in the larger fleet of about 15,000 locomotives used by non-Class I railroads, and for local, branch line and switching service. Past practice for these locomotive duties has been to use locomotives retired from Class I line haul service, and older, lower-power four-axle locomotives, with periodic rebuilds and upgrades. However, most of these rebuilds and upgrades did not involve complete replacement of diesel engine prime mover, but rather the installation of new controls, electrical equipment and other components. Thus the opportunities to make an impact on fuel efficiency were limited. The current high price of diesel fuel, and EPA’s more stringent emissions requirements for rebuilt locomotives mean the past practice of simply keeping older locomotives in service with regular rebuilds and minor technology upgrades is no longer acceptable. Emerging departures from traditional practice are:

- Regional railroads and the larger short lines are purchasing new locomotives instead of former Class I locomotives on the second-hand market. Greater savings in fuel costs, together with the other benefits of new locomotives such as improved reliability, lower maintenance costs, and improved availability more than offset the higher upfront cost;
- The major locomotive manufacturers now offer a “re-powering” program where older four-axle and six-axle locomotives can have the diesel engine, alternator, cooling system and engine and traction controls completely replaced with 8 or 12 cylinder versions of the diesel engines used in new locomotives. These programs are relatively new, so there is limited information available from which to estimate how many re-powered locomotives will be put into service each year. However, the approach offers most of the fuel consumption benefits of a new locomotive at a substantially lower cost, and there is clear potential for attracting customers who cannot justify the purchase of a new locomotive;
- Use of Genset and hybrid locomotives for switching and local service continues to grow, with several hundred in service or on order. This growth is still largely dependent on government grants directed at reducing diesel engine emissions, most notably in Texas and California. So far, there has been no significant purchase (other than trial units) of hybrid or Genset locomotives without government grant support. The industry view is that these locomotives still do not meet the railroads’ ROI threshold. Most manufacturers claim a fuel consumption reduction of 25% or more, depending on duty cycles, and significantly higher reductions in specific pollutants.

The most important observation about these three developments is that they are applied to locomotives used mainly in mixed freight service, rather than intermodal or bulk commodity unit train service. Further, since the locomotives being replaced are very old, the fuel consumption improvement, at about 25%, is larger than that from replacing an older line-haul locomotive. Thus, the benefit will apply principally to truck-competitive commodities moving in carload service and could contribute on the order of 5% reduction in total fuel consumption for carload shipments. The substantial fuel consumption benefit, together with stricter EPA regulations on rebuilt locomotives, and continued long term growth in fuel price means that there is a high likelihood that most existing switching and local freight service locomotives will be replaced or re-powered over the next 20 years. This would end the era of continually rebuilding old locomotives, with mostly minor modifications, for secondary services.

Continuing technical improvements are expected in most areas of diesel engine technology. Most of these developments follow trends established in past years, reflecting the conservatism of the major Class I railroads that purchase most of the new locomotives. Developments are discussed in the following areas:

- Diesel engine technology;
- Electrical traction systems, including alternators, control systems and motors;
- Hybrid and Genset locomotives;
- Trucks, brakes and adhesion controls.

DIESEL ENGINE TECHNOLOGY

The application of new technologies currently in research and development could lower fuel consumption by 20% by 2030.[71] This estimate was derived from expected developments in heavy duty truck engines due to their shorter life cycles, higher demand, and need to comply with more stringent EPA emission standards. As these technologies mature, they may be adopted by the railroad industry to reduce operating costs and meet EPA emission regulations. For this reason, future improvements to locomotive engines will be the result of technologies currently being researched or deployed in the trucking industry. These technologies fall into three categories: engine combustion, exhaust gas utilization, and control technology.

Ideal combustion efficiency is limited by the diesel thermodynamic cycle to 56%. In practice, current engines achieve 40% efficiency. Improvements to fuel combustion components eliminate sources of energy loss within the engine. Promising technologies include:

- **Homogenous Charge, Compression-Ignition (HCCI) technology**, which improves the mixture of fuel in the combustion chamber, allowing for more complete combustion. HCCI can lower fuel consumption by 15% while reducing NO_X emissions. Significant research challenges include the design of variable valve timing systems to control air intake and exhaust;
- **Fuel injection technology**, which improves efficiency and reduces emissions by controlling the rate of mixing in the engine cycle. Past development efforts have focused on Common-Rail injection systems for on-road diesel vehicles. Future research is needed to implement this technology on locomotive engines.

New exhaust technologies capture and recover waste energy in the engine exhaust stream, increasing overall fuel efficiency. Future advances may come from:

- **Turbochargers**, which redirect the energy of exhaust gases to increase air-flow into the engine. Locomotive engines currently utilize turbochargers to reduce fuel consumption. Future research in this area will optimize the operation of this technology for wider ranges of engine speed and power output;
- **Intercooling systems**, which dissipate excess heat from exhaust, turbocharger, and engine components, reducing engine temperature. New intercooling methods can increase efficiency by managing system temperatures. Additional work is required to implement intercooling strategies on locomotive engines.

The engine and exhaust technologies discussed above require sophisticated on-board control systems for optimum operation under changing conditions. Advances in this category will improve the efficiency of current engine technology and enable the application of future technologies. Avenues of research include:

- With improved emissions sensors, engine systems can adjust operation according to real-time measurements. For example, engine sensors can monitor exhaust to prevent emission levels from exceeding regulatory thresholds. Future research is required to develop sensor technology as well as engine applications;
- Adaptive control systems alter computer engine controls in response to feedback from engine or vehicle sensors. For example, adaptive controls may tune engine performance

[71] Argonne National Laboratory (2002): Railroad and Locomotive Technology Roadmap. ANL/ESD/02-6. Available online at http://www.doe.gov/bridge

in response to changes in grade or cargo weight. More research is required to develop feedback mechanisms as well as develop optimized control algorithms.

ELECTRIC TRACTION SYSTEMS

The basic AC or DC power train of the diesel electric locomotive, using solid state power electronics for control, is not likely to change in the next several years. Continuing refinements to the variable frequency, variable voltage inverters for AC traction motors will slowly increase maximum tractive effort from AC motors relative to DC motors. This together with a narrowing of the price differential between DC and AC will mean that the market share of AC will continue to grow. As an indicator, Norfolk Southern has recently taken delivery of its first AC locomotives. NS evaluates investments carefully and conservatively, and until 2008 had not considered that an investment in AC locomotives could be justified. The tipping point was that a pair of the latest generation AC locomotives could replace three DC locomotives on some of their coal routes, showing a clear financial advantage.

Further in the future, there is potential for major improvements in motor design and in the power electronics devices used for motor control. One example is a brushless DC electric motor that is receiving funding from a TRB IDEA program and would reduce the weight and bulk of traction motors and controls. Any development of this nature would likely be applied first for the lower power motors used for electric rail transit cars, where the market is less cost sensitive and reducing weigh and bulk has more value. Such developments, however, are probably 10-20 years in the future.

HYBRID AND GENSET LOCOMOTIVES

With the success of hybrid automobiles, it was a logical step that hybrid railroad locomotives would follow suit. As discussed in Section 2.1.2 hybrid locomotives have become an attractive application for switching locomotives. Also, that section illustrated that Genset locomotives were not as fuel efficient as hybrids, but they have proved successful in service with over 250 units ordered for delivery.

The only caveat with hybrid and Genset developments for switching service is that the economics remain uncertain. Most purchases of hybrid and Genset switchers to date have been financed in part with air quality improvement grants[72], and it may be hard to compete (without the grants) with the much cheaper alternative of an existing older model 4-axle locomotive on the second-hand market. However the trends are encouraging. There is only a limited supply of suitable older locomotives and prices are rising. Rebuilding these older locomotives triggers more stringent emissions standards, which reduces the cost differential, and the value of fuel saving is now greater than when the locomotives were first introduced into service.

For the future, if there are sustained high fuel prices, it is likely that the next generation of production main line or switching locomotives will have hybrid capability and could contribute an overall 5-10% improvement in fuel efficiency for line haul operations and up to 25% for switching and local freight service.

[72] The Carl Moyer Air Quality Standards Attainment Program in California, and the Texas Emissions reduction Program.

TRUCKS, BRAKES AND ADHESION CONTROLS

Truck, brake and adhesion control developments have three basic goals:

- Increase the available adhesion for traction. On routes with steep grades and sharp curves, the number of locomotives needed on a train is governed by the traction force needed rather than total horsepower. Reducing the number of locomotives needed for a given service has direct benefit in reduced capital requirements and reduced operating and maintenance costs. Significant fuel savings result from a reduction in total train mass and the elimination of fuel consumed for idling and auxiliary systems on the eliminated locomotive;
- Reduce forces between the truck and track structure to minimize wear and deterioration, and more generally to increase the durability of truck components. Many locomotives now have radial trucks, using a linkage between axles to allow the axles to take up a radial position on curves. Radial trucks reduce lateral forces between wheel and rail, thus reducing wear and rolling resistance, as well as longitudinal steering forces between wheel and rail. This last effect increases adhesion available for traction. Linkages are also used to provide the longitudinal connection between trucks and the locomotive in a way that minimizes the weight transfer between axles when braking or pulling hard, while allowing lateral and vertical movements on the locomotive suspension. Weight transfer is undesirable, as it tends to reduce the maximum braking or traction force that can be applied through the truck;
- Maximize the effective use of available adhesion between wheel and rail to transmit traction and braking forces between track and train. This involves applying very sensitive sensors that can measure microslip between wheel and rail and used the sensor data to control motor torque or braking force. Microslip, actually caused by elastic distortion of wheel and rail materials and surface contaminants, is the mechanism by which tangential force is transmitted between wheel and rail. As force is increased, slip increases, until a break-away point is reached, at which gross slip occurs and force decreases rapidly. The objective with braking and traction controls is to work as close to the breakaway point as possible without gross slip. Slip sensing and motor controls are key to maximizing traction force, thus enabling railroads to reduce the number of locomotives assigned to a train on many routes, thus realizing the fuel efficiency and other benefits from using fewer locomotives.

Individual Car Developments

This section discusses technical developments in individual freight cars that provide fuel efficiency benefits. Many of the cited improvements are the continuing development of technologies introduced in Chapter 2. Some general points should be considered when forecasting the penetration of new technologies into the railroad industry:

- Freight cars used in carload service have much lower productivity (annual loaded miles) than those used in unit-train service. This means any given innovation will yield a much higher ROI from unit-train cars than from carload-service cars. This limits the opportunities to apply fuel-saving technologies to cars used in mixed freight;
- A majority of freight cars are owned by leasing companies or shippers rather than by the railroads. When an innovation provides economic benefits to the railroad, the car owner must be compensated for investing in the innovation through a rate adjustment or other means. This can be administratively difficult in carload service, where freight rates are not

usually linked to the detailed features of individual cars. In contrast, such rate adjustments are common for unit train contracts that specify the characteristics of the specific cars provided by the shipper for the trains.

Technical developments in individual cars can be applied one car at a time, and an increment of benefit will result for each car with the improvement that enters service. Most of these developments have been described in Chapter 2, so these notes focus on the potential for increasing application through the industry in future years.

- **286,000-pound gross weight cars:** These cars will gradually expand into all applications and almost completely replace lower weight cars over the next 20 years. At the same time, the track segments that cannot accommodate these cars at present, because of weight-limited bridges and similar constraints, will be strengthened;
- **Lightweight car construction:** There is probably limited scope for applying lightweight construction techniques to mixed-freight cars. These techniques tend to increase costs and will be hard to justify for these car types;
- **Specialized car types:** This development is largely complete, and these cars are already being used for most commodities where they are useful. Probably the most useful development will be car design features that simplify loading and unloading, such as very wide or full length doors for easy access. Any development that speeds turnaround can improve utilization and thus the potential for applying fuel-saving innovations;
- **Steering or radial trucks:** The prospects for the wide use of radial trucks beyond high utilization cars used in bulk-commodity unit train service are uncertain. Barriers include uncertain benefits for cars that are not used on fixed routes and the mechanisms for the car owner to obtain a return on the significant investment involved. In addition, application of other technologies that reduce car rolling resistance, such as low friction bearings and rail lubrication techniques, will erode the potential benefit from radial trucks. The most likely outcome is that radial trucks will remain a niche product used in a limited number of high return applications;
- **Low friction bearings:** Development and refinement of very low friction bearings continues, especially using innovative seals, with impressive results. Low friction bearings are likely to become standard practice on all freight car types, with almost universal application in the next 15-20 years;
- **Improved freight car aerodynamics:** Attempts have been made to reduce aerodynamic drag by streamlining cars in different ways. Examples include minimizing the gaps between cars, providing covers for open top hoppers and gondolas, and rounding the corners of the car body. Few of these initiatives have been widely adopted, usually because the ROI is insufficient, or the improvements are vulnerable to damage or interfere with loading and unloading operations. However, higher fuel prices should prompt a re-examination of some of these initiatives, and some contribution to fuel efficiency from improved aerodynamics may be expected.

Train-Level Developments

These developments must be applied over a complete train to realize a benefit. There are three developments of interest: electronically controlled brakes (ECP) applied to unit and intermodal trains, distributed power, and rail lubrication techniques.

ELECTRICALLY CONTROLLED PNEUMATIC BRAKES

FRA continues to promote the adoption of ECP brakes and in October 2008 issued its final rule on the advanced train braking technology. The rule permits trains to travel up to 3,500 miles without stopping periodically for certain routine brake inspections – more than double the current limit – because ECP brake systems contain continual electronic self-diagnostic 'health check' capabilities that inform train crews when maintenance is required.

The application of ECP brakes is expected to grow rapidly for unit and intermodal trains, probably becoming universal for these applications in 10-15 years.

DISTRIBUTED POWER

Distributed power is the practice of placing remotely controlled locomotives part way down the train. Using distributed power reduces in-train forces and increases practical train length. The benefits are an increase in train crew productivity, a significant reduction in longitudinal traction forces through the train and a modest reduction in train rolling resistance. This latter effect is due to lower traction forces, reducing the tendency to pull the cars inward on curves causing greater lateral force between wheel and rail. A limited reduction in fuel consumption derives from the reduction in rolling resistance and potential indirect effects from a reduction in congestion.

RAIL AND WHEEL LUBRICATION

Several forms of rail lubrication techniques are being applied throughout the rail industry, all of which can contribute to reduced rolling resistance of locomotives and cars and thus fuel consumption. These are:

- **Traditional wayside curve lubrication:** Treadle-operated lubricators have been common practice on sharp curves for many years. These lubricators apply grease to the side of the rail head to reduce friction and rail and wheel wear. At this point in time, almost all economically justifiable locations are equipped, and there will be limited opportunities for further expansion. Development effort will be concentrated on reducing maintenance costs and improving reliability and performance;
- **Locomotive flange lubrication:** Use of on-board lubricators on locomotives that apply the lubricant to the flange (but not the tread) of the wheel will reduce wheel flange and rail wear and rolling resistance, leading to a limited reduction in fuel consumption. The systems are carefully designed and installed to minimize the risk of lubricant on wheel treads which would reduce adhesion and thus maximum traction force. To the extent that lubricant remains on the rail after the locomotives have passed by, these systems will also reduce wear and rolling resistance of following freight cars;
- **Top of rail lubrication:** In this approach lubricant is applied to the top of the rail after the trailing axle of the locomotive, to reduce the rolling resistance of following freight cars. Top of rail lubrication reduces both longitudinal and lateral forces between the wheels and rail of freight cars as the truck responds to curves and alignment irregularities of the track, leading to the reduction of rolling resistance. Note that this process reduces the same component of rolling resistance as radial trucks and the application of one reduces the benefit of adding the other.

System-Wide Developments

The principal system-wide developments of interest are ECP applied to carload-service freight cars and integrated inspection and condition monitoring systems.

- **Universal ECP brakes:** Presently ECP brakes are being applied to complete unit trains, one at a time. This works because these trains travel from origin to destination without intermediate switching and the cars are usually dedicated to a specific service. In contrast, mixed trains are subject to intermediate switching and may contain any one of the several hundred thousand cars used in this kind of service. All these cars need to be equipped with ECP before system wide use. The advantages of ECP are substantial, and growing experience with current and near future applications strengthens the case for universal application. The likely evolution is that after equipping all unit and intermodal trains, ECP will be applied in niche areas where it is possible to build complete trains from a selected group of cars;
- **Integrated monitoring and inspection systems:** Faults in track, signal systems, cars and locomotives are a major source of operations delays and unpredictability, and reduce network capacity. Integrated inspection and monitoring systems of all kinds are designed to reduce delay and unpredictability by identifying and correcting incipient faults before actual failure. They are also used to maintain systems in good condition. Many of these systems such as ultrasonic inspection for fatigue cracks in rail, have been in use for many years. What is new and still evolving is the integration of all these data to actively manage system performance and reliability. A hypothetical example would be the lineside sensors that are used to identify hot bearings. Formerly, if an individual sensor detected an apparently hot bearing, the train had to stop and the bearing was checked manually before the rain could continue. The integrated system would track all measurements of each bearing in service and first establish the patterns exhibited by failing bearings and then flag bearings as suspect only when they exhibited these patterns. This approach reduces false alarms, increases the chance of identifying genuinely damaged bearings and improves the effectiveness of preventative maintenance programs. At the same time, new remote monitoring and inspection technologies are being added to the integrated systems. Almost all railroad systems and components critical to safe and reliable operations can be approached in this way. A key result of these developments is a significant reduction in service delays, leading to reduced fuel consumption in stop-go operation and idling.

Control Systems

The most important development in railroad control systems is Positive Train Control (PTC). PTC has been under study by the freight railroad industry for over 20 years, and several trial installations have been put into service. The primary functions of PTC systems are to reduce train accidents, especially collisions, by automatically:

- Enforcing signal indications and operating authorities, especially to ensure that trains cannot pass a stop signal;
- Enforcing permanent and temporary speed restrictions;
- Enforcing work zone limits, so that trains do not enter areas occupied by maintenance crews.

Thus PTC will prevent most of the more serious human-error accidents. After many tests and demonstrations, PTC systems have matured to the point that implementation on freight railroads is technically and economically possible. The key technical developments that have made PTC feasible for freight railroad applications include:

- Use of Differential GPS and related technologies to provide precise train location;
- Digital radio communications between the control center, individual trains and track equipment such as switches for all safety-critical rail operating data (train location, movement authority limits for each train, switch settings, work zone limits and speed limits;
- An on-board computer that constantly monitors train location and speed, and initiates braking to slow or stop the train to keep within speed and authority limits if the operator fails to do so;
- A control center computer linked to a computer-aided dispatch system that allows the dispatcher to issue digital train movement authorities and ensures that authorities do not conflict with each other.

Although PTC-like automatic train control (ATC) systems have been used on high speed and high density passenger lines for many years, these are hardwired systems with simple electronic devices that provide the key functions, and have been far too costly to be practical for a freight railroad.

A good example of a new-technology PTC system is the Electronic Train Management System (ETMS) supplied by Wabtec to the BNSF Railway. ETMS is a modular and expandable system which allows the railroad to select the functions required for a specific line. ETMS also provides a communications backbone for non-safety communications such as remote engine condition monitoring and monitoring and controlling train speeds for optimum capacity and fuel economy. Thus installation of communications-based PTC enables the implementation of very precise control of train operations with direct fuel efficiency benefits

It now can be confirmed that PTC will be widely implemented on freight railroads over the next decade. A rail safety law that mandates installation of PTC on all Class I railroad main lines used by passenger trains and for poisonous and “toxic by inhalation” (TIH) hazardous materials by December 31, 2015 was signed into law on October 16, 2008. The AAR, representing the Class I railroads has stated that the industry is fully committed to complying with this legislation, and the largest freight railroads are actively working to finalize PTC interoperability standards.

Operating Practices

In the medium term, there will be continued refinement and expansion of the short term developments described in Section 5.2.2. These are concerned with employee training and monitoring to encourage economical operating practices, expanded engine shutdown procedures to minimize idling, improves scheduling and pacing of trains to minimize stop-go operation and similar efforts. Increasingly, these efforts will be supported by automated systems as these migrate through the locomotive fleet, and older locomotives that lack the control interface for automated systems are retired. An example is the “LEADER” system manufactured by New York Air Brake Corp. LEADER combines GPS location, an on-board database with the route profile (grades), pre-calculated brake and throttle setting for minimum fuel consumption while meeting schedule requirements, and an algorithm that helps the engineer minimize longitudinal forces in the train. LEADER also records engineer actions on each trip for management review, and to help identify best operating practices, which can then be incorporated into recommended practices. Idling-reduction systems monitor shut down locomotive engines when not in use and monitor engine fluid temperatures. Main engines or an auxiliary power unit are restarted when engine temperatures fall to present minima.

In the medium to longer term, broad installation of PTC and the availability of precise train location and speed data open up numerous opportunities to optimize train operations, balancing journey time, capacity and fuel consumption. The realities of freight railroading present a considerable challenge in this regard. While some freight trains (for example premier intermodal services) can be operated to a precise schedule, like a passenger train, many others are subject to significant unpredictability. As freight trains operate over long distances on a complex network, an incident can affect operations several hundred miles away. The scheduler's challenge is to construct an efficient schedule, much of it in real time, which can accept a measure of unpredictability and a mix of trains with different operating characteristics while at the same time meeting service requirements and minimizing operating costs including fuel consumption. Increasingly, simulation techniques are being used to optimize operations over a specific track segment, both at the planning level and in real time. Some in the industry advocate moving towards a fully scheduled operation (like a busy passenger railroad), and setting procedures in place to achieve very high-reliability without incurring excessive costs. The automated inspection and monitoring systems described in Section 2.1.4 will be critical to achieving this reliability.

5.2.4. Long-Term and Speculative Developments

A number of longer term and speculative technology and operations developments could be applied over the next 20+ years to improve fuel efficiency of freight railroads and to facilitate the use of alternative power plants, alternative fuels and renewable energy sources. Not all these developments would necessarily improve fuel efficiency, but all would affect the mix of energy sources and consequently the fuel efficiency and carbon footprint of freight railroads.

Railroad Electrification

Locomotives operating on electrified railroads draw electric power from an overhead catenary or a third rail for traction. The technology for electric locomotives and power distribution systems is very well established, and there are numerous electric railroads throughout the world, used for all types of rail service from high-speed passenger to heavy-haul freight. Indeed, a heavy electric freight locomotive will be very similar to a diesel-electric locomotive, with the primary difference being that a transformer will replace the diesel engine and alternator. The usual choice today for a new main-line electrification project is to energize the catenary at 25,000 volts, 60HZ AC, and third rail low voltage DC electrification is typically used only in subway and commuter passenger rail systems.

Electric traction has a number of advantages over diesel traction:

- The locomotives are non-polluting at the point of use, and can contribute to air quality improvement goals in the locations where they are used. Overall GHG emissions may or may not be reduced depending on what fuels are used at electric power plants;
- Electric power may be generated from renewable or non-polluting sources;

- Once the electrification is in place, operating and maintenance costs may be reduced significantly. Depending on the energy source, electric power may be cheaper than diesel, and electric locomotives might need less maintenance and are more reliable than the diesel equivalent;
- Braking power can be fed back into the catenary, to be used by other trains in the vicinity or stored by wayside power storage devices for later use. Wayside energy storage may also be useful if the railroad relies in part on intermittent power sources such as solar or wind.

In spite of these potential advantages, mainline freight railroads in the U.S. have not been electrified. The primary reason has been that the financial case has only been attractive during periods of high petroleum prices. In addition, there is the difficulty of funding the very large capital investment required, much of which must be done in a single project. Full benefits are only realized after a critical mass of electrified territory is in service. However, the financial and policy advantages of electrification are becoming stronger, with the likelihood of sustained high petroleum prices and concerns over GHG emissions and the volume of oil imports. In addition, rail traffic density on principal main lines is much higher than in the past. Electrification economics improve markedly at high traffic density, where the largely fixed cost of the catenary and power supply is supported by a greater volume of traffic.

The principal technical challenge of implementing main line electrification in the U.S. is arranging for power supplies to trackside. An electric railroad using 25kv overhead power supply requires a substation approximately every 40 miles. Many main lines, especially on western railroads, run through sparsely populated territory remote from major transmission lines. One solution is to construct the transmission line along the railroad right of way, above the contract catenary. This solution is far from new – the Pennsylvania Railroad provided a transmission line (which is still in place) above the railroad when electrifying between New York and Washington DC in the 1920s and 1930s. There is some opposition to the concept of overhead transmission lines because of derailment potential, as well as track maintenance and signaling issues. The second issue is the quantity of power needed and the fuel source used. A rough calculation suggests that the BNSF Railway main line from Chicago to Los Angeles (a leading electrification candidate) would consume about 1,500 MW, the equivalent of about three large conventional power plants. New capacity would be needed, requiring numerous decisions regarding plant size, type and location, sitting of transmission lines, how to best minimize carbon emissions etc.

Fuel Cell Locomotives

Fuel cells have obvious potential for railroad locomotive applications. As in other transportation applications, the advantages of fuel cells are that there are no greenhouse gas or other emissions at the point of use (assuming hydrogen fuel is used and the locomotive does not have an on-board reformer to convert a fuel source, such as natural gas, into hydrogen fuel), and overall thermal efficiency is better than an internal combustion engine. The disadvantages are likewise similar: high cost, on-board storage of a hazardous fuel, and the inability to quickly increase or decrease power output.

The most current development is by BNSF Railway which plans to convert a “Green Goat” hybrid switching locomotive to fuel cell power. If this experiment is successful, then further developments leading to a production fuel cell locomotive could follow. Railroads are likely to be followers rather than leaders in fuel cell applications. If the cells and associated systems are available from developments outside the rail industry at a competitive price and performance, then rail applications will likely follow.

Automated Operation

The combination of PTC, comprehensive on-board monitoring and diagnostic systems, and in-cab video cameras means that fully automated train operations are technically possible. Almost all train crew functions can be performed remotely, the exception being occasional en-route repairs, such as replacing a couple knuckle, performed by the crew. Automatic operation is being used today on a couple of short, dedicated coal mine to power-plant lines, and is used on many metro systems around the world. Conventional freight railroad applications will likely develop in stages, first reducing train crew to a single person (common on passenger trains and many European freight trains), then eliminating the in-cab crew entirely on selected route segments. Fuel efficiency benefits could result from the precision of automated operation, but would likely be modest.

Dedicated High Performance Corridors

At present, railroad main lines carry a mix of traffic types, with the inevitable inefficiencies that follow from operating a mix of trains with different acceleration and braking capabilities and top speeds. As traffic becomes more concentrated on key corridors and capacity is added in the form of additional running tracks, opportunities grow to dedicate one track or a pair of tracks to one type of service, for example intermodal service or coal unit trains. Where parallel routes exist, specific types of traffic can be concentrated on each route. The fuel efficiency benefits follow from a reduction in train delays due to conflicts between different train types and the opportunities to run the railroad in a highly disciplined “conveyor belt” fashion. Other benefits include quicker and more predictable customer service, better asset utilization, and the ability to optimize infrastructure, trains and operations without having to accommodate multiple train types. While it will likely take 20 years or more for a true high performance freight corridor to emerge in the U.S., some of the building blocks can be observed today. Dedicated mineral railways such as the iron ore railways in Northwest Australia achieve tremendous productivity, far ahead of any multipurpose railroad. Netherlands Railways has built a dedicated freight line from a point near Rotterdam to the German border, primarily for containerized freight to and from the port. The Alameda Corridor in Los Angeles, though shorter has a similar function. In Washington State, long range plans for passenger service envisage a dedicated high speed passenger line parallel to freight lines in the corridor between Seattle and Portland. A third running track has been added in very high density freight railroad route segments in several locations around the U.S.

5.3. Truck Fuel Efficiency

As indicated in Chapter 2, average truck fuel efficiency for long-haul trucks has improved by about 11% between 1992 and 2002. More importantly, the average fuel efficiency for a 2002 truck utilized in long-distance movements was about 6.2 mpg, up from 5.2 mpg for a 1990 model year. Most of this improvement occurred independently of strong incentives of rising diesel fuel prices after 2004. The main factors behind the improvements in truck fuel efficiency were:

- Truck engine improvements, including the switch to electronic fuel injection, air-to-air aftercooling, and turbocharging in the early 1990s;
- Non-engine technological improvements, such as increasing penetration of aerodynamic devices, low-friction lubricants, and tare weight reduction, amongst others;
- Changes in operating practices, such as speed reduction and idling reduction.

The implementation of these changes will likely continue, driven primarily by increasing costs of diesel fuel. ORNL's report "Scenarios for a Clean Energy Future" includes estimates from EIA's National Energy Modeling System (NEMS) model on future truck fuel economy.[73] This report includes a business-as-usual (BAU) scenario, a moderate scenario, and an advanced scenario. The BAU scenario is largely based on the energy consumption data from the reference case case published in EIA's Annual Energy Outlook, while the moderate and advanced scenarios include more vigorous R&D efforts that result in both engine and non-engine technological improvements. The NEMS model results indicate that all three scenarios will result in an increase in freight truck fuel economy, though the moderate and advanced scenarios make far more significant gains. ORNL estimates that the base case will result in a 7% improvement in fuel economy from 2005 to 2020, while the moderate and advanced scenarios will result in far greater improvements, 27% and 48%, respectively (Exhibit 5-2).

These estimates are consistent with a recent paper[74], which indicated that freight (combination) trucks could achieve 10 mpg by using a variety of currently available strategies and technologies, which are discussed in this chapter.

The following sections address both the external factors affecting truck fuel efficiency and the developments in truck operations and technology that may be implemented to improve efficiency. Section 5.3.1 describes the external factors that may affect fuel efficiency and the trucking industry's operating priorities. Section 5.3.2 describes truck engine improvements, including hybrid powertrains and the use of biofuels. Section 5.3.3 describes non-engine technological improvements, which were already included in Chapter 2, but whose implementation still has room for expansion. Section 5.3.4 describes operational changes that might have an effect on future truck fuel economy. Section 5.3.5 is a summary of the findings.

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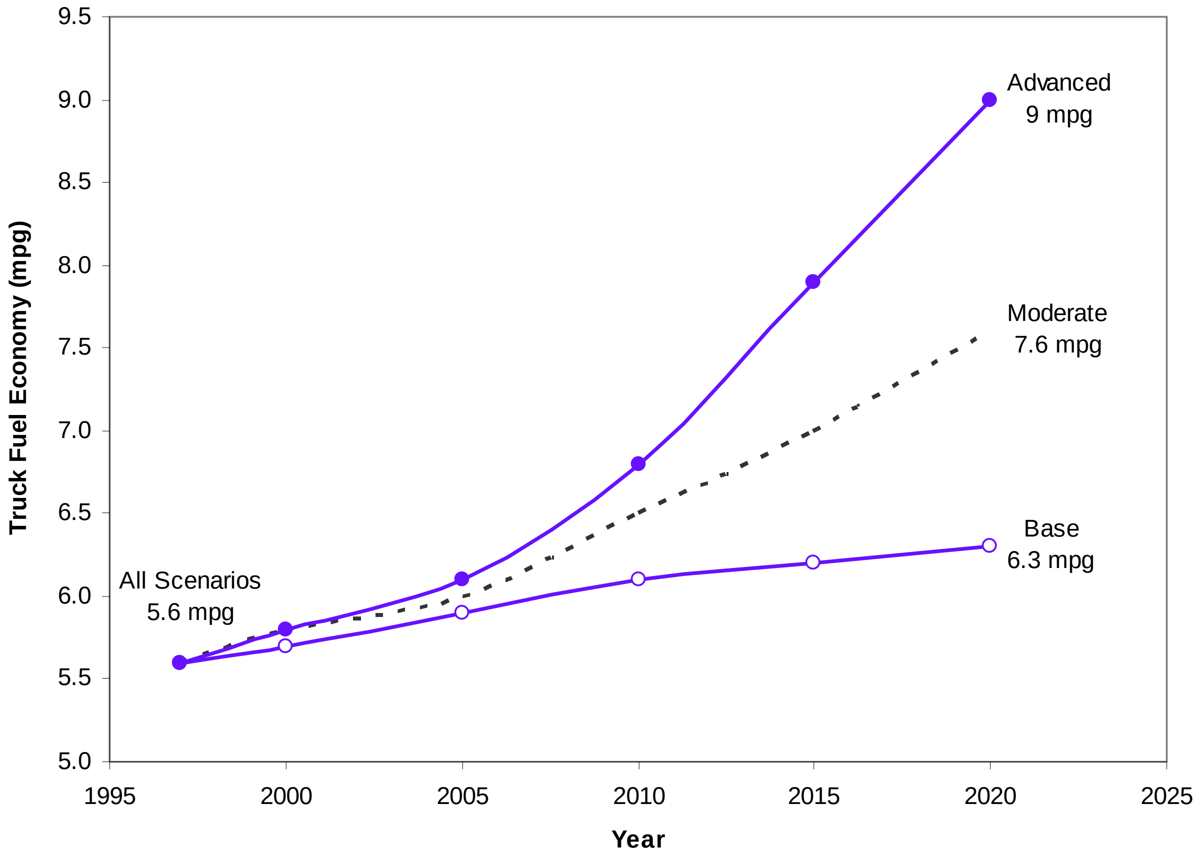
[73] Interlaboratory Working Group (2000): Scenarios for a Clean Energy Future (Oak Ridge, TN; Oak Ridge National Laboratory and Berkeley, CA; Lawrence Berkeley National Laboratory), ORNL/CON-476 and LBNL-44029, November. Available at http://www.ornl.gov/sci/eere/cef/

[74] Saricks, C., Anant, D., Stodolsky, F., Maples, J. (2003): Fuel Consumption of Heavy-Duty Trucks: Potential Effect of Future Technologies for Improving Energy Efficiency and Emissions. Transportation Research Record 1842, Paper No. 03-3648.

Exhibit 5-2. Projected fuel economy of freight trucks (ORNL)



5.3.1. External Factors Affecting Truck Fuel Efficiency

The trucking industry relies on both technological and operational strategies to improve fuel efficiency. Several external factors drive the extent to which these strategies are implemented. This section examines the external forces that drive investment in fuel efficiency, how they will evolve in the future, and how the trucking industry will respond. The influence of diesel fuel and energy prices, which apply to both rail and trucks, were discussed in Section 5.1.

Future Changes in Traffic Mix

Truck freight activity, measured in ton-miles, increased by over 50% between 1990 and 2005.[75] One of the factors behind such rapid growth has been the shift from push to pull logistics, where “manufacture-to-supply” logistics systems are being replaced by “manufacture-to-order”

[75] Bureau of Transportation Statistics (2005): National Transportation Statistics. Available online at http://www.bts.gov/publications/national_transportation_statistics/

systems.[76] Many shippers, especially in the automotive industry, rely on just-in-time systems with minimal inventory and very frequent shipments that do not necessarily utilize the full capacity of a truck.

With transportation costs increasing due to higher diesel fuel costs, the balance between transportation and inventory costs could affect such systems, and encourage shippers to maximize truck capacity at the expense of slightly higher inventory costs. It is unclear how average payloads would increase as a result of this trend. However, if that is indeed the case, average truck fuel economy measured in gallons per mile could actually decrease due to higher payloads.

Future Changes in Network Utilization and Congestion

Road congestion certainly has an effect on vehicle fuel economy, since short bursts of acceleration generate emissions that are considerably higher than those in steady state speed. Previous research has indicated that truck fuel economy is reduced by about 40% when there is a drop in road level of service from A to F.[77,78] Therefore, an analysis of future truck fuel economy needs to consider future congestion levels, especially along intercity corridors where trucks compete more directly with rail.

FHWA predicts that total road VMT (i.e., passenger and freight) will increase at an annual rate of 2.5% between 1998 and 2020, while truck VMT is expected to increase by more than 3% in the same time period.[79] Unless significant infrastructure expansion takes place, congestion will likely worsen substantially. Although most of future congestion is expected within urban areas, rural Interstate segments connecting urban regions will also be affected.

There are many strategies that are external to the trucking industry that aim at mitigating future roadway congestion. Those strategies are generally divided into three types: highway expansion, operational improvements, and land use changes. Highway expansion has become increasingly more difficult due to funding constraints, increased right-of-way and construction costs, and opposition from local and national organizations. At the same time, highway expansion is critical at locations where the lack of physical capacity is the main contributor to congestion levels. From 1990 to 2005, the number of lane-miles in the rural Interstate system where trucks compete directly with rail, did not keep pace with the growth in highway activity, and VMT per lane-mile increased by 40%.[80] There have been extensive discussions of dedicated truck-only lanes, but so far the concept has not gained much traction.

Operational improvements aim at utilizing existing highway capacity more efficiently, and can include incident management systems (to quickly clear accidents), real-time traffic information

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[76] ICF International (2004): 2010 and Beyond: A Vision of America's Transportation Future – 21st Century Freight Mobility. NCHRP Project 20-24(33) A, Final Report, August 2004.

[77] Level of Service, which characterizes congestion levels, is the primary measurement used to determine the operating quality of a roadway segment or intersection. Level of service is graded into one of six LOS designations, ranging from A (free flow) to F (heavy congestion).

[78] Facanha, C. (2009): Effects of Congestion and Road Level of Service on Vehicle Fuel Economy. To be presented at the 2009 Transportation Research Board Conference.

[79] Federal Highway Administration (2004): The Freight Story – A National Perspective on Enhancing Freight Transportation. Available online at http://ops.fhwa.dot.gov/freight/freight_analysis/freight_story/index.htm

[80] Bureau of Transportation Statistics (2008): Roadway Vehicle-Miles Traveled (VMT) and VMT per Lane-Mile by Functional Class – Table 1-33.

systems, and ramp metering, amongst others. For a more comprehensive discussion of strategies to mitigate congestion, please refer to FHWA's Traffic Congestion and Reliability Study.[81]

EPA Emissions Regulations

In the coming years, there will be two main drivers for truck engine improvements; required emissions standards, which impact fuel economy, and demands from customers to design more fuel-efficient engines. Since emissions regulations can negatively impact fuel economy, but are required for new trucks, there are significant incentives for engine manufacturers to meet these standards while avoiding fuel economy penalties (or at least minimizing the reductions in fuel economy). The most certain driver for truck engine modifications in the near future are EPA's new 2010 regulations, which will reduce NO_x emissions to approximately 10% of the 2004 standard. Although the EPA estimated that the 2010 emission standard would reduce fuel economy from 5-20% when compared to engines meeting 2004 standards[82], more recent estimates developed by ICF indicate a reduction from 5-10%. It is important to note that EPA's standards apply to new trucks only, so it will take some time until the vast majority of trucks will meet the 2010 engine regulations.

Engine manufacturers are pursuing one of two technologies to meet the 2010 regulations. Some manufacturers are designing engines with selective catalytic reduction (SCR). An engine with SCR mixes a diesel exhaust fluid, composed of urea and water, with the engine exhaust, to convert the NO_x in the exhaust into water vapor and nitrogen.[83] Other manufacturers are designing engines with exhaust gas recirculation (EGR), which sends some exhaust gas into the engine cylinder, reducing temperatures during combustion and thus minimizing NO_x emissions.[84]

In 2008, California proposed a plan to require older trucks to adhere to the 2010 engine regulations through retrofits.[85] The regulation would require any truck operating in the state to be retrofitted with a diesel particulate filter and other equipment to control NO_x emissions. The schedule requires this equipment to be installed between 2010 and 2022. California aims for all trucks to eventually adhere to the 2010 engine regulations, regardless of age. To the extent that other states might follow suit, this could have an effect on the national fleet as well.

Anti-Idling Policies

Although there are currently no federal mandates on truck idling restrictions, state and local governments have created their own anti-idling legislations. The American Transportation Research Institute (ATRI) has recently published a compendium of idling regulations.[86] About

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[81] Federal Highway Administration (2005): Traffic Congestion and Reliability – Trends and Advanced Strategies for Congestion Mitigation. Prepared by Cambridge Systematics and Texas Transportation Institute.

[82] U.S. Environmental Protection Agency (2002): Highway Diesel Progress Review. EPA420-R-02-016.

[83] Department of Energy (2009): Diesel Selective Catalytic Reduction. Energy Efficiency and Renewable Energy. Alternative Fuels and Advanced Vehicles Data Center. Available at http://www.eere.energy.gov/afdc/vehicles/diesels_catalytic.html.

[84] Cummins Turbo Technologies (2009): Exhaust Gas Recirculation. Available at http://www.holset.co.uk/mainsite/files/2_5_2_1-exhaust%20gas%20recirculation.php.

[85] Kiel, F. (2008): California Emissions Plan Pushes New Engines. Transport Topics. July 7, 2008.

[86] American Transportation Research Institute (2008): Compendium of Idling Regulations. Updated July 2008. Available online at http://www.atri-online.org/research/idling/Truck_Idling_Regulations.htm.

15 states and many local counties have passed anti-idling policies that are applicable to different vehicle classes.

In California, for example, operators of diesel-fueled trucks, with a gross vehicle weight rating over 10,000 pounds, cannot idle for more than five minutes.[87] As of January 1, 2008, California extended the prohibition even during extended rest periods for trucks with a sleeper berth, which requires drivers to use an idle reduction device.[88] Since this rule covers all trucks operating in the state, and not just those registered in California, many companies that only occasionally travel to the state will have to reconsider serving locations in the state or purchase idle reduction devices.

Besides state and local regulations, the U.S. EPA has developed a national voluntary anti-idling program to address environmental and transportation issues associated with long-duration engine idling through the SmartWay Transport Partnership. Eight major truck manufacturers currently offer at least one long haul model that meets SmartWay specifications.

5.3.2. Truck Engine Improvements

Other than EPA's required emission standards for truck engines, demands from customers to design more fuel-efficient engines will also affect the design of future truck engines. The two main developments related to truck engines are improvements in internal combustion engines, high-efficiency transmissions, hybrid powertrains, and the use of biofuels.

Improvements in Internal Combustion Engines

The internal combustion diesel engine is a mature transportation technology and the engine of choice for heavy-duty trucks due to its inherent thermal efficiency, high power delivery, low life-cycle costs, and reliability.[89]

Engine efficiency of modern heavy-duty trucks approaches 45%, and can be increased to 50% in the near future if research designs improve its cost-effectiveness. Amongst the technologies included to achieve such improvement are reduced internal friction, increased peak cylinder pressure, improved fuel injection, use of turbochargers and turbo-compounding, and improved thermal management (Exhibit 5-3).

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[87] California Air Resources Board (2007): Heavy-Duty Vehicle Idling Emission Reduction Program. Available online at http://www.arb.ca.gov/msprog/truck-idling/truck-idling.htm

[88] California Air Resources Board (2008): Idle Reduction Technologies for Sleeper Berth Trucks. June 11, 2008. Available at http://www.arb.ca.gov/msprog/cabcomfort/cabcomfort.htm.

[89] Office of Heavy Vehicles Technologies (2000): Technology Roadmap for the 21st Century Truck Program: A Government-Industry Research Partnership. Report 21CT-001. U.S. Department of Energy, 2000.

Exhibit 5-3. Ongoing Improvements in Internal Combustion Engines

Strategy	Fuel Economy Gains (%)
Reduced internal friction	2%
Increased peak cylinder pressure	4%
Improved fuel injection (e.g., electronic unit injectors, electronic unit pumps, electronic distributor pump systems)	6%
Use of turbochargers and turbo-compounding	10%
Reduced waste heat and improved thermal management	10%

Transmissions

Transmission systems transfer engine power to the axles and wheels. High-efficiency transmission technologies can reduce mechanical losses by 25% to 30%, resulting in a fuel economy improvement of 1% to 3%.[74] Continuous variable transmission (CVT) technology has not been widely accepted by the trucking industry because of concerns about cost and durability, but new emerging technologies might change that perception. CVT technology enables engines to operate at more optimized speed/load conditions. The fuel economy benefits from CVT technology are more difficult to quantify due to the interactions between driver and engine.[89]

Hybrid Powertrains

Hybrid powertrains for heavy-duty trucks are currently being tested and used in certain applications. Hybrids attain a gain in efficiency by using the battery rather than engine for secondary power (e.g., during idling), which is inefficient for the engine. Hybrids can also use the battery to supplement the engine during certain periods, such as an uphill start.[90] According to a report by the National Commission on Energy Policy[91], hybrid engines will not be cost-effective for typical intercity combination trucks in the near future. The 21st Century Truck Partnership also concluded that hybrid engines will not be economically viable for heavy-duty combination truck operations by 2025.[74]

Contrary to these studies, some truck operators and engine manufacturers are researching and testing hybrid powertrains in heavy-duty combination trucks. Wal-Mart and ArvinMeritor are currently developing a hybrid version of the International ProStar class 8 tractor, powered by a Cummins engine. This is one strategy Wal-Mart has adopted to meet its goal of doubling its fleet's fuel economy in the next 10 years.[92] Eaton and PACCAR, the maker of Kenworth and Peterbilt trucks, have announced plans to develop a hybrid heavy-duty truck and bring it to

90 ICF International (2007): Analysis of Good Movement Emissions Reduction Strategies. Task 1 Final Report. Prepared for Southern California Associations of Governments. December 2007.

91 Langer, T. (2004): Energy Savings through Increased Fuel Economy for Heavy-Duty Trucks. Prepared for the National Commission on Energy Policy. 2004. Available online at http://www.bipartisanpolicy.org/files/news/finalReport/III.4.a%20-%20Heavy-Duty%20Trucks.pdf.

92 Green Car Congress (2007): ArvinMeritor and Wal-Mart to Develop Hybrid Drivetrain for Class 8 Tractor. January 10, 2007. Available online at http://www.greencarcongress.com/2007/01/arvinmeritor_an.html.

market by 2009.[93] Volvo has also developed a hybrid truck with a reported 35% improvement in fuel economy.[94]

Biofuels

Biofuels, such as biodiesel, represent an emerging fuel source for heavy-duty trucks. The Department of Energy has indicated that B20 (20% biodiesel and 80% conventional diesel) can reduce fuel economy by about 2%.[95] Specific chassis dynamometer testing on Class 8 trucks indicated that there is a fuel economy drop of about 2% in city driving and 0.5% in highway driving cycle. Another study concluded that there is no difference in fuel economy between conventional diesel and B35.[96] Because trucks compete with rail mostly in the long-distance market, the effects of biodiesel on long-distance truck fuel economy are not expected to be significant. While there are no direct energy savings from biodiesel use for long-distance trucks, the life-cycle energy (the energy resulting from production, transportation and combustion of the fuel) may in fact be higher than conventional diesel.

Some states, especially in the Midwest, have mandated the blending of small fractions of biodiesel in all diesel fuel sold. In other cases, individual truck operators are using B5 or B20. Some truck operators still support biodiesel because it is a domestically produced fuel, and it reduces America's dependence on foreign oil. Additionally, the American Society for Testing and Materials (ASTM) has recently approved new biodiesel standards; the conventional diesel specification can now be blended with up to 5% biodiesel without being labeled as a different type of fuel.[97]

EIA monitors historical consumption and projects future use of biodiesel in transportation.[98] Biodiesel consumption has increased dramatically, especially since 2000. EIA projects that the consumption of biodiesel used to blend with conventional diesel will grow 16-fold between 2005 and 2030, from 0.01 to 0.16 quadrillion BTU, including fuel used in passenger and freight applications. EIA also estimates that the share of biodiesel in total freight truck energy consumption will go from 0.24% in 2005 to about 2.5% in 2030.

5.3.3. Non-engine Technology Improvements

There are numerous non-engine technologies that truck operators can use to improve fuel economy. Some of these options, such as aerodynamic cabs, are already widely used. Others, like auxiliary power units – which have substantial up-front costs, but substantial long-term benefits – are used frequently by large trucking companies, but only occasionally by smaller

93 Paccar (2007): PACCAR and Eaton Announce Heavy-Duty Hybrid Truck Technology Agreement. August 22, 2007. Press Release. Available online at http://www.paccar.com/NewsReleases/article_news.asp?file=2183.

94 Muldoon, D. (2007): Volvo revving up its trucks with heavy-duty hybrid drivetrains. Autobloggreen.com. January 15, 2007. Available online at http://www.autobloggreen.com/2007/01/15/volvo-revving-up-its-trucks-with-heavy-duty-hybrid-drivetrains/

95 U.S. Department of Energy (2006): Effects of Biodiesel Blends on Vehicle Emissions. National Renewable Energy Laboratory. NREL/MP-540-40554.

96 Wang, W.G., Lyons, D.W., Clark, N.N., and M. Gautam (2000): Emissions from Nine Heavy Trucks Fueled by Diesel and Biodiesel Blend without Engine Modification. Environmental Science & Technology, 34(6), pp. 933-939.

97 Schill, S. (2008): ASTM approves new biodiesel blend standards. Biodiesel Magazine. July 2008.

98 Energy Information Administration (2008): Annual Energy Outlook and Monthly Energy Review.

operations. Other technologies are still being tested and developed, but rarely yet used in the real world.

As part of its SmartWay Transport Partnership, EPA has begun to certify new tractors and trailers.[99] These tractors and trailers, manufactured by all the major OEMs, include a variety of technologies designed to save fuel. To be certified as a SmartWay tractor, the vehicle must be equipped with a model year 2007 or later engine, full aerodynamic package (integrated cab fairing, mirrors, bumper, side fairings), fuel efficient tires such as single-wides, and a system to reduce long periods of idle, such as an auxiliary power unit or bunk heater. SmartWay-certified trailers must be equipped with side skirts, weight-saving technology, fuel efficient tires, and either a boat tail or a gap reducer on the front of the trailer. EPA's goal is to increase the usage of these fuel saving technologies, and it hopes that truck operators will be more inclined to use them if the manufacturers sell trucks with the equipment as a standard feature.

Recently, California announced a regulation that would require all trucks, old and new, that operate in the state to adhere to the SmartWay tractor and trailer standards. Truck operators could either buy new SmartWay trucks, or retrofit existing trucks to meet the requirements. The plan requires all new heavy-duty tractors to meet the SmartWay regulations by 2011. Older trucks would have to meet the regulations by 2014, under a phase in schedule. This regulation would apply to all trucks operating in California, not just those registered in the state.

Aerodynamic Devices

Most new tractors are equipped with full aerodynamic packages, including cab roof fairings, side fairings, and aerodynamic mirrors and bumpers. Jointly, these devices increase fuel economy by about 3.5%.[100] In 2007, the estimated market penetration in the long-haul fleet of tractor aerodynamic devices was 78% of VMT. As older trucks are replaced with new or late-model vehicles, the market penetration of tractor aerodynamics will increase.

Trailer aerodynamics, which are currently far less common, should become more popular in the future. As indicated in Chapter 2, trailer aerodynamic devices include: (1) trailer 'side skirts', a fairing between the front of a trailer and the wheels at the rear that stops air from flowing beneath the trailer, (2) 'boat tails', which are connected to the end of the trailer, and (3) gap reducers, which reduce the gap between the tractor and the trailer.

Such devices are estimated to improve fuel economy in combination trucks by about 3.8%.[74] Section 5.3.5 summarizes the fuel economy improvements from many technological and operational strategies.

As noted in Chapter 2, there is little interaction between tractor and trailer manufacturers, and as a result, there has been no effort to treat tractor-trailer aerodynamics as an integrated whole. Additionally, some truck operators are skeptical of trailer aerodynamic devices. The side skirts can become damaged, especially in winter weather when tractors drive through snow and icy conditions. Boat tails can also block the rear doorway, making it difficult to load and unload the trailer.

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[99] See http://www.epa.gov/smartway/transport/what-smartway/tractor-trailer.htm for more information on SmartWay Tractors and Trailers.

[100] Saricks, C., Anant, D., Stodolsky, F., Maples, J. (2003): Fuel Consumption of Heavy-Duty Trucks: Potential Effect of Future Technologies for Improving Energy Efficiency and Emissions. Transportation Research Record 1842, Paper No. 03-3648.

Another emerging technology is a pneumatic blowing system. This type of device, currently being tested and developed, blows compressed air over parts of the trailer to smooth the airflow, improving aerodynamics. Pneumatic blowing can also lift some of the trailer weight off of the tires. Estimates indicate that fuel economy improvements from a pneumatic blowing system are about 5%.[100]

Rolling Resistance

As noted in Chapter 2, reducing tire rolling resistance is the second most important factor in improving fuel economy of heavy-duty trucks. Wide-based tires, which replace dual tires on a truck's drive and trailer axles, can improve fuel economy by reducing rolling resistance and tare weight (Exhibit 2-21). However, some truck operators avoid wide-based tires because of the risk of tire blowouts, which require a truck to stop immediately for a repair. An alternative to single wide-based tires are high-efficiency dual tires, which enable a truck to drive slowly to the nearest service station, potentially saving time and allowing the driver to get back on the road sooner. Other operators extensively use wide-based tires without problems. Saricks estimates that both wide-based and efficient dual tires will improve fuel economy by 3%. By 2025, he expects 33% of tires to be wide-based, and the other 66% to be efficient dual tires.[100]

Other than blowing compressed air over parts of the trailer to improve aerodynamics, pneumatic blowing can also improve rolling resistance by creating a lift that reduces the weight carried on the tires. Previous research estimates that this strategy can improve fuel economy by 1.2%, and that 25% of trucks will achieve this efficiency gain by 2025.[100] Exhibit 5-4 summarizes the fuel economy improvements from many technological and operational strategies.

Transmissions and Lubricants

As noted in Chapter 2, friction losses in the drivetrain (transmission and differential) and engine can be lowered using lower viscosity lubricants. Low viscosity lubricants are usually synthetic and exhibit superior high temperature stability and low temperature fluidity. Synthetic lubricants are widely used among truck operators and future estimates indicate that 66% of class 7 and 8 truck engines will be equipped with improved lubricants and bearings by 2025, up from 10% in 2005. These improvements may yield a 2% improvement in fuel economy.[100] Please refer to Exhibit 5-4 for a summary of fuel economy improvements.

Auxiliary Power and Idle Reduction Technology

Auxiliary power requirements stem from many vehicle functions, including trailer refrigeration, hotel loads, engine and fuel heating, air conditioning, lighting, auxiliary components (e.g., pumps, starter, compressors fans), computers, entertainment systems, and on-board appliances (refrigerator, microwave, coffee pot, hot pad). The vast majority of today's trucks convert fuel energy to mechanical and electrical energy to be used as auxiliary power. Despite being reliable, durable, and cost-competitive, belt- and gear-driven systems convert energy inefficiently and typically have constant outputs rather than supplying power on demand.

Because many heavy-duty trucks used in the long-distance markets idle overnight, large improvements can be achieved by supplying auxiliary power more efficiently. Auxiliary power units (APUs), which are usually small internal combustion engines equipped with a generator and heat recovery system, generate electrical and mechanical energy independently of truck engine operation, and can provide fuel economy savings of about 1.5%.[100] Fuel cells are also being developed as APUs. The potential of high efficiency (up to 50%) in converting fuel energy to electrical energy makes fuel cells an attractive alternative, with potential savings in fuel economy of 6%. It is estimated that by 2025, 65% of class 7 and 8 trucks will have one of the two devices.

Market penetration of APUs has been limited due to its high initial cost and potential loss of payload due to the APU weight. The Energy Policy Act of 2005 includes a provision for a 400-pound weight exemption for APU use, which would not force trucks that are close to their maximum weight to reduce their payload. However, FHWA determined that the exemption be honored by states on a voluntary basis, which obviously poses challenges to most long-distance trucks that cross state boundaries.

Another alternative to reduce truck idling is truck-stop electrification, which enables trucks to plug into electrical outlets at truck stops during rest periods. Truck-stop electrification requires modifying both the truck and truck stops.

Weight Reduction

The use of alternative, lightweight materials can reduce truck tare weight significantly, thus providing two benefits: (1) a lighter truck needs less energy to operate, and (2) reducing tractor and trailer weight allows for higher payloads. If a trailer cubes out (i.e., it reaches its volume capacity before its weight limit), the weight reduction will positively impact fuel economy, since no additional cargo weight would be added. If instead, the truck weighs out, the operator can add more freight or travel with less weight and reap the fuel benefits. Previous research indicates that by 2025, 30% of class 7 and 8 trucks will use lightweight materials that can increase fuel economy by up to 10%.[100]

5.3.4. Operational Strategies

Operational strategies are associated with the efficiency of truck operations. They aim at maximizing economic output (e.g., goods transported) while minimizing economic input (e.g., transportation equipment, infrastructure, fuel). Changes in operational characteristics of truck operations will likely have a significant impact on future freight fuel economy. Diesel prices and low profit margins will drive truck operators to continue to take aggressive steps towards saving fuel. Operational strategies have the potential to reduce fuel consumption in three ways: travel reduction, idling reduction, and congestion reduction.

Some strategies can reduce truck miles traveled. New infrastructure, which was discussed in Section 5.3.1, can reduce travel circuity and shorten the distance between freight origin and destination. Other strategies can increase truck payload, such as truck equipment weight reduction (discussed in Section 5.3.3), and longer combination vehicles, which is discussed below. Information technology also supports a reduction of truck VMT through load matching (and consequently reducing empty miles), route planning, dynamic traffic information, and vehicle tracking systems.

When freight vehicles and equipment are idling, they consume fuel and produce emissions without productivity. Some idling is unavoidable, but there are many opportunities to reduce idling. Trucks idle overnight to provide heating, cooling, or other driver amenities. Queuing and idling at pick-up and drop-off locations, toll stations, and intermodal facilities contribute significantly to inefficiencies in truck movements and to excessive emissions. Sections 5.3.1 and 5.3.3 addressed idling reduction technologies as well as regulations that sometimes drive the use of such technologies.

Vehicle fuel consumption in congested corridors tends to be higher, since the acceleration and deceleration patterns in stop-and-go conditions are generally associated with higher fuel consumption than at steady speed. The impacts of increasing congestion on long-distance trucks were discussed in Section 5.3.1. Speed reduction, on the other hand, is generally associated with lower fuel consumption on a per-mile basis (see below).

Speed Reduction

As noted in Chapter 2, truck fuel economy can be improved by reducing highway driving speeds. Aerodynamic drag and tire rolling resistance increase with travel speed, thereby reducing fuel economy. For each 1 mph over 55 mph, fuel economy is reduced by 0.1 mpg.[101] Many motor carriers have adopted a maximum speed policy for their drivers as a way to save fuel expenses and to promote safety. The American Trucking Association (ATA) supports a national maximum speed limit of 65 mph, as well as requiring all new trucks to have a speed limiter of 68 mph or less.[102] No action has been taken by the government to implement a national speed limit or limit on new trucks, but EPA's SmartWay Transport Partnership does support speed reduction as one measure to reduce emissions and increase efficiency.

Longer Combination Vehicles

A longer combination vehicle (LCV) is a tractor that pulls two or three trailers of varying length, rather than a single trailer. There is currently a freeze on increasing the size and weight of trucks, but states that allowed LCVs before June 1, 1991 can continue to allow them. There are 23 states that allow LCVs on designated routes. Some in the trucking industry favor lifting the freeze, and some are opposed. There is strong political opposition from other interests, and the prospects for lifting the freeze are uncertain. The main advantages are a reduction in total trips for a given level of tonnage, since each truck can carry more freight, which leads to fewer VMT less fuel consumed, and fewer emissions per ton. To the extent that lower costs of LCVs attract freight from rail, these may not be absolute reductions. LCVs might also lead to a reduction in labor cost, since fewer trucks would be needed to transport a given amount of freight. Cost savings could be realized by the shippers, carriers, and consumers. There are some disadvantages of LCVs, especially safety concerns. A recent study by USDOT did not attempt to resolve the issue of whether productivity gains from increased limits would outweigh safety costs. The report noted that LCVs "generally show poorer stability or control properties than the base tractor-semitrailer configuration."[103] The larger, heavier vehicles can also contribute to more roadway deterioration, but that would also depend on the number of axles, since road deterioration is directly correlated with weight per axle rather than total vehicle weight. Aditionally, cargo being hauled on LCVs that is being diverted from rail would probably consume more fuel on a ton-miles basis.[104]

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101 Ang-Olson, Jeffrey and Will Schroeer (2002): Energy Efficiency Strategies for Freight Trucking, Potential Impact on Fuel Use and Greenhouse Gas Emissions. Transportation Research Record Paper No. 02-3877.

102 Truckline (2008): ATA Calls For Comprehensive Plan To Ensure Affordable Oil. Press Release. July 11, 2008. Available online at http://www.truckline.com/NR/rdonlyres/3EA423E2-B705-4396-A3DD-2DCBA65F95CE/0/LynchHouseAgJuly112.pdf.

103 U.S. Department of Transportation (2000): Comprehensive Truck Size and Weight Study, August 2000, Executive Summary, p. ES-10.

104 ICF International (2007): Analysis of Good Movement Emissions Reduction Strategies. Task 1 Final Report. Prepared for Southern California Associations of Governments. December 2007.

5.3.5. Summary of Findings

The previous sections provided a brief description of the many technological and operational strategies that have the potential to improve heavy-duty truck fuel economy. Exhibit 5-4 summarizes the findings from two previous studies, and provides fuel economy benefits and maximum market penetration by 2025 for each analyzed strategy.

Exhibit 5-4. Projected Impact of Strategies on Truck Fuel Economy in 2025[29,74]

Strategy	Fuel Economy Gains (%)	Current Penetration	Maximum Penetration by 2025
Improvements in Internal Combustion Engines			
Reduced internal friction (improved lubricants and bearings)	2%	10%	66-100%
Increased peak cylinder pressure	4%	N/A	40%
Improved fuel injection	6%	N/A	40%
Use of turbochargers and turbocompounding	10%	N/A	N/A
Reduced waste heat and improved thermal management	10%	N/A	35%
Transmission			
High-efficiency transmission technologies	1-3%	N/A	100%
Tractor Aerodynamic Devices			
Tractor Aerodynamic Package (Van Trailer)	3.5	78	35
Tractor Aerodynamic Package (Van Trailer)	3.6	52	65
Trailer Aerodynamic Devices			
Cab top deflector, sloping hood, cab side flares	2.0	N/A	70
Improved Trailer Aerodynamics	3.8	0	65
Closing tractor and trailer gap, aerodynamic bumper, underside air baffles, wheel well covers	2.5	?	40
Trailer leading and trailing edge curvatures (e.g., boat tails)	1.3	?	50
Pneumatic Blowing	5.0	?	30
Rolling Resistance			
High-efficiency dual tires	3.0	N/A	66
Single wide-based tires	2.6-3.0	5	33-100
Automatic Tire Inflation Systems	0.6	5	100
Pneumatic Blowing	1.2	N/A	25
Auxiliary Power			
Direct-Fire Heater	4.3	5	38
Auxiliary Power Unit (electrical)	1.5-8.1	0	38-50
Auxiliary Power Unit (fuel cell)	6	0	15
Automatic Engine Idle	5.6	8	38
Weight Reduction			
Tare Weight Reduction	10	N/A	30
Speed Reduction			
70 to 65 mph	6.0	49	63
65 to 60 mph	7.6	10	63

Appendix A. Detailed Results for Rail Movements

Exhibit A-1. List of Rail Movements

Movement	Train Type	Origin	Destination	Route Distance (miles)	Rail Grade Severity
1	Mixed	Fort Valley, GA	Jacksonville, FL	280	1.7
2	Double-Stack	Columbus, GA	Savannah, GA	294	1.8
3	Mixed	Detroit, MI	Fort Wayne, IN	133	1.3
4	Mixed	Arcadia, OH	Jacksonville, FL	1,083	1.9
5	Mixed	Atlanta, GA	Huntsville, AL	242	2.2
6	TOFC	Chicago, IL	Atlanta, GA	790	2.0
7	Mixed	Chicago, IL	Atlanta, GA	790	2.0
8	Double-Stack	Decatur, IL	Frank, OH	352	1.4
9	Mixed	Decatur, IL	Frank, OH	352	1.4
10	Auto	Detroit, MI	Decatur, IL	367	1.4
11	Auto	Dayton, OH	St Louis, MO	561	1.8
12	Mixed	Toledo, OH	Memphis, TN	910	2.1
13	Double-Stack	Memphis, TN	Atlanta, GA	450	2.2
14	Double-Stack	Chicago, IL	Fargo, ND	673	1.5
15	Double-Stack	Oakland, CA	Clovis, NM	1,415	2.0
16	Double-Stack	Chicago, IL	Los Angeles, CA	2,232	2.6
17	Auto	Kansas City, MO	Chicago, IL	445	1.5
18	Double-Stack	Houston, TX	Los Angeles, CA	1,805	2.0
19	Double-Stack	Memphis, TN	Los Angeles, CA	2,090	2.6
20	Double-Stack	Clovis, NM	Memphis, TN	1,034	1.5
21	Double-Stack	Seattle, WA	Chicago, IL	2,150	2.6
22	Double-Stack	Clovis, NM	Atlanta, GA	1,484	1.7
23	Mixed	Kansas City, MO	Los Angeles, CA	1,788	2.6

Exhibit A-1. List of Rail Movements

Movement	Locomotives			Cars		Average Speed (mph)	Trailing Weight (tons)	HP per Trailing Ton
	Type	HP	Number	Type*	Number			
1	D9-C40/SD70	4,000	2	BC	105	14	7,140	1.1
2	D9-C40/SD70	4,000	2	DS	40	18	5,508	1.5
3	D9-C40/SD70	4,000	2	G	36	31	4,116	1.9
4	D9-C40/SD70	4,000	2	BC	95	21	6,544	1.2
5	D9-C40/SD70	4,000	2	G	85	17	4,026	2.0
6	D9-C40/SD70	4,000	2	TOFC	39	27	4,854	1.6
7	D9-C40/SD70	4,000	2	CH	73	21	6,062	1.3
8	D9-C40/SD70	4,000	2	DS	27	25	5,668	1.4
9	D9-C40/SD70	4,000	2	CH	87	21	5,732	1.4
10	D9-C40/SD70	4,000	1	A	43	27	2,903	1.4
11	D9-C40/SD70	4,000	1	A	43	20	2,903	1.4
12	D9-C40/SD70	4,000	2	G	85	21	6,386	1.3
13	D9-C40/SD70	4,000	2	DS	39	29	4,243	1.9
14	C44-9	4,380	3	DS	74	50	6,288	2.1
15	C44-9	4,380	4	DS	65	45	6,500	2.7
16	C44-9	4,380	4	DS	85	46	8,107	2.2
17	C44-9	4,380	2	A	65	51	4,281	2.0
18	C44-9	4,380	3	DS	75	39	7,543	1.7
19	C44-9	4,380	3	DS	67	44	5,293	2.5
20	C44-9	4,380	2	DS	69	41	5,589	1.6
21	C44-9	4,380	3	DS	74	48	6,288	2.1
22	C44-9	4,380	2	DS	60	37	5,181	1.7
23	C44-9	4,380	4	T	95	43	7,695	2.3

* A = Auto Rack; BC = Box Car; CH = Covered Hopper; DS = Double-stack; G = Gondola; TC = Tank Car; TOFC = Trailer on Flat Car

Exhibit A-1. List of Rail Movements

Movement	Commodity	Total Fuel Consumed (gallons)	Trailing Weight-mile per Gallon	Load (tons)		Fuel Consumed by Load (gallons)	Fuel Efficiency (ton-miles per gallon)
				Tare	Payload		
1	Newsprint/paper	3,315	603	32	66	46	406
2	Intermodal	2,166	747	36	38	29	384
3	Waste/scrap	1,217	450	36	73	32	301
4	General merchandise	10,255	691	35	74	171	469
5	Waste/scrap	2,653	367	31	96	84	278
6	Intermodal	5,844	656	21	15	43	273
7	Other foodstuffs	7,469	641	31	98	159	487
8	Intermodal	2,591	771	32	30	28	373
9	Other foodstuffs	3,183	634	32	95	71	475
10	Motorized vehicles	1,729	616	53	18	42	156
11	Motorized vehicles	2,627	620	53	18	64	157
12	Base metals	9,063	641	38	91	183	452
13	Intermodal	3,249	588	48	30	60	226
14	Intermodal	7,729	548	31	54	104	348
15	Intermodal	17,576	523	31	69	270	361
16	Intermodal	28,675	631	31	65	338	426
17	Motorized vehicles	3,512	542	46	20	54	164
18	Intermodal	21,000	648	31	70	281	449
19	Intermodal	18,785	589	31	48	280	358
20	Intermodal	6,974	829	31	50	101	512
21	Intermodal	20,977	644	31	54	284	409
22	Intermodal	9,058	849	29	39	119	490
23	Ethanol	21,590	637	34	47	227	370

Appendix B. Detailed Results for Truck Movements

Exhibit B-1. List of Truck Movements

Movement	Origin	Destination	Route Distance (miles)	Road Grade Severity	Weight (tons)		
					Tare	Payload	Total
1	Fort Valley, GA	Jacksonville, FL	302	2.2	14	17	31
2	Columbus, GA	Savannah, GA	330	3.1	14	11	25
3	Detroit, MI	Fort Wayne, IN	197	1.7	14	24	37
4	Arcadia, OH	Jacksonville, FL	1,039	2.7	12	25	37
5	Atlanta, GA	Huntsville, AL	239	3.5	14	24	37
6	Chicago, IL	Atlanta, GA	704	2.6	14	15	29
7	Chicago, IL	Atlanta, GA	704	2.6	14	24	37
8	Decatur, IL	Frank, OH	439	1.7	14	9	23
9	Decatur, IL	Frank, OH	439	1.7	14	17	31
10	Detroit, MI	Decatur, IL	326	2.0	15	15	30
11	Dayton, OH	St Louis, MO	350	2.4	15	15	30
12	Toledo, OH	Memphis, TN	595	2.9	14	24	37
13	Memphis, TN	Atlanta, GA	447	3.2	14	15	29
14	Chicago, IL	Fargo, ND	636	2.4	14	17	31
15	Oakland, CA	Clovis, NM	1,303	2.6	14	17	31
16	Chicago, IL	Los Angeles, CA	1,983	2.9	14	17	31
17	Kansas City, MO	Chicago, IL	518	2.7	15	15	30
18	Houston, TX	Los Angeles, CA	1,531	2.4	14	17	31
19	Memphis, TN	Los Angeles, CA	1,771	2.9	14	17	31
20	Clovis, NM	Memphis, TN	780	2.5	14	17	31
21	Seattle, WA	Chicago, IL	2,046	2.9	14	17	31
22	Clovis, NM	Atlanta, GA	1,226	2.7	14	17	31
23	Kansas City, MO	Los Angeles, CA	1,591	2.9	12	11	23

Exhibit B-1. List of Truck Movements (cont)

Movement	Trailer Type*	Commodity	Total Fuel Consumed (gallons)	Truck Fuel Economy (mpg)	Fuel Efficiency (ton-miles per gallon)
1	DV	Newsprint/paper	48	6.3	104
2	C	Intermodal	53	6.2	70
3	D	Waste/scrap	36	5.4	129
4	T	General merchandise	201	5.2	132
5	D	Waste/scrap	58	4.1	98
6	DV	Intermodal	123	5.7	85
7	FS	Other foodstuffs	127	5.6	133
8	C	Intermodal	58	7.6	68
9	DV	Other foodstuffs	66	6.6	110
10	A	Motorized vehicles	61	5.4	81
11	A	Motorized vehicles	68	5.1	77
12	FS	Base metals	126	4.7	112
13	DV	Intermodal	81	5.5	82
14	C	Intermodal	108	5.9	100
15	DV	Intermodal	231	5.6	93
16	DV	Intermodal	372	5.3	88
17	A	Motorized vehicles	105	4.9	74
18	DV	Intermodal	260	5.9	98
19	DV	Intermodal	326	5.4	90
20	DV	Intermodal	128	6.1	101
21	DV	Intermodal	377	5.4	90
22	DV	Intermodal	216	5.7	94
23	T	Ethanol	256	6.2	70

* DV = 53’ Dry Van; A = Auto Hauler; C = 40’ Container; D = Dump Truck; FS = Flat Bed with Sides; T = Tanker Truck.

Appendix C. Grade Severity

A numeric rating system is used to describe the level of grade severity for rail and truck routes. The rating numbers range from 1 (low) to 5 (high), and do not represent the actual grade. Instead, they are intended to provide a qualitative scale to describe route severity.

To develop the rate numbers for each route, the entire length is divided in sections of similar grade. Each section is given a rating based on the scale included in Exhibit C-1. This value is then multiplied by the share of miles this section represents out of the entire route. The grade severities included in Appendices A and B are the weighted grade severity rates.

Exhibit C-1. Grade Severity Rating

Rating	Grade (%)
1.0	0.0000%
1.5	0.1875%
2.0	0.3750%
2.5	0.5625%
3.0	0.7500%
3.5	0.9375%
4.0	1.1250%
4.5	1.3125%
5.0	1.5000%

Appendix D. Fuel Consumption from Non-Line-haul Movements

Because the simulation of rail movements does not account for short branchline movements or yard switching operations from general mixed freight rail movements, their associated fuel consumption needs to be calculated separately. The same applies to truck drayage and intermodal terminal operations for intermodal rail movements. All truck movements are associated with some level of truck idling during loading/unloading operations, breaks, and overnight stays. This appendix includes the methodology and assumptions used to calculate fuel consumption associated with these activities.

D.1. Short Branchline Movements and Yard Switching Operations

This section includes two methods to estimate fuel consumption associated with short branchline movements and yard switching operations from general mixed freight rail movements. The first method is a top-down approach, relying on aggregate data on fuel consumption and number of carloads from AAR data.[1] The second method relies on a bottom-up approach, modeling an average mixed freight rail movement.

D.1.1. Top-Down Method

Aggregate data from the 2006 edition of AAR's Analysis of Class I Railroads provide both the number of carloads and the amount of fuel used in yard switching operations. The number of general mixed freight carloads can be roughly estimated by subtracting coal, 60% of grain, and "all other" (mainly intermodal) from the total. Fuel consumed in the category "yard switching operations" includes both short branchline movements and yard switching operations per se.

Exhibit D-1. Fuel Consumption from Branchline and Switching (Top-Down Method)

Region	General Mixed Freight Carloads	Fuel Consumed (million gallons)	Gallons / Rail Car
East Region (CSX, NS and CN)	6,296,000	108.17	17.2
West Region (BNSF, UP, KCS, and CP)	5,616,000	206.90	36.8
Total	11,912,000	315.08	26.5

The primary reason for the difference between the East and West regions is that length of haul is much greater in the West. An estimate of length of haul (for all traffic, not just general mixed

[1] Association of American Railroads (2006): Analysis of Class I Railroads.

freight) can be obtained by dividing revenue ton-miles by tons shipped. This calculation is as follows:

- East Region: 512,000 million RTM/852 million tons shipped = 601 miles
- West Region: 1,260,000 million RTM/1,104 million tons shipped = 1,141 miles

Obviously these are very approximate calculations, as many carloads are interchanged between the Eastern and Western region railroads. However, it does indicate a logical relationship between length of haul and fuel consumed in yard switching operations.

D.1.2. Bottom-Up Method

A bottom up method assumes specific activities associated with the handling of general mixed freight carloads.

Short Branchline Movements

Even though the distance that freight moves varies by product and by terminal, this study would assume a fixed distance at each end of the trip, and the following assumptions:

- **Locomotive:** GP38 with a total gross weight of 137 tons.
- **Train:** the train would consist of 20 loads (1,800 tons) and 10 empties (300 tons) for a total trailing weight of 2,100 tons.
- **Distance:** The distance traveled (one-way) is 30 miles in the East region, and 75 miles in the West region at 0 percent grade. A return (empty) trip of equal distance is also assumed.
- **Speed:** The maximum speed traveled is 30 miles per hour.
- **Number of stops:** The train makes three 20-minute stops for switching.
- **Trip time:** In the East region, 90 minutes are assumed to move 30 miles, and 60 minutes are assumed for 3 stops, with a total trip time of 2.5 hours. In the West region, 225 minutes are assumed to move 75 miles, and 60 minutes are assumed for 3 stops, with a total trip time of 4.75 hours.
- **Throttle positions:** The average throttle position for moving and switching are #5 and #3, respectively.
- **Total fuel consumption:**

East: 90 minutes moving (Average throttle #5):	95.7 gallons
West: 225 minutes moving (Average throttle #5):	239.3 gallons
60 minutes switching (Average throttle #3):	15.7 gallons

  Total: 111.4 gallons (East); 255 gallons (West)

- **Fuel consumption per car (loaded)**:

90 tons / 2,100 tons = 4.29%

East: 111.4 gallons x 4.29% x 2 trips = 9.55 gallons

West: 255 gallons x 4.29% x 2 trips = 21.88 gallons

- **Fuel consumption per car (empty):**

  30 tons / 2,100 tons = 1.43%

  East: 111.4 gallons x 1.43% x 2 trips = 3.19 gallons

  West: 255 gallons x 1.43% x 2 trips = 7.29 gallons

- **Total fuel consumption per car:**

  East: 9.55 + 3.19 = **12.74 gallons**

  West: 21.88 + 7.29 = **29.17 gallons**

Yard Switching Movements

Yard switching operations include switch movements to classify cars in a general mixed freight train. Although the number of switch movements to make up a given block can vary widely, estimates were assumed for simplification purposes. The basic approach was taken from the 1991 report, adjusting for areas that needed to be modified.

It is assumed that a GP-9 or an SD-9 locomotive is used to switch the train into four blocks. The amount of fuel consumed is estimated for an 80-car train. The assumptions for this analysis are:

- **80-car train:** requires 30 switching moves averaging 4 minutes per move, totaling 120 minutes at average throttle #3.5 (30.2 gph) – 60.4 gallons/yard-train
- **Frequency of yards:** it is assumed that there is one switching yard at every 400 miles in the East region, and one every 700 miles in the West region.
- **Total fuel consumption per car:**

  East Region, assuming an average distance of 601 miles: (601 x 60.4) / (400 x 80) = 1.13 gallons x 2 (to account for empty movement) = **2.27 gallons**

  West Region, assuming an average distance of 1,141 miles: (1,141 x 60.4) / (700 x 80) = 1.23 gallons x 2 (to account for empty movement) = **2.46 gallons**

D.1.3. Comparison of Methodologies

The two methods result in comparable results, with the top-down approach providing results that are about 15% higher than the bottom-up approach (Exhibit D-2). The difference might rely on the fact that the bottom-up approach does not account for fuel consumption associated with locomotive idling, so this analysis assumed the results from the first method for conservative purposes.

Exhibit D-2. Fuel Consumption from Branchline and Switching (Comparison of Methods)

Region	Top-Down Method	Bottom-Up Method	Variation
East Region (CSX, NS and CN	17.2 gallons/car	15.0 gallons/car	15%
West Region (BNSF, UP, KCS, and CP)	36.8 gallons/car	31.6 gallons/car	16%
Total	17.2 gallons/car	15.0 gallons/car	15%

D.2. Truck Drayage and Intermodal Terminal Operations

Intermodal shipments require truck drayage and handling at intermodal terminals, and this analysis includes the fuel consumed by drayage trucks and yard trucks. The assumptions included in this section are:

- **Truck drayage movements:** A one-way distance of 30 miles at each end of the trip is assumed for trips in the East Region, and 75 miles are assumed for trips in the West Region. An average fuel economy of 5.5 miles per gallon is assumed for drayage trucks. Therefore, drayage trucks consume:

  East Region: 30 miles x 2 trips / 5.5 miles/gallon = 10.9 gallons

  West Region: 75 miles x 2 trips / 5.5 miles/gallon = 27.3 gallons

- **Intermodal terminal operations:** A container or trailer is assumed to be moved by 0.1 mile within the rail yard, and yard trucks are assumed to operate continuously with an average fuel economy of 4 gallons per mile. Therefore, yard trucks consume:

  0.1 mile / 4 miles per gallon = 0.025 gallons (independently of the region)

D.3. Truck Idling

The following assumptions are made for the calculation of fuel consumed in truck idling, and Exhibit D-3 summarizes the assumed cycle for a long-distance route.

- **Breaks and overnight stays:** consistent with the hours of service regulations, it is assumed that a driver takes a 10-hour prolonged break after 14 hours of duty-time (i.e., driving, loading, unloading, short breaks) or 11 hours of driving time. The analysis also assumes a one-hour break for every four hours of driving time.
- **Loading and unloading operations:** a one-hour loading/unloading time is also assumed at each end of the trip.
- **Fuel rate during truck idling:** it is assumed that fuel is consumed at a rate of 0.5 gallons per hour during truck idling activities. The use of an auxiliary power unit or electrified stops is not assumed given the lower penetration of such strategies.

Appendix E. Development of Truck Route Elevation Profiles

The ICF Geospatial Solutions helped to determine the elevation (derived from 30 meter resolution USGS Digital Elevation Models[2]) of every 500 meters along trucking routes. The ICF Geospatial Solutions produced a tool to perform this analysis so that as different routes are identified it may be repeatable. This tool produced a file of the Cartesian coordinates and elevation of each observation along the route.

The tool created a route from the designated Start City to the Finish City. A point was placed every 500 meters along the route. These points were then intersected with the USGS quad index to identify which DEMs should be loaded.[3] With a route of 50km or less there could be up to four DEMs within the specified distance. The points were compared to the DEMS and the elevation at the specified point was associated. For each point the closest town was identified from ESRI's 2008 Cities geodatabase. The road name was also identified by intersecting the point with the route and extracting the name of the road. This was written out to a text file that included:

- Route Name
- Distance from Start Point (i.e. 500m, 1000m, 1500m etc.)
- Elevation
- Road Name
- Closest Town
- Length (this is needed because the final portion will not always be evenly divisible by 500m)

2 A digital elevation model (DEM) is a digital file consisting of terrain elevations for ground positions at regularly spaced horizontal intervals.

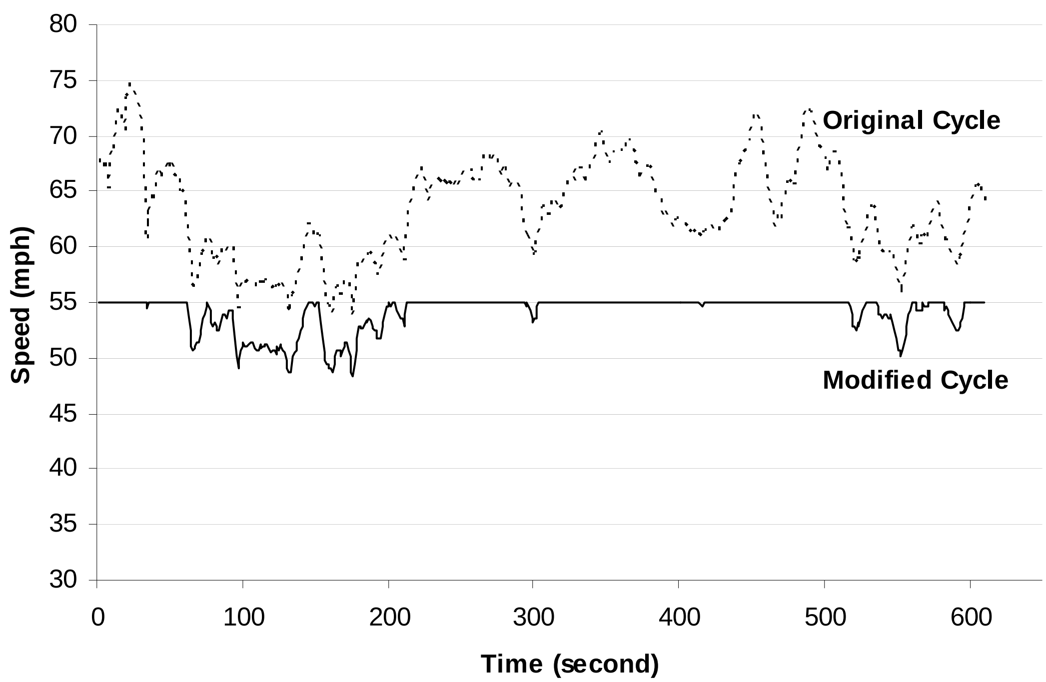
3 Due to the sheer size of the DEM data, it is not possible to load all available DEMS at once; rather only those that are needed for that particular run of the analysis will be loaded.

Appendix F. Development of Truck Driving Cycles

A driving cycle is a series of data points representing the speed of a vehicle versus time, usually on a second-by-second basis. Fuel rate is highly dependent on the acceleration and deceleration patterns, so it is important to consider a realistic driving cycle.

Because the development of project-specific driving cycles is time and resource-intensive, it is possible to use standard driving cycles. A U.S. EPA research project developed a set of driving cycles under a variety of congestion levels for different road types.[4] A variation of the freeway high-speed cycle was considered in this study. As illustrated in Exhibit D-1, the original cycle was scaled down by 10% to reflect the fact that heavy-duty trucks travel at a lower speed than passenger automobiles, for which these cycles were originally developed. Additionally, the top speed was set at 55 mph to comply with most interstate top speed limits for heavy-duty trucks.

Exhibit F-1. Baseline Truck Driving Cycle



Because the driving cycle both started and ended at 55 mph, it was possible to combine multiple cycles to form longer cycles. The baseline driving cycles was also adjusted for each route individually depending on the road grade, since heavy-duty trucks have to slow down

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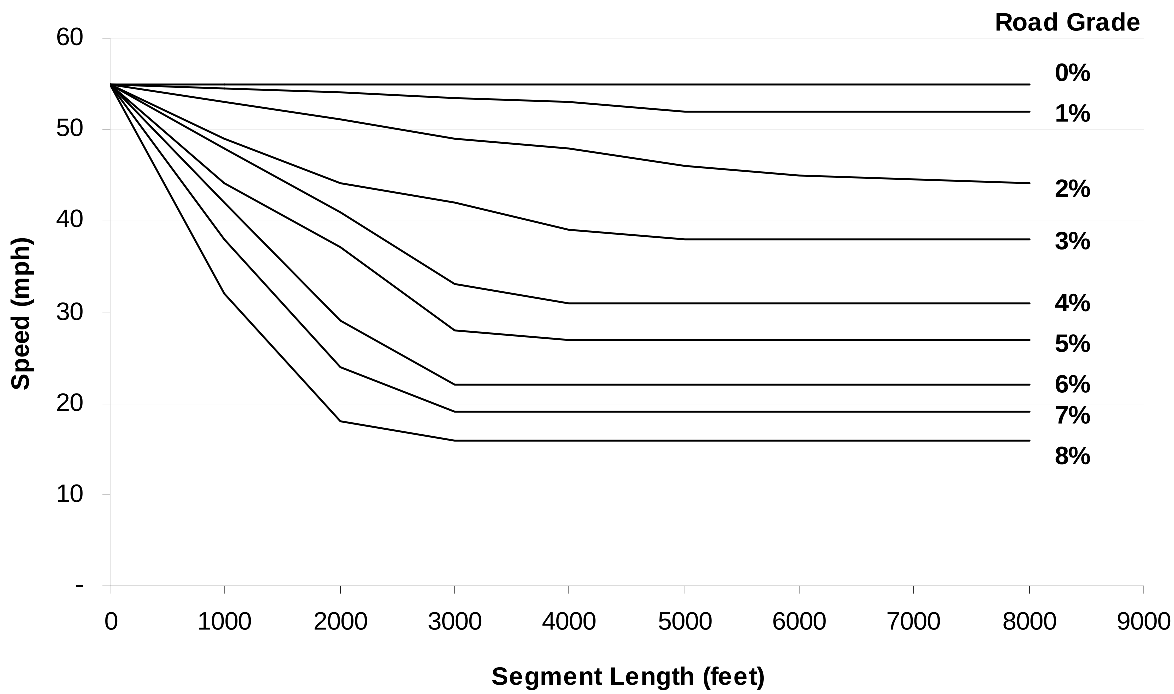
[4] Sierra Research (1997): Development of Speed Correction Cycles. Prepared for the U.S. Environmental Protection Agency. Document Number M6.SPD.001.

substantially as road grade increases. Such correction was based on truck performance curves from the Highway Capacity Manual (Exhibit F-2).[5]

Exhibit F-2. Truck Performance Curve

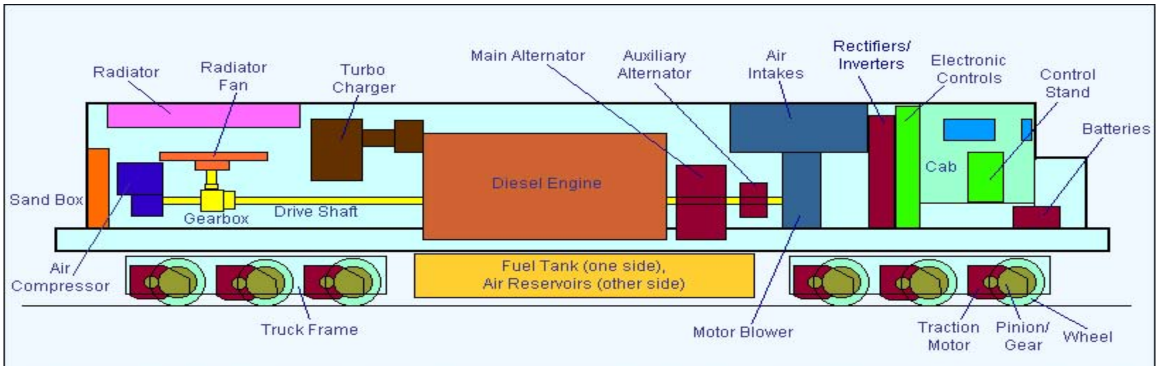


[5] Transportation Research Board (2000): Highway Capacity Manual. Exhibit A23-2.

Appendix G. Description of a Typical Diesel-Electric Locomotive

This brief description of a typical North American diesel electric locomotive is provided for readers unfamiliar with locomotives and to support understanding of the impact of new technologies. Exhibit G-1 is a diagram of a typical 1980's locomotive.

Exhibit G-1. Diagram of Typical North American Freight Locomotive[6]



Block diagram of typical US diesel-electric locomotive showing the location of the main parts. There are many variations between different designs and some in other countries use different layouts and techniques, e.g. electrically driven air compressors instead of directly driven.

Click on the part name for a description.

Construction of a locomotive starts with the underframe, often called the platform. The platform is not labeled in the diagram but is the horizontal structure directly under the diesel engine. The platform comprises a horizontal steel plate 1.5-2 inches thick covering the full length and width of the locomotive, stiffened on the underside by longitudinal H-beams welded to the plate. The components located under the platform are:

- Two three-axle trucks. All new main line freight locomotives since the early 1990s have been six-axle. Railroads also own large numbers of older four-axle, four-motor locomotives used for switching and branch line service. Only passenger operators have purchased completely new four-axle locomotives in recent years.
- Six traction motors mounted on the truck parallel to each axle, driving the axle through a pair of gears. Cooling air is fed through the motors from sources above the platform to keep motor interiors clean.
- Fuel tanks and air reservoirs are located between the trucks.
- Coupler gear (not shown on the diagram) is mounted at each end and just below the platform.

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[6] Railway Technical Web Pages (2007): Available online at http://www.railway-technical.com

The components mounted above the platform from the cab end (on the right in the diagram) are:

- The operators cab with control stand or console, required instruments, and access to the electronic control modules in the cabinets behind the cab.
- Cabinets for engine control modules for all locomotive functions, including locomotive health monitoring systems.
- Solid-state electrical power controls, including the main rectifier to convert AC power from the main alternator to DC power before being fed to the main traction controls.
- Engine air intakes and filters.
- Main and auxiliary alternators, attached directly to the diesel engine crankshaft.
- The main diesel engine, usually a four-stroke (GE) or a two-stroke (EMD) 12- or 16-cylinder engine.
- The engine turbocharger. All high-power line haul locomotives are turbocharged, but lower-power locomotives used for switching and branch line service are often not turbocharged since they do not need the additional power and benefit from the consequent lower maintenance costs.
- Engine cooling fans and radiators. While the diagram indicated a direct coupling of auxiliaries to the engine crankshaft, many locomotives use separate electric motors to drive fans and the air compressor.
- Main air compressor for train air brakes.

In summary, the main power train of the locomotive is as follows.

The main diesel engine is coupled to an alternator to produce alternating current (AC) electric power, which is then converted into direct current (DC) power by a solid state rectifier. Prior to the availability of reliable high power rectifiers (early to mid 1960s), diesel locomotives used DC generators. Some locomotives of this type are still operating. From the output of the rectifier, DC power is supplied to traction motor controls and thence to the AC or DC electric traction motors mounted on the trucks.

There are two main elements to the control system. The first element comprises the "supervisory" modules that control the diesel engine itself and matches diesel engine output to the power demanded by the operator. The second element comprises the power switching and regulating devices that convert DC input from the rectifier into the desired traction motor input. For a DC motor, power is usually controlled by rapid on/off switching using solid-state power electronics, with power output determined by the relative length of on/off periods. With an AC traction motor, solid state power electronics devices produce variable voltage and variable frequency output to each AC motor. Most of the key developments in the diesel locomotive from 1990-2006 have been in the supervisory and power controls. Evolutionary development of the diesel engine itself has continued too, generally in line with developments in the wider diesel engine industry.

Appendix H. Calculation of Truck Payload

Two steps are taken to calculate truck payload:

- **Step 1 – Determine commodity density**: for each rail movement, the average commodity density is determined by dividing the rail car payload by the rail car volume.

$$\text{Commodity Average Density} = \frac{\text{Payload (tons)}}{\text{Rail car Volume (cu.ft.)}}$$

- **Step 2 – Determine truck payload:** truck payload is initially determined by multiplying commodity density and truck volume. If the resulting payload is higher than 37 tons (truck weighs out), then payload is assumed to be 65% of the truck weight limit minus the truck tare weight (in the case of dry vans and containers), and 90% of the truck weight limit minus the truck tare weight (for other types of trailers). If the resulting payload is lower than 37 tons (cubes out), then payload is assumed to be the product between commodity density and truck volume.

Appendix I. Preliminary List of Competitive Movements

This appendix describes the steps taken in the development of the preliminary list of competitive movements. It starts with a description of the three data sources utilized in the selection of movements, followed by the actual selection of movements. The preliminary list of movements includes O-D pairs at the state level, and commodities at the 2 or 3-digit level.[7] After receiving feedback from key industry stakeholders, a more detailed analysis followed to develop a final list of movements, which considers O-D pairs at the metropolitan region level.

I.1. Data Sources

Three data sources were utilized in the identification of competitive movements. The **Commodity Flow Survey** (CFS) and the **Freight Analysis Framework** (FAF2) are based on similar datasets, but the latter provides some methodological updates, which have also been much criticized by the freight community. Both data sources pull rail data from the **Rail Waybill Sample**, which was used in this analysis to provide details on rail flows that were not available on the other two data sources.

Commodity Flow Survey (CFS)

The Commodity Flow Survey, sponsored by the U.S. Census Bureau, was designed to provide data on the flow of goods in the U.S., including origin, destination, 5-digit Standard Classification of Transported Goods (SCTG) code, weight, value, freight activity (measured in ton-miles), and mode of transportation. This survey is performed every 5 years. Data from the 2002 survey is currently available; data from the 2007 survey (processing currently underway) will not be available in time for this study.

There are two reasons for considering CFS data as the first step in this task. First, between the two databases containing information about multimodal freight flows in the U.S. (CFS and FAF2), the CFS tends to be better regarded by the freight community because it provides a better representation of actual flows, versus FAF2 that relies heavily on modeling. Second, CFS has readily available data on freight activity measured in ton-miles. In contrast, FAF2 only provides data in tonnage, and ton-mileage needs to be calculated based on estimates of the average distance between geographic zones.

However, the CFS has two major shortcomings. First, it is believed the CFS under-reports freight movements. Earlier research suggests that previous CFS surveys underestimated total U.S. freight by a significant amount. A study by ORNL concluded that the 1997 CFS captured only 75 percent of total U.S. freight shipments measured in tons, 74 percent when measured in ton-miles, and 81 percent when measured in value.[8] Most of the sectors that are not included in

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[7] In the CFS and FAF2 databases, we used 2-digit SCTG commodity groups. In the Rail Waybill Sample, we used either the 2-digit or the 3-digit STCC commodity group, depending on the commodity.

[8] Oak Ridge National Laboratory (2000): Freight USA. Highlights from the 1997 Commodity Flow Survey and Other Sources. Report prepared for the Bureau of Transportation Statistics U.S. Department of Transportation, Washington, D.C 20590.

the CFS (e.g., crude petroleum, fisheries, retail, construction, services, publishing, and government) do not rely heavily on rail transport, so the CFS should still capture most of the sectors of interest for this analysis.

The second shortcoming is that the publicly available tables from the CFS are not detailed enough for the purposes of this study. For example, the most detailed table is limited to origin state, destination state, commodity, and transportation mode.[9]

Because of these two shortcomings, the CFS can provide a good first estimate of competitive movements, but further details about geographic zones are necessary (the CFS table including both origin, destination, commodity, and mode contained geographic information only at the state level). Additionally, the results from CFS need to be validated against FAF2 to account for the list of commodities not included in CFS.

Freight Analysis Framework (FAF2)

The Freight Analysis Framework (FAF) is a commodity flow database developed by the Federal Highway Administration in cooperation with the Bureau of Transportation Statistics.[10] FHWA developed a new and improved version, FAF2, in 2002. It includes international and domestic shipments with information on origin, destination, port of entry or exit (for international shipments), commodity, transportation mode, value, and weight.

FAF2 is based on the CFS, but it relies on modeling to fill some gaps in the CFS. The two major gaps were the level of detail in the origin and destination zones, and the lack of many commodity categories in the CFS. As previously mentioned, the most detailed table in CFS consisted of origin and destination at the state level. Information at the metropolitan region level was only available in tables that contained either totals by origin or by destination. FAF2 utilized economic metrics to disaggregate origin and destinations at the state level to the metropolitan region level. Additionally, FAF2 utilized other data sources to estimate the flows for commodities that were not included in the CFS. However, FAF2 is often criticized by the freight community exactly because of the methodology used to fill in these gaps.

Rail Waybill Sample

The Rail Waybill File contains data from a stratified sample of freight railroad movements as reported to the STB. The data include origin and destination (rail station and BEA codes), commodity based on the Standard Transportation Commodity Code (STCC), number and type of cars and intermodal units, tons, short-line miles (length of haul)[11], participating railroads, and interchange location information, among other items. The records included in the file represent actual sampled movements and therefore accurately reflect freight rail movement patterns.

Of the three datasets used in this analysis the Waybill file is the most complete and accurate. However, it contains only rail movement data and thus is not useful (on its own) as a means to identify truck-competitive rail moves. Additionally, the Waybill file identifies commodities using a

9 Michael Sprung from FHWA, responsible for managing FAF2, indicated that it is not possible to obtain more than the publicly available CFS data from the U.S. Census Bureau.

10 Federal Highway Administration (2007): Freight Analysis Framework 2. Available online at http://ops.fhwa.dot.gov/freight/freight_analysis/faf/index.htm

11 "Short Line miles" comprise the shortest rail route over which carload traffic can be moved without transfer of lading. For a complete explanation, see STB Docket No. 28300.

code system specific to the railroads, which further complicates the process of identifying truck-competitive movements.

The Confidential Waybill Sample was used to assist in the characterization of rail movements, including the participating railroads and exact equipment configuration.

Comparison of Data Sources

Exhibit I-1 includes a comparison of the three data sources utilized in the identification of competitive movements. The Confidential Waybill sample contains actual rail movement data as reported by the railroads, and as such, it is the most detailed and reliable rail movement data source available. However, it does not include trucking data. It is also the only data source that contains equipment information, which is key in the configuration of rail movements. The CFS, which includes both rail and trucking movements, is considered the most reliable data source for trucking, but it does not provide the same level of detail found in the rail Waybill sample. For example, it only provides origin-destination data at the state level (the Waybill provides O-D data at the BEA level), and commodity data at the two-digit level (the Waybill provides commodity data at the seven-digit level). The most substantial drawback of the CFS is that it under-estimates freight carriage and may be missing important flows. The FAF2 database is based on the CFS, but it relies on modeling to disaggregate commodity flows at the state level to individual counties. It also uses data sources other than the CFS to account for the commodities not included in the CFS. FAF2 contains information at a more detailed level than the CFS (metropolitan region as opposed to state), but it is generally regarded as less reliable by the freight community. The use of these three data sources provides cross-validation amongst them and it helps reduce the associated uncertainty.

Exhibit I-1. Comparison of Data Sources

Data Element	Waybill Sample	CFS	FAF2 (Public Version)
Available Modes	Rail only	Rail and Trucking	Rail and Trucking
Equipment Information	Yes	No	No
Geographic Level of Detail	BEA	State	Metropolitan Region
All Commodities Included?	Yes	No	Yes
Commodity Level of Detail	7-digit STCC	2-digit NAICS	2-digit SCTG
Sampled or Modeled?	Sampled	Sampled	Sampled/Modeled
Metrics	Tons, Revenue, Ton-mile	Tons, Value, Ton-mile	Tons, Value

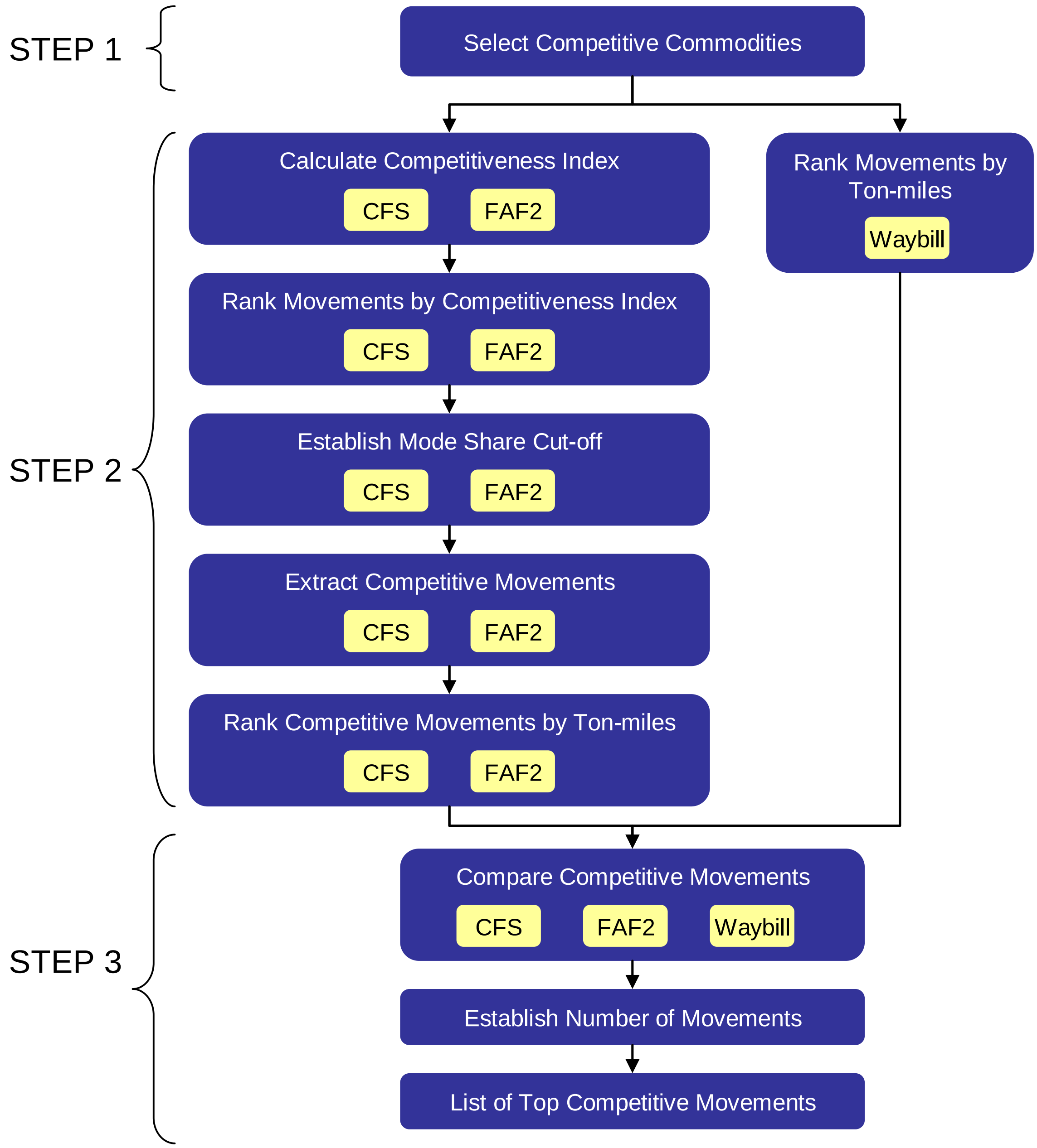
I.2. Preliminary List of Competitive Movements

This section includes the methodology to develop the preliminary list of the top competitive movements with O-D pairs at the state level, and commodities at the 2-3-digit commodity level. Because no single data source provided the appropriate levels of detail and reliability for both rail and trucking movements, the preliminary list was created from data in the Commodity Flow Survey (CFS), the Freight Analysis Framework (FAF2), and the rail Waybill sample.

In terms of geographical zones, the Waybill sample provides rail data at the BEA level, while the CFS and FAF2 provide data at the state and county levels. The preliminary list considers geographical zones at the state level for two reasons. First, it is the lowest denominator amongst the three data sources. Second, and most importantly, it reduces the number of candidate movements for consideration.

Exhibit I-2 illustrates the steps taken in the development of the preliminary list of competitive movements. The analysis started with the identification of the commodities where truck and rail compete (Step 1). Because of the high number of individual movements, a cut-off was established to narrow the number of commodities. Based on this set of competitive commodities, the CFS, FAF2, and Waybill datasets were evaluated (Step 2), and finally the three datasets were compared to determine the preliminary list of competitive commodities (Step 3).

Exhibit I-2. Development of Preliminary List of Competitive Movements



Step 1 - Identification of Competitive Commodities

This first step evaluated mode share (by tonnage) for all commodities included in the CFS and FAF2. The commodities were ordered by their competitiveness index, which is a measure that depends on the rail/truck modal split for any given commodity. The competitiveness index, whose calculation is illustrated in Exhibit I-3, varies from 0 to 1. The closer the rail/truck modal split is to 50%, the closer the competitiveness index is to 1.

Exhibit I-3. Competitiveness Index

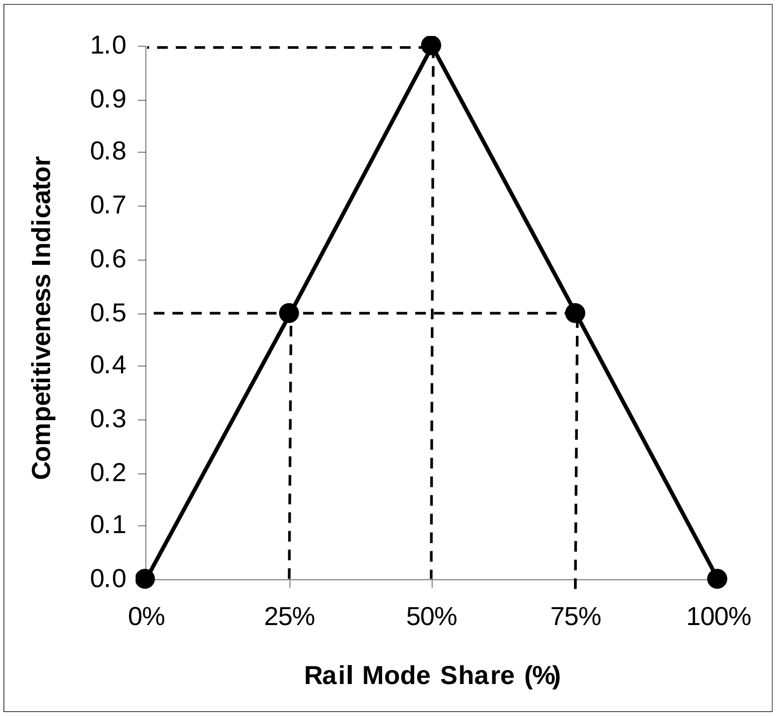


Exhibit I-4 presents mode share and competitiveness index for all commodities considered in the identification of top competitive movements. The two data sources – CFS and FAF2 - provided consistent mode shares, with differences of less than 15 percent for all commodity groups. Coal and metallic ores, which have high competitiveness indexes (0.4140 and 0.5402 respectively), were excluded from Exhibit H-4 because they tend to be transported by truck only where there is no rail access or for very short moves.

The cutoff that defined the commodities that were included in this evaluation is arbitrary in nature. The preliminary analysis accounted for all commodities with a competitiveness index equal or greater than 0.10 in the CFS or FAF2, which is the equivalent of the rail mode share being higher than 5 percent. Due to the aggregate nature of this data, a low cutoff was chosen to ensure that most relevant competitive movements be identified.

Exhibit I-4 contains all commodities included in the list of competitive commodities in the 1991 report. The intermodal traffic categories, with STCC codes 41-47 in the Waybill Sample, do not have a direct counterpart in the CFS or the FAF2, because they are not associated with a specific commodity but with general categories of shipments (e.g., miscellaneous shipments, freight forwarder, shipper associations). It is assumed that all such commodities (STCC 41-47) are rail-truck competitive, and they are included in a separate list of movements.

Exhibit I-4. Mode Share (tonnage) and Competitiveness Index (CI) by Commodity

Commodity	CFS			FAF2			Average CI
	Rail Share	Truck Share	CI	Rail Share	Truck Share	CI	
Fertilizers	39%	61%	0.7762	32%	68%	0.6454	0.7108
Basic chemicals	35%	65%	0.7028	34%	66%	0.6737	0.6883
Cereal grains	45%	55%	0.9011	14%	86%	0.2750	0.5881
Newsprint/paper	29%	71%	0.5789	25%	75%	0.5081	0.5435
Plastics/rubber	23%	77%	0.4600	22%	78%	0.4464	0.4532
Coal-n.e.c.	24%	76%	0.4717	20%	80%	0.3944	0.4331
Waste/scrap	34%	66%	0.6815	8%	92%	0.1567	0.4191
Metallic ores	81%	19%	0.3729	77%	23%	0.4524	0.4126
Nonmetallic minerals	20%	80%	0.3973	16%	84%	0.3250	0.3611
Base metals	15%	85%	0.2947	14%	86%	0.2744	0.2845
Wood prods.	15%	85%	0.2996	13%	87%	0.2513	0.2754
Motorized vehicles	14%	86%	0.2762	12%	88%	0.2399	0.2581
Milled grain prods.	13%	87%	0.2563	12%	88%	0.2301	0.2432
Other ag prods.	16%	84%	0.3250	7%	93%	0.1424	0.2337
Other foodstuffs	11%	89%	0.2159	9%	91%	0.1878	0.2018
Animal feed	11%	89%	0.2144	9%	91%	0.1873	0.2009
Alcoholic beverages	8%	92%	0.1632	7%	93%	0.1338	0.1485
Chemical prods.	8%	92%	0.1545	6%	94%	0.1172	0.1358

Step 2 - Evaluation of Competitive Movements in the Three Datasets

As previously indicated, a movement is here defined as a combination of an O-D pair (at the state level) and a commodity group (at the 2 or 3-digit level).[12] Based on the competitive commodities identified in Step 1, all movements were ranked in the CFS, FAF2, and the Waybill.

First the competitiveness index was adjusted to take into account the fact that the Waybill Sample sometimes considers a single movement that goes through an interchange point as two movements. For example, a movement from California to New York through Chicago might show as two independent movements (one from California to Chicago, and another from Chicago to New York) in the Waybill, and consequently in the CFS and the FAF2. Because the Waybill is a sample, there is also the possibility that only one of the two independent moves be included. It is important to take this factor into consideration because a truck movement from California to Chicago is not equivalent to (part of) a rail movement from California to New York.

12 In the CFS and FAF2 databases, we used 2-digit SCTG commodity groups. In the Rail Waybill Sample, we used either the 2-digit or the 3-digit STCC commodity group, depending on the commodity.

Therefore, the interchange index was created to adjust the rail volume at each O-D pair. The adjustment is done by excluding the share of cargo that either originates or terminates at locations other than those described in the O-D pair.

The competitiveness index was used to prioritize movements in the CFS and FAF2. A mode share cut-off, which is arbitrary but necessary to reduce the pool of competitive movements, was applied. All movements in the CFS and FAF2 that had a rail mode share of less than 30% (equivalent to a CI of 0.6) were eliminated. All remaining movements were then ranked by total ton-miles. The purpose of this last step is to weight the competitive index with a measure of freight activity, since the underlying objective is to identify those competitive movements with the highest impact on fuel consumption. Because the Waybill only includes rail volumes, all movements in the Waybill were ranked by ton-miles. Since the final list of movements should include a range of short, medium, and long-distance routes, the analysis was performed separately for each route length category: 0-50, 50-100, 100-200, 200-500, 500-1000, 1000-2000, and over 2000 miles.

All movements identified in the CFS or in the FAF2 were rated on a scale from 0 to 100, depending on their ranking. For example, the highest ranked movement in the CFS was rated 100, while the lowest ranked movement in the CFS was rated 0. The same procedure was repeated for the FAF2 movements. Because the CFS and FAF2 were used to identify competitive movements, only the Waybill movements that were included in either the CFS or the FAF2 were considered in this preliminary analysis. It is possible that competitive movements were not included in either CFS or the FAF2, and we solicited feedback from stakeholders to ensure that no significant competitive traffic groups were excluded from the final list of movements. The Waybill movements that were considered in the analysis were also rated on a scale from 0 to 100, based on ton-miles. For example, the movement with the highest volume shipped (in ton-miles) was rated 100, and the lowest-ranked movement was rated 0.

Intermodal movements, which were all assumed to be competitive, were considered separately because they are not accounted for explicitly in the CFS or FAF2. Therefore, the list of competitive intermodal movements was based solely on the rail Waybill sample. Ton-miles were adjusted based on the interchange index, which considers the fact that a movement in the Waybill might be part of a longer movement. Therefore, the analysis excluded the share of cargo that either originates or terminates at locations other than those described in the O-D pair. All intermodal movements were ranked by ton-miles, and rated on a 0-100 scale.

Step 3 - Comparison of Three Datasets

For non-intermodal movements, the average of the three rankings (CFS, FAF2, and Waybill) was used to order movements. Intermodal movements, which were selected solely from the Waybill sample, were ordered by ton-miles. The top 50 intermodal movements, which account for over 80% of all freight activity in the Waybill Sample, were selected for the preliminary list of movements (Exhibit I-5). For consistency, the top 50 non-intermodal movements were also included in the preliminary list of movements (Exhibit I-6).

The top 100 movements were about twice as high as the number of scenarios that could realistically be evaluated based on the constraints of this project. This ensured that a sufficient number of scenarios were taken into consideration.

Exhibit I-5. Top 50 Competitive Movements (Non-intermodal)

Distance Block	Origin	Destination	Commodity (FAF2 Classification)	Ranking* FAF2	CFS	Waybill	Average
0-50	GA	FL	Newsprint/paper	X	100.00	96.72	98.36
	AR	MO	Wood prods.	100.00	X	83.61	91.80
	LA	MO	Newsprint/paper	X	66.67	90.16	78.42
	LA	AR	Newsprint/paper	X	83.33	69.67	76.50
	MS	IL	Newsprint/paper	X	50.00	85.25	67.62
50-100	MI	KY	Motorized vehicles	X	100.00	92.51	96.26
	OK	KS	Fertilizers	X	80.00	70.93	75.46
	AL	IN	Newsprint/paper	X	60.00	88.99	74.49
	KY	TN	Basic chemicals	100.00	X	19.38	59.69
	IA	MN	Other foodstuffs	X	40.00	58.59	49.30
100-200	NC	SC	Basic chemicals	X	90.48	91.63	91.05
	IN	IN	Waste/scrap	X	95.24	86.80	91.02
	FL	OH	Other foodstuffs	83.33	X	96.14	89.73
	MS	MS	Other foodstuffs	X	85.71	88.41	87.06
	LA	WI	Newsprint/paper	X	76.19	86.96	81.57
200-500	TX	TX	Coal-n.e.c.	X	100.00	98.50	99.25
	TX	TX	Cereal grains	100.00	X	98.30	99.15
	OR	CA	Wood prods.	X	97.62	100.00	98.81
	TX	TX	Basic chemicals	X	95.24	99.46	97.35
	WA	CA	Wood prods.	89.29	92.86	99.66	93.93
500-1000	IL	PA	Other foodstuffs	100.00	X	99.75	99.87
	LA	TX	Basic chemicals	97.56	100.00	99.05	98.87
	MI	MO	Motorized vehicles	95.12	98.21	99.45	97.59
	IL	VA	Other foodstuffs	90.24	X	98.95	94.59
	LA	TX	Newsprint/paper	87.80	96.43	98.54	94.26
	SC	IL	Newsprint/paper	92.68	X	92.97	92.83
	IL	PA	Milled grain prods.	85.37	X	99.75	92.56
	LA	GA	Newsprint/paper	X	87.50	95.88	91.69
	AR	TX	Base metals	X	85.71	97.64	91.68
	IN	IA	Base metals	X	94.64	87.34	90.99
1000-2000	CA	TX	Other foodstuffs	100.00	X	99.70	99.85
	IN	TX	Base metals	X	100.00	97.49	98.75
	PA	TX	Base metals	X	93.33	98.57	95.95
	OH	TX	Motorized vehicles	96.30	X	92.30	94.30
	AL	TX	Newsprint/paper	X	90.00	97.55	93.78
	ME	IL	Newsprint/paper	92.59	86.67	95.22	91.49
	CA	TX	Basic chemicals	85.19	X	97.25	91.22
	IL	MA	Other foodstuffs	81.48	X	96.78	89.13
	ME	WI	Newsprint/paper	X	80.00	96.12	88.06
	TX	CA	Newsprint/paper	X	76.67	98.09	87.38
2000+	IL	CA	Other foodstuffs	100.00	100.00	99.83	99.94
	IA	CA	Other foodstuffs	98.55	X	99.91	99.23
	CA	NY	Other foodstuffs	97.10	X	96.05	96.57
	OR	MN	Wood prods.	92.75	X	95.88	94.31
	CA	NJ	Other foodstuffs	94.20	90.00	98.37	94.19
	AL	CA	Base metals	85.51	X	98.54	92.02
	OH	CA	Other foodstuffs	95.65	X	80.67	88.16
	OH	CA	Motorized vehicles	79.71	X	95.02	87.36
	CA	IL	Other foodstuffs	X	75.00	99.66	87.33
	CA	MN	Other foodstuffs	82.61	X	91.49	87.05

Exhibit I-6. Top 50 Competitive Movements (Intermodal)

Distance Block	Origin	Destination	Commodity (FAF2 Classification)	Ranking* FAF2	CFS	Waybill	Average
0-50	GA	FL	Mixed freight	X	X	100.00	100.00
	FL	GA	Mixed freight	X	X	92.31	92.31
	IL	MS	Mixed freight	X	X	84.62	84.62
	NC	VA	Mixed freight	X	X	76.92	76.92
	VA	NC	Mixed freight	X	X	69.23	69.23
50-100	IN	AL	Mixed freight	X	X	100.00	100.00
	OH	GA	Mixed freight	X	X	94.44	94.44
	GA	OH	Mixed freight	X	X	88.89	88.89
	TN	AL	Mixed freight	X	X	83.33	83.33
	AL	TN	Mixed freight	X	X	77.78	77.78
100-200	FL	FL	Mixed freight	X	X	100.00	100.00
	OH	FL	Mixed freight	X	X	97.73	97.73
	GA	GA	Mixed freight	X	X	95.45	95.45
	VA	VA	Mixed freight	X	X	93.18	93.18
	FL	OH	Mixed freight	X	X	90.91	90.91
200-500	CA	OR	Mixed freight	X	X	100.00	100.00
	VA	OH	Mixed freight	X	X	99.15	99.15
	OH	VA	Mixed freight	X	X	98.31	98.31
	CA	WA	Mixed freight	X	X	97.46	97.46
	KY	VA	Mixed freight	X	X	96.61	96.61
500-1000	NJ	OH	Mixed freight	X	X	100.00	100.00
	NJ	FL	Mixed freight	X	X	99.44	99.44
	OH	NJ	Mixed freight	X	X	98.87	98.87
	UT	CA	Mixed freight	X	X	98.31	98.31
	IL	TX	Mixed freight	X	X	97.74	97.74
	CA	UT	Mixed freight	X	X	97.18	97.18
	TX	AZ	Mixed freight	X	X	96.61	96.61
	NJ	MI	Mixed freight	X	X	96.05	96.05
	MI	NJ	Mixed freight	X	X	95.48	95.48
	FL	NJ	Mixed freight	X	X	94.92	94.92
1000-2000	CA	TX	Mixed freight	X	X	100.00	100.00
	TX	CA	Mixed freight	X	X	99.38	99.38
	KS	CA	Mixed freight	X	X	98.76	98.76
	CA	KS	Mixed freight	X	X	98.14	98.14
	TX	GA	Mixed freight	X	X	97.52	97.52
	NS	IL	Mixed freight	X	X	96.89	96.89
	CA	CO	Mixed freight	X	X	96.27	96.27
	TX	NC	Mixed freight	X	X	95.65	95.65
	GA	TX	Mixed freight	X	X	95.03	95.03
	CO	CA	Mixed freight	X	X	94.41	94.41
2000+	IL	CA	Mixed freight	X	X	100.00	100.00
	CA	AR	Mixed freight	X	X	99.47	99.47
	AR	CA	Mixed freight	X	X	98.95	98.95
	TN	CA	Mixed freight	X	X	98.42	98.42
	CA	LA	Mixed freight	X	X	97.89	97.89
	CA	TN	Mixed freight	X	X	97.37	97.37
	LA	CA	Mixed freight	X	X	96.84	96.84
	CA	IL	Mixed freight	X	X	96.32	96.32
	IL	WA	Mixed freight	X	X	95.79	95.79
	WA	MN	Mixed freight	X	X	95.26	95.26

An “X” indicates that a movement was not considered in a given dataset.

Industry Feedback

The preliminary list of movements was circulated amongst the main stakeholders in this project, including the FRA, AAR, the two railroads that participated in the simulation of rail movements, and a few selected trucking firms. In the process of reviewing the preliminary list of movements, the main goals were to verify the soundness of the methodology, to examine whether it captured the most relevant[13] movements, and to confirm that the involved railroads had the capability to model such movements.

Most feedback received indicated that the most relevant movements were indeed included in the preliminary list of movements. A few movements had to be eliminated because they were not part of the participating railroads' simulation network.

[13] By relevant, we mean movements that have comparable rail and trucking mode shares (Criteria 1), and movements that are representative in terms of freight activity, measured in ton-miles (Criteria 2).

Appendix J. Equipment Configuration

Appendix J includes both rail and truck equipment for each commodity group.

Exhibit J-1. Relation between Commodity Group and Equipment

Commodity Group	Commodity Assumed for Analysis	Rail Equipment	Truck Equipment
Fertilizers	Ammonium nitrate. Most fertilizers are dry powders or granular products, but some are liquid.	Covered hopper (4,000 – 5,200 cu ft depending on density)	Dump
Basic Chemicals	Chlorine, hydrochloric acid. Most basic chemicals are liquid, but some are dry bulk.	Tank cars	Tanker Truck
Newsprint / Paper	Newsprint in rolls. Other paper products are shipped on pallets	Boxcar (typically 60 ft car with 100+ ton capacity, and various door and interior packing arrangements)	Van
Plastic Materials	Primary form plastics (e.g., pellets). Other products are plastic and rubber manufactured items.	Covered Hopper (large volume plastic pellet cars, 6000 cu ft.+) Non-bulk items in boxcars. This heading could include a lot of auto parts and building items	Van
Waste and Scrap Materials	Steel scrap.	Low side gondola	Flatbed with sides
Nonmetallic Minerals	Crushed stone. Other products are sand, gravel, china clay, and possibly cement.	Open top hoppers	
Primary Metal Products	Mostly steel plates, bars and rolled sections for construction, also sheet in rolls (e.g for auto bodies)	Low side gondolas, flat cars or bulkhead flat cars for plates and sections , specialized coil cars for coiled sheet	Flatbed
Wood Products	Wood chips, dimensional lumber, or plywood or particle board. Wood chips are for paper plants or for making particle board.	Wood chips in large volume (6000 cu ft +) covered hoppers. Lumber in bulkhead/spine flat cars, more refined products such as high grade plywood in boxcar	Flatbed
Motorized Vehicles	New autos, vans and light trucks	Tri-level auto rack for cars, bi-level for vans and light trucks	Auto
Milled Grain Products	Wheat flour, corn and oat meals, and similar products	Covered Hopper	Flatbed with sides
Food Products	Wide variety of packaged products and perishable items (fruit and veg)	TOFC / Box Car(* see Note 1) Refrigerated boxcar for perishables	Van
Animal Feed	Mostly grain products of various kinds, carried in bulk. Some prepackaged in cans or bags	Covered hopper, various sizes depending on product density. Boxcar for packaged items	
Beverages	Beer, wine and soft drinks	TOFC or boxcar, may be refrigerated	Van
Chemical Products	Wide variety of bulk liquids and gases, and packaged items	Box Car / Tank Car	Van
Lumber	See wood products entry	Flat Car	Flatbed
Containerized Freight	All kinds	Double Stack cars of various designs	Container/Van