MPC Report No. 13-250

Analysis of Railroad Energy Efficiency in the United States

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May 2013

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OVERVIEW

The energy efficiency of freight transportation is a critical issue in the United States in light of the price volatility of fuels and America's dependence upon foreign sources of petroleum. Moreover, energy efficiency is important to environmental policy. The use of fossil fuels for transportation purposes results in the emission of air pollutants such as nitrogen oxides, particulate matters, and volatile organic compounds. Because emissions increase with gallons of fuel consumed, energy efficiency is a necessary condition for improved environmental quality.

The U.S. Department of Transportation (USDOT) has identified Environmental Sustainability as a major goal. The goal calls for improving energy efficiency and reducing greenhouse gas emissions. Recently adopted benefit/cost guidelines call for the quantification of "expected reductions in emissions of CO_2 or fuel consumption" when transportation projects are evaluated (USDOT, 2010, p. 21700). According to USDOT, a "projected decrease in the movement of people or goods by less energy-efficient vehicles or systems will be given priority" (Ibid).

While the sustainability goals are clear, techniques for quantifying energy comparisons are lacking. For want of better information, system-average modal efficiency factors are often used. At the national level, a great deal of effort has been devoted to emissions modeling. As a result, models such Mobile6 have emerged and are being widely used. However, much less attention has been paid to models for quantifying differences in fuel consumption. Within the multimodal investment framework articulated by USDOT, conservation of fuel is a critical factor in assessing intercity freight options.

Research Objectives. The purpose of this study is to provide information about railroad fuel efficiency that may be useful in evaluating transportation energy policies and assessing the sustainability of potential projects. The specific objectives are to (1) develop railroad energy efficiency models that describe differences in fuel economy among classes of trains and commodities; (2) apply these models to a wide range of movements to estimate fuel efficiency ratings for coal, grain, iron ore, food products, and other key commodities; (3) develop comparable procedures for estimating truck and waterway fuel consumption; and (4) compare rail, truck, and waterway energy efficiencies. The focus on railroads in this study is appropriate, because many of the alternatives to highway investment involve railroad transportation or multimodal options.

Energy Efficiency Measures. The two indicators of energy efficiency used in this study are (1) the gross ton-miles of cars and contents produced with a gallon of fuel (GTMC/G), and (2) revenue ton-miles per gallon (RTM/G). Gross ton-miles of cars and contents reflect the weights of containers, trailers, freight cars, and cargo. Only the cargo weight is reflected in revenue ton-miles.

Observed Efficiency Ratings. In 2008, railroads achieved efficiency ratings of 806 GTMC/G and 457 RTM/G. However, these ratings varied significantly among regions. The observed GTMC/G values were 779, 908, and 809 in the eastern, central, and western regions, respectively. The observed RTM/G values were 431, 501, and 464 in the same regions. These variations reflect differences in terrain, geography, and networks. Railroads in the central or plains region do not cross mountain ranges. In contrast, western railroads encounter substantial grades while crossing the Rocky Mountains and coastal ranges. Similarly, eastern railroads operate in the Appalachian Mountains.

Trends in Energy Efficiency. GTMC/G increased by 45% from 1985 to 2008. In comparison, RTM/G increased by 61% during the same period which is equivalent to a 2.6% annual growth rate. The growth in GTMC/G implies that railroad fuel savings are due in part to technological and operational efficiencies that have enabled the movement of a given weight with fewer gallons of fuel. However, the higher rate of growth in RTM/G indicates that additional energy gains are attributable to moving more revenue tons in a single car—i.e., increasing the net to gross weight ratio.

Methods of Estimating RTM/G. Two methods of estimating railroad energy efficiency are considered in this study (1) an analytical procedure based on train resistance factors, speeds, changes in elevation, and car weights; and (2) a statistical procedure that utilizes observed data. In the second approach, a model of railroad fuel consumption is estimated from GTMC, shipment classification, and region. In both procedures, fuel consumption is estimated from weight and distance—e.g., GTMC. Both procedures are used to estimate the efficiencies of coal, grain, iron ore, and other shipments. The two methods produce similar (but not identical) results. The analytical procedure (which is previewed next) illustrates the underlying forces that affect fuel efficiency and provides a benchmark for the statistical model.

ANALYTICAL PROCEDURE

In the analytical method, the horsepower-hours (hp-hr) required to move a uniform train of like cars over level terrain at a steady velocity are derived from train resistance equations that account for axle, wheel tread, flange, and air resistance. While wheel and flange resistance levels vary linearly with speed, air resistance increases with the square of velocity and varies with the streamline coefficients of the vehicles and their cross-sectional areas. In some cases, air resistance per ton is much greater for movements of empty cars than for loaded ones. These differences are especially great for open hopper and gondola cars that haul coal, ore, and aggregates. For example, the resistance of a loaded gondola car weighing 139 tons traveling at 45 mph is 4.0 lb/ton. In comparison, the resistance of an empty gondola car weighing 23 tons and traveling at the same speed is 17.1 lb/ton.

Locomotive Resistance and Drawbar Force. Resistance factors are used to estimate the combined resistance of a train of like cars, which, in turn, is used to estimate the number of locomotives needed as a function of horsepower, tractive effort, and drawbar force. The latter is the residual tractive effort available to pull cars once the locomotive resistance has been overcome.

Acceleration and Speed Limit Changes. A train routinely varies speeds as a result of changes in speed limits, planned stops, and traffic control. Fuel consumption at steady velocities represents only part of the total energy requirements of a trip. In this study, a speed profile is constructed from timetable speed limits. Using this profile, the excess fuel consumed during acceleration and traffic control delays is estimated and added to the fuel consumed at steady speeds.

Lifting Resistance. It takes 200,000 ft-lb of work to lift one ton 100 ft. Since 1.98 million ft-lb are equivalent to 1 hp-hr, it follows that 0.10 hp-hr are needed to lift one ton 100 ft in elevation. To quantify lifting resistance, an elevation profile is developed for a mountain crossing in the western region. Using this profile, the additional fuel consumed from changes in elevation is estimated and added to the energy needed to overcome rolling resistance and acceleration.

STATISTICAL MODEL

While the analytical procedure is insightful, it cannot practicably be used to estimate the energy efficiency of thousands of rail movements. For this reason, a regression model is formulated that reflects regional variations and differences in train service. The model is estimated from 24 years of R-1 reports submitted by Class I railroads to the U.S. Surface Transportation Board (STB). The R-1 database includes the reported gallons of fuel consumed for freight purposes, as well as the gross ton-miles and revenue ton-miles of operation. The variables utilized in the model are summarized in Table 1.

Train Service Levels. The type of train service has a major effect on energy efficiency. Single carloads typically travel in way trains at origin and/or destination. These trains operate primarily between branch-line stations and railroad yards, stopping frequently to drop off and pick up cars en route. In comparison, through trains usually move from yard to yard, performing only limited switching en route. Unit trains are characterized by shuttle service—e.g., the cycling of trains between origin and destination. Because way and through train movements are linked, these two categories are combined to form "non-unit train" GTMC. A non-unit train movement may consist of individual carloads, blocks of carloads moving to the same destination, or an entire trainload. The distinguishing characteristic is that some marshaling or gathering of cars is required at origin and/or destination, where car blocks may arrive or depart in way trains, traveling to or from nearby industry locations, ports, or terminals.

Regions. While many railroad mergers have occurred in the United States, railroads can be organized into three geographic regions that have remained constant over time: east, central, and west. Each current or merged railroad in the R-1 database is assigned to one of these regions. Once the assignments are made, the GTMC and gallons of fuel consumed by individual railroads are summed to derive regional totals. Although the model is estimated from Class I data, the regions are interpreted as geographic entities. While statistics for regional railroads are not available, the physical relationship between fuel consumption and GTMC is expected to be the same for any railroad operating the same train over the same route under the same conditions.

Indicator Variables. Each region in the R-1 database is represented by an indicator variable—e.g., Region 3. When the observation is for the western region, Region 3 equals 1. Otherwise, Region 3 equals 0. To avoid singularity, only $n - 1$ indicator variables are included in the model. The signs and magnitudes of the variables are interpreted in relation to the excluded effect, which is subsumed in the intercept.

Parameter Estimates and Probabilities. The estimates from the fuel model and their corresponding standard errors are shown in Table 2. As shown in column 3, the standard errors of the variables are small in relation to the estimated values. The probabilities (or p values) in column 5 are all highly significant (i.e., values of less than .0001), indicating less than a one in 10,000 chance of observing t values as large as those observed. The signs of the eastern and central regions are negative in relation to the west, which is characterized by challenging grades and rough terrain. The parameter estimate of time is positive, meaning that the fuel needed to transport a given quantity of gross ton-miles is less today than in previous years. The main predictions are (1) after controlling for time and region, an increase of 1,000 unit-train GTMC results in the consumption of 0.75 gallons of fuel, and (2) an additional 1,000 GTMC in other (non-unit) trains consumes 1.11 gallons of fuel (ceteris paribus).

Key Model Properties. The model has 66 error degrees of freedom, which should be sufficient to realize large sample properties. The R-square of 0.998 suggests that the model explains almost all of the variation in fuel consumption. The coefficient of variation of 3.45% (which is computed as the standard error of the regression divided by the mean of the dependent variable [gallons of fuel] multiplied by 100) suggests that the model provides a very precise fit. Nevertheless, to confirm its precision, the model is used to predict the values (i.e., gallons of fuel consumed) in each region in 2008. The average prediction error is less than 1.5%.

Marginal versus Average Estimates. Two types of estimates are generated from the statistical model: marginal and average. The former do not include overhead fuel that cannot be traced directly to GTMC. The marginal fuel efficiencies derived from the model's coefficients are 1,343 and 903 GTMC/G for unit and non-unit trains, respectively. However, these values are applicable only to small changes in railroad output and do not reflect regional variations. In comparison, the average predicted GTMC/G values for 2008 (which include overhead and fixed-system fuel) are 699, 819, and 697 for non-unit train movements in the eastern, central, and western regions, respectively. In comparison, the predicted GTMC/G levels are 944; 1,188; and 931 for unit train movements in the same regions. Unlike the marginal estimates, average values are applicable to large changes in traffic and can be used to compare energy efficiencies among modes. However, because GTMC/G estimates reflect the tare weights of cars and containers, they must be transformed into RTM/G before meaningful comparisons can be made.

Net/Gross Ratios. GTMC/G factors are transformed into estimates of RTM/G for specific commodities and service levels using net to gross car weight ratios. These ratios are computed from the 2008 waybill sample using empty/loaded ratios derived from the R-1 report. The calculation of a net/gross ratio is illustrated for a plain gondola car used in unit train service (Table 3). In this example, the net/gross ratio is computed as the net car weight (116 tons) divided by the sum of the gross car weight (139 tons) and the tare weight (23 tons), after the latter has been multiplied by the empty return ratio (1.0)—i.e., 116 / (139 + (23 × 1.0)) = 0.72. While many movements are analyzed in this study, commodities of strategic importance (such as coal, grain, and iron ore) are emphasized.

COAL

Coal is critically important to U.S. energy sufficiency. According to the U.S. Energy Information Administration (2010), 93% of the coal mined in the United States is used to generate electricity. Approximately 71% of the coal used by utilities is delivered by railroads. In comparison, trucks deliver less than 14% of the coal needed to generate electricity.

Environmental Importance of Western Coal. Roughly 42% of the coal mined in the United States originates from the Powder River Basin (PRB) of Wyoming. Although anthracite and bituminous coals generate more BTUs per ton, PRB subbituminous coal possesses relatively low levels of sulfur and ash. In order to comply with stricter sulfur emission regulations, many utilities throughout the United States burn PRB coal. Because the mines are located far from navigable rivers and lakes, western coal is moved primarily to utilities and transloading facilities by rail.

Energy Efficiency of Coal Movements. Car weights, distances, and shipment type (i.e., unit versus non-unit) are key variables affecting fuel efficiency. Values for these parameters are estimated from the 2008 waybill sample for coal movements within and between regions. As shown in Table 3, 93% of the coal transported by railroads moves in unit trains of 75 cars or greater. More than half of the coal is moved in gondola cars. The remainder moves in open-top hoppers. The average trip distance is 661 miles (Table 4). However, there are considerable variations within and between regions. Because of terrain, the greatest efficiencies are realized within the central region (848 RTM/G), which reflects movements of PRB coal to Texas and states in the south-central region, as well as eastward movements to the Mississippi River, Great Lakes, and utilities located in the northern plains. In comparison, the movement of PBR coal to the eastern United States by rail (which requires an interchange of shipments) results in 762 RTM/G. Movements within the eastern and western regions (which travel through and within mountain ranges) average 611 and 632 RTM/G, respectively.

Coal Unit Trains. The average gondola unit train contains 120 cars, while the average unit train of specialized hopper cars is comprised of 112 cars. Gondola trains have the highest net/gross ratios, followed by unit trains of specialized hopper cars. On average, coal unit trains are 60% more energy efficient than non-unit train shipments, averaging 744 RTM/G for all regions and flows. Unit train movements in the central region are particularly energy efficient, averaging 856 RTM/G. The average for all coal movements (irrespective of shipment type and region) is 722 RTM/G.

Analytical Estimates of Coal Train Efficiency. The values presented above (computed from the regression model and waybill sample) are compared to estimates derived from the analytical procedure. When variations in speed limits and traffic control delays are considered, a coal unit train of gondola cars is expected to achieve 976 RTM/G on flat terrain. Of course, this estimate is purely theoretical, since no route is perfectly flat. For example, PRB coal must first move north or south from the basin through rugged terrain before heading south or east. The effects of severe gradients are illustrated in the report for shipments crossing the Rocky and Cascade Mountains. On this route, the same unit coal train is expected to achieve 676 RTM/G, after the additional fuel needed to overcome lifting resistance is considered. However, neither of these estimates reflects common or overhead fuel use. For this reason, the analytical estimates will always exceed the statistical ones (ceteris paribus). In effect, the analytical estimates establish an upper bound for estimates generated from the statistical model. While the analytical procedure predicts a coal train efficiency of 976 RTM/G in flat terrain, the statistical model predicts 856 RTM/G in the flattest region. While the analytical procedure predicts a coal train efficiency of 676 RTM/G in the western region, the statistical model predicts an efficiency rating of 654 RTM/G.

OTHER STRATEGIC COMMODITIES

Grain. Railroads transported nearly 152 million tons of grain in 2010, which is equivalent to roughly one-third of the total tonnage (Association of American Railroads, 2011A). Approximately 48% of the grain transported by railroads travels in unit trains with a median length of 108 cars. The vast majority of grain tonnage (i.e., 98%) is transported in covered hopper cars. However, certain specialty crops (for which identity preservation is critical) travel in containers. Based on 2008 waybill data, the average unit train has a net/gross ratio of 0.63 and achieves 693 RTM/G. However, the average efficiency of unit trains traveling in the central region is 748 RTM/G, versus 598 RTM/G in the west. In comparison, the average non-unit train shipment has a net/gross ratio of 0.60 and achieves 454 RTM/G. The overall efficiency of grain shipments (irrespective of region and shipment type) is 556 RTM/G. In comparison, the estimated unit train efficiencies using the analytical method are 862 and 649 RTM/G in flat and mountainous terrain, respectively. The average distance of all grain shipments is 1,450 miles.

Iron ore is critical to the production of steel and durable goods. Approximately 59.1 million tons of iron ore were mined in the United States in 2008 (U.S. Geological Survey, 2008). Seventy-seven percent of this total originated from the Mesabi Range of Minnesota. Another 23% originated from the Upper Peninsula of Michigan. According to the waybill sample, railroads moved 53 million tons of iron ore in 2008, which equals 90% of the tonnage mined. Approximately 75% of these tons were moved in unit trains. The average unit train consisted of 132 cars, each weighing 25 tons empty, 116 tons loaded, and hauling 91 payload tons. More than 98% of the ore tonnage was hauled in open hopper cars. The average trip length was 569 miles. In 2008, the average energy efficiency of an ore unit train was 740 RTM/G. Unit train shipments in the central region (where most of the traffic is concentrated) are even more efficient, averaging 765 RTM/G (Table 5). The overall efficiency of ore movements in the United States (irrespective of train service and region) is 668 RTM/G.

Major Commodity Groups. Additional commodities such as ethanol and soda ash are analyzed later in the report. However, to provide a holistic overview, the average fuel efficiencies of major commodity groups are presented next. In this part of the study, net/gross ratios and RTM/G values are estimated at the two-digit Standard Transportation Commodity Code (STCC) level (Table 6). As noted earlier, coal and ore shipments generate 722 and 668 RTM/G, respectively. Movements of farm products (including grain) and food and kindred products (including flour) achieve 543 and 411 RTM/G, respectively. In addition, railroads are an energy-efficient means of transporting chemicals and allied products (429 RTM/G) and waste and scrap materials (389 RTM/G). The RTM/G values for containerized freight (STCC 46) and empty containers (STCC 42) are relatively low. Nevertheless, according to ICF International (ICFI, 2009), movements of double-stack containers by rail are more energy-efficient than truck movements.

VALIDATION OF MODELING PROCESS

The railroad modeling process described above produces very reasonable results. The overall (predicted) net/gross ratio using the statistical model and 2008 waybill sample is 0.55. In comparison, the actual net/gross ratio from the R-1 report is 0.57. The overall fuel efficiency rating predicted from the statistical model and waybill sample is 456 RTM/G. In comparison, the observed 2008 fuel efficiency rating is 457 RTM/G. In effect, the predicted and actual values are nearly identical. As these comparisons suggest, procedures based on the statistical model and waybill sample slightly underestimate the observed net/gross ratios and efficiency ratings. However, on a national scale, the estimates are quite accurate and do not overstate railroad fuel efficiencies. The next step in the process is to estimate truck fuel efficiency ratings so that railroad estimates can be placed in a multimodal context.

TRUCK FUEL EFFICIENCY

During the nine-year period from 2000 to 2008, the average fuel efficiency of combination trucks (i.e., tractors pulling trailers or semitrailers) ranged from 5.1 to 5.9 mpg. The average for the period is 5.4 mpg, which is the same as the 2008 value. However, because of grandfather clauses, many varieties of combination trucks operate in the United States. The weights of many of these trucks exceed the 80,000-pound federal limit. Consequently, the use of a simple mile-per-gallon average would misstate the fuel economies of specific trucks.

In an earlier study, the U.S. Department of Transportation estimated fuel efficiency factors for a wide range of trucks, including longer configuration vehicles (LCVs). While these values are outdated, the relative efficiency factors are not, since most (if not all) heavy duty tractors have experienced similar improvements in engine technology to meet stricter emission regulations. Based on this assumption, a table of truck efficiency factors is developed by indexing USDOT's original values to account for improvements in tractor fuel economy since the late 1990s (Table 7). Some of the trucks shown in Table 7 (such as Rocky Mountain Doubles, triple trailers, and eight- or nine-axle combinations) are limited to turnpike operations and movements in western states. In comparison, the five-axle tractor-semitrailer and five-axle twin trailer trucks are legal nationwide.

Variations in Fuel Economy with Weight. As shown in Table 7, fuel economy decreases with weight. According to Delorme, Karbowski, Sharer (2009), the fuel economy of a five-axle tractor semitrailer increases by roughly 0.06% with each thousand pounds of weight reduction. However, fuel economy varies with tractor performance, the aerodynamics of the truck configuration, and other factors. Because of these variances, relationships between LCV and semitrailer fuel economy are not based solely on weight.

Variations in Fuel Economy with Speed. According to Peterbilt Motors Company (2011), the power necessary to overcome aerodynamic drag at speeds of 50 mph is equal to roughly half the power needed to overcome rolling resistance and the energy consumed by accessories. At 75 mph, the power needed to overcome aerodynamic drag is roughly 2.5 times the power needed to overcome rolling resistance and accessory drain (Ibid). According to Goodyear (2008), each mile per hour increment above 55 mph increases fuel consumption by 2.2%.

Empty Truck Miles. Railroad empty/loaded ratios are reflected in the RTM/G estimates presented earlier. However, there is no comprehensive source of empty/loaded ratios for trucks, since the Vehicle Inventory and Use Survey (VIUS) has been discontinued. In its 2009 report, ICFI summarized data from the 2002 VIUS survey and, in doing so, discovered that the percentages of empty miles attributable to van trailers ranged from 26% at distances of 200-500 miles to 19% at distances > 500 miles. In comparison, the percentages of empty miles incurred by tanker trailers ranged from 43% at distances of 200-500 miles to 31% at distances > 500 miles. The percentages of empty miles for dump trucks ranged from 41% at distances of 200-500 miles to 38% at distances > 500 miles. Because more specific information is not available, van trailers are conservatively assumed to incur 25% empty miles. A similar assumption is made for hopper trailers hauling grain. However, backhauls are much more difficult to obtain for specialized trailers such as hopper and dump trailers.

Fuel Attributable to Empty Truck Miles. According to simulations in Delorme et al. (2009), the fuel efficiency of an empty five-axle tractor semitrailer is 23% to 27% greater than the fuel efficiency of the same truck loaded to 80,000 pounds, at speeds ranging from 50 to 70 mph. These estimates seem reasonable, given the fact that a large percentage of the fuel consumed at higher speeds is attributable to aerodynamic resistance rather than weight. Based on the aforementioned simulations, a liberal assumption is made that allows for potential energy savings during acceleration and speed change cycles. Empty truck fuel consumption (in gallons per mile) is assumed to be 70% of loaded consumption. The same percentage of fuel savings is applied to Rocky Mountain Doubles and twin-trailer trucks, even though the empty aerodynamics of these trucks is worse than the aerodynamics of a tractor-semitrailer. Because of these liberal assumptions, the allowances made for empty-mile fuel savings in this study should not understate the benefits of reduced weights.

RAIL-TRUCK COMPARISONS

Modal comparisons are made on an RTM/G basis (i.e., per mile of operation). These values can be used to estimate the fuel consumed by each mode for a specific origin and destination based on miles traveled. However, because of differences in network coverage and routes, one mode may require more or less miles than another mode to move a commodity between the same origin and destination. As discussed later, this inconsistency is accounted for through the use of circuity factors.

Coal Transportation in the Eastern United States. Most of the competition for coal between railroads and trucks occurs in the eastern United States, where several states have increased their truck weight limits for movements on designated highways, allowing trucks to weigh as much as 60 tons, with some overweight tolerance. Three varieties of trucks are widely used to transport coal in these states (1) three-axle trucks with tandem rear axles, (2) five-axle tractors with semitrailers, and (3) six-axle tractor-semitrailer combinations with triple or tridem rear axles. The maximum allowable gross weights for these trucks are 40 tons, 45 tons, and 60 tons, respectively, on designated roads. Of these trucks, the six-axle tractor semitrailer is the most economical truck for longer hauls from mines to river transfer facilities and utilities. With a tare weight of roughly 15 tons, this truck can haul 45 tons in a single trip. Because coal trucks often operate in shuttle service and have limited backhaul opportunities, the empty/loaded ratio is assumed to be 1.0. Because of the six-axle truck's greater weight (60 tons instead of 40 tons), its fuel efficiency (4.9 mpg) is less than that of a typical 80,000-lb tractor-semitrailer. With 50% empty miles, the average efficiency of this truck is 130 RTM/G. In comparison, the average efficiencies of non-unit and unit train coal shipments in the eastern United States (as predicted from the regression model and waybill sample) are 460 and 637 RTM/G, respectively. As these comparisons suggest, non-unit and unit train coal movements in the eastern United States are 3.5 and 4.9 times more fuel efficient than movements of the heaviest truck approved for travel on designated state routes on a per mile basis.

Coal Transportation in the Western United States. While most western coal is moved to the central and eastern United States, some movements occur within the western region. In several western states, coal is moved in LCVs under exceptions to the 80,000-pound vehicle weight limit. In some areas, coal is moved in double-trailer combinations with gross weights of 129,000 pounds or more. With a tare weight of 22.5 tons, these trucks can haul 42 tons in a single trip. With a fuel efficiency rating of 5.2 mpg and no backhaul, these trucks can achieve 128 RTM/G. In comparison, the average fuel efficiencies of non-unit and unit train movements in the western United States (as predicted from the regression model and waybill sample) are 444 and 654 RTM/G, respectively. In effect, these shipments are 3.7 to 5.4 times more fuel efficient than movements in the heaviest truck allowed under grandfather clause exemptions, on a per mile basis.

Grain Transportation. Grain is shipped from elevators to markets, transfer locations, and export facilities in large commercial trucks. The two most common types are the five-axle tractor semitrailer and the seven-axle Rocky Mountain Double—which consists of a 40- to 48-foot semitrailer followed by a smaller "pup" trailer with two single axles. A third truck configuration (which is used primarily in cross-border movements between the United States and Canada) has four sets of tandem axles and nine axles, altogether. All three trucks are equipped with hopper trailers with top loading and bottom (gravity) discharging capabilities. The typical weights of these trucks are shown in Table 8, where the gross weight of the twin-trailer truck is an average of individual state weight limits that range from 105,500 to 137,800 pounds. Movements of this truck are confined to limited geographic areas near the northern border. In comparison, Rocky Mountain Doubles are common in the western United States under grandfather clauses, but are rare east of the Mississippi River. However, the tractor-semitrailer combination is legal nationwide and is therefore the dominant truck used in grain transportation.

RTM/G Estimates for Grain Trucks. Because of their specialized nature, the empty/loaded mile ratios are higher for hopper trailers than for van trailers. If half of the truck's miles are empty (e.g., zero backhaul), the estimated fuel efficiencies are 86, 109, and 126 RTM/G for the five-axle, seven-axle, and nine-axle trucks, respectively. If 25% of the truck's miles are empty, the estimated fuel efficiencies are 119, 150, and 174 RTM/G for the five-axle, seven-axle, and nine-axle trucks, respectively.

Relative Energy Efficiencies of Railroad and Truck Grain Movements. As noted earlier, unit and non-unit train movements of grain achieve 693 and 464 RTM/G, respectively. The overall efficiency rating of railroad grain movements is 556 RTM/G. As these factors suggest, grain movements by rail are 6.5 times more fuel efficient on a per-mile basis than grain shipments in five-axle tractor-semitrailer trucks with no backhaul (column 2 of Table 9), and 5.1 and 4.4 times more fuel efficient than movements in Rocky Mountain Doubles and twin-trailer trucks, respectively, with no backhaul. The relative fuel advantages are even greater for grain unit trains, which are 8.1, 6.4, and 5.5 times more efficient than highway movements in five-axle tractor-semitrailers, Rocky Mountain Doubles and twin-trailer trucks, respectively (column 3). If trucks incur 25% empty miles, grain unit trains are 5.8, 4.6, and 4.0 times more fuel efficient than highway movements in five-axle tractor-semitrailers, Rocky Mountain Doubles and twin-trailer trucks, respectively (column 5). The energy advantage of railroads is even greater in the central region, where grain unit trains achieve their maximum fuel efficiency of 748 RTM/G. In this region, a railroad unit train is five times more fuel-efficient than a Rocky Mountain Double, on a per mile basis.

Energy Efficiencies of Iron Ore Movements by Rail and Truck. Minnesota does not allow LCVs. So, the heaviest vehicle that can operate with a routine permit is a six-axle tractor-semitrailer that weighs 90,000 pounds. With a tare weight of 13.5 tons and 25% empty miles, this truck can achieve 138 RTM/G. The maximum weight of a double trailer combination in Michigan with typical axle spacing and no special permit is 109,000 pounds. At 25% empty miles, this truck can achieve 157 RTM/G. As noted earlier, the efficiency of an ore unit train in the central region is 765 RTM/G. Thus, on a per mile basis, an ore unit train is 4.9 and 5.5 times more fuel efficient than highway movements in Michigan and Minnesota, respectively, in the heaviest combination trucks routinely allowed in those states. With these ratios, it is not surprising that iron ore in the central region moves almost exclusively by rail and water.

Flour and Grain Mill Products. Railroads transported more than 10 million tons of flour and related grain mill products in 2008. All of these shipments moved as individual carloads. About 86% of this tonnage moved in covered hopper cars with an average load factor of 93 tons. The average trip length was 784 miles. The overall efficiency rating was 429 RTM/G. Because final demand sites (such as bakeries) are distributed throughout the United States and because of the protective needs of the cargo, truck transportation is the only feasible alternative to rail. While it is possible for bulk flour to be transported in LCVs, flour is more likely to move in five-axle tractor semitrailers. With 25% empty miles, the typical efficiency of a flour movement by truck is 118 RTM/G. On average, railroad movements of bulk flour are 3.6 times more fuel efficient than highway movements on a per mile basis. However, this ratio may not be applicable to bagged flour movements in van trailers and boxcars, or other bagged or packaged grain mill products.

Soda Ash. Sodium carbonate or soda ash is an important industrial compound that is essential to the manufacture of glass, detergents, paper, and various chemicals. In 2008, approximately 12.5 million tons of soda ash were produced in the United States, mostly in Wyoming and California. Most of this product is transported long distances (e.g., an average of 1,300 miles) to manufacturers located throughout the United States by railroads in covered hopper cars with an average load factor of 104 tons and an average efficiency rating of 479 RTM/G. Because of the west to east orientations of these movements, river transportation is infeasible on a broad scale. Moreover, because of the nationwide distribution of soda ash, the only practical truck option is the five-axle tractor semitrailer which, with 25% empty miles, can achieve 118 RTM/G. In effect, soda ash movements by rail are 4.1 times more energy efficient than movements by truck on a per mile basis.

Ethanol. Movements of ethanol are important to clean fuel programs in several states, including California. According to the American Association of Railroads (AAR, 2011B), railroads account for 70% to 75% of ethanol transportation. Ethanol is transported primarily in large tank cars with an average load factor of 93 tons. With a net/gross ratio of 0.58, these movements realize an efficiency rating of 443 RTM/G and are 3.9 times more fuel efficient than movements in five-axle tractor semitrailers with 25% empty miles. Because of the east-west orientations of these movements, river transportation is infeasible on a broad scale. However, waterway transportation is critically important to coal and grain logistics.

WATERWAY FUEL EFFICIENCY MODEL

Waterway fuel consumption rates are estimated from the River Efficiency Model (REM) developed by the Tennessee Valley Authority (TVA). REM uses vessel and lock performance models to estimate horsepower and speed for each river segment, as well as average processing and delay time at each lock. Fuel usage is derived from speed, horsepower, lock time, and other performance data. The individual computations for river segments are added to determine the total fuel consumption for each waterway. While REM cannot be used to analyze fuel consumption for specific commodity movements, average fuel efficiency factors can be estimated for particular waterways. These factors (shown in Table 10) reflect both loaded and empty barge movements and fuel consumed during lock transits and queuing.

RTM/G Estimates by River Segment. While railroad energy efficiency has increased consistently over time, waterway fuel efficiency has fluctuated from year to year. Moreover, there are considerable differences in fuel efficiency among river segments (Table 10). In 2008, the average efficiency from Minneapolis to the mouth of the Missouri River was 348 RTM/G. The average efficiency on the Illinois River was 287 RTM/G. However, down-river fuel efficiencies were much greater—e.g., 656 RTM/G for the open river segment from the mouth of the Ohio River to Baton Rouge, LA. In 2009, the estimated fuel efficiencies were 482 and 771 RTM/G for the Minneapolis to Missouri River and Ohio River to Baton Rouge segments, respectively. Moreover, the estimated efficiency of the Illinois River was much greater than in 2008—i.e., 395 RTM/G instead of 287. These differences are partly explained by the major flood that occurred on the Mississippi River in 2008, resulting in the second highest crest ever recorded for stations such as Quincy, IL. Because of the flood, a three-year average of waterway fuel efficiency (centered around 2008) is used in the comparison (column 3, Table 10). While averaging has a minimal effect on Ohio River fuel efficiency, it significantly alters the values used for the Mississippi and Illinois Rivers.

Illinois and Upper Mississippi Rivers. In addition to floods, the fuel efficiencies of the Upper Mississippi and Illinois Rivers are constrained by small aging locks, many of which are programmed for replacement in the future. At many of these locks, barge operators must separate a tow into two components, and move the blocks through separately. Afterward, the tow must be reassembled. This process may be repeated at several locks as a shipment travels on the Upper Mississippi River or Illinois Waterway. Queuing and double locking maneuvers significantly increase fuel consumption. The estimated RTM/G ratings for shipments originated from upper river stations (which are computed by weighting the RTM/G estimates on each river segment by the distance traveled) are shown in Table 11. A shipment from Minneapolis (the head of navigation) to the port of New Orleans yields 619 RTM/G, while a shipment from Quincy, IL (located only 130 miles from the mouth of the Missouri River) to New Orleans yields 702 RTM/G.

Ohio River System. The average revenue ton-miles per gallon for shipments on the Ohio River (592 RTM/G) is higher than on the Upper Mississippi River (436 RTM/G). Ohio River fuel efficiency is illustrated for a barge shipment from Greenup, KY, (located 640 miles from the mouth of the Ohio River) to the port of New Orleans. The estimated efficiency of this shipment (which travels a total of 1,492 river miles) is 678 RTM/G.

General Inferences Regarding River Transportation. Several patterns are apparent from the data. (1) Open river fuel efficiencies are the greatest. Propulsive energy is minimized when loaded barges travel downstream with the current. (2) Shipments that travel the shortest distances on the Upper Mississippi or Illinois Rivers are more efficient than shipments originated farther upstream. Movements originated in the northernmost reaches of the river must transit more locks en route to New Orleans and, thus, consume more fuel in queuing and lock transits.

Rail versus Barge Energy Efficiency in Coal Transportation. As shown in Table 10, the average fuel efficiency of shipments on the Ohio River is 592 RTM/G. In comparison, the average efficiency of coal shipments in the eastern United States is 611 RTM/G. A precise comparison is difficult because the comparative distances from mines to rail and river transfer facilities are unknown. Nevertheless, it appears that the energy efficiency of coal shipments in the eastern region is at least comparable to barge shipments on the Ohio River. As noted earlier, coal mined in the western United States is often railed from the Powder River Basin to the Great Lakes or Upper Mississippi River Valley. Because these movements are complementary, direct modal comparisons are not considered. Nevertheless, it can be said that unit coal train movements in the central region are more energy-efficient than barge movements on the Illinois or Upper Mississippi Rivers.

Grain Movements from Upper Mississippi River Stations to the Gulf. As noted earlier, the weighted average fuel efficiency of a waterway movement from Minneapolis to New Orleans is 619 RTM/G. This is higher than the average for a non-unit train movement within the central region (497 RTM/G). However, the typical waterway fuel efficiency is less than that of a grain unit train (748 RTM/G) traveling in the same region. Moreover, a unit train movement in the central region is more fuel efficient than movements from all of the Upper Mississippi River stations shown in Table 11.

Grain Movements from Upper Ohio River Stations to the Gulf. As noted earlier, the average fuel efficiency of barge shipments from Greenup, KY, to New Orleans is 678 RTM/G. In comparison, a non-unit train movement within the eastern region yields 431 RTM/G, while a grain unit train movement generates 596 RTM/G. In this example, Ohio River barge movements offer greater energy efficiencies than railways for movements of grain to the Gulf of Mexico at average regional efficiency levels.

TRANSPORTATION CIRCUITY

The comparisons presented thus far have not been adjusted for circuitous routing. As noted earlier, the comparisons reflect a one-mile haul by each mode. If one mode requires fewer miles than another to move the same product between origin and destination, such comparisons could misstate the energy requirements of a trip. In surface transportation, out-of-line movements and meandering routes create additional mileage known as "circuity," which is the difference between the most direct (as the crow flies) route and the actual miles traveled between origin and destination. There are essentially two types of circuity: (1) network and (2) route. The former is a function of the built transportation network and how much it deviates from great circle distances. The latter is a measure of the extent to which shipments do not take the most direct path between origin and destination. In some cases, a longer alternative path with a shorter travel time may be selected. In other cases, a longer path may be followed to avoid congestion, severe gradients, or hazards. The consolidation and distribution of freight at origin and destination may contribute to circuity, resulting in way train and truck flows counter to the prevailing direction of movement. Total circuity is the sum of network and route circuity.

Circuity Factors. A circuity factor or multiplier is equal to 1.0 plus the percentage (or proportion) of circuitous miles. The latest factors were estimated in the early 1980s. According to the Congressional Budget Office (CBO, 1982), the average network circuity factors for intercity carriers are 1.83 for barges, 1.32 for railways, and 1.15 for trucks. In comparison, route circuity multipliers are 1.15 and 1.06 for railroads and trucks, respectively (Ibid). Barge route circuity is assumed to be zero, since there is rarely more than one river path between an origin and destination. While CBO's truck estimate is dated, it may still be applicable, because most of the interstate and intercity arterial highway network was in placed by 1982. However, the latest railroad estimate of 1.135 was developed in 1983 (STB, 2009). This circuity factor reflects both unit and non-unit train traffic, which have substantially different operating characteristics. Because out-of-line routing for purposes of yard classification is not required, unit trains typically travel the shortest path between origin and destination. In the Uniform Railroad Costing System, the STB assumes a circuity factor of 1.0 for unit trains (2009). After adjusting for the substantial increase in unit train traffic that has occurred over time, the weighted-average route circuity factor of 1.09 (estimated for 2008) reflects a non-unit train circuity factor of 1.16 and a unit-train circuity factor of 1.0. Using these factors, the overall ratio of railroad to truck circuity for non-unit train movements is 1.22. For unit train movements, the ratio of rail to truck circuity is 1.09. For unit train movements, the ratio of barge to rail circuity is 1.24.

Railroad-Truck Comparisons Adjusted for Circuity. The ratios of railroad to truck and railroad to barge energy efficiencies discussed earlier are summarized in Table 12 (columns 3-5), along with a set of ratios that have been adjusted for circuity (columns 6-8). As expected, the railroads' energy advantage over trucks drops after the adjustments. However, railroads still hold substantial energy advantages for all of the commodities analyzed. For example, coal unit trains are still 4.5 and 5.0 times more energy efficient than truck movements in the largest vehicles allowed under grandfather clauses in the eastern and western regions respectively. Unit grain train movements in the central region are still 4.6 times more fuel efficient than movements in Rocky Mountain Doubles.

Effects of Circuity on Railroad and Barge Energy Comparisons. While railroad to truck efficiency ratios drop when circuity is considered, railroad to barge ratios increase. The Minneapolis to New Orleans movement is an interesting example. The shortest railroad distance is 1,273 miles. In comparison, the river distance is 1,706 miles. In this example, the actual ratio of barge to rail circuity is 1.34, instead of the 1.24 factor computed earlier. However, this ratio reflects only network circuity. If another route to New Orleans is selected, the rail distance will be greater. As a result, the barge-to-rail circuity ratio will be much smaller.

ISSUES AND LIMITATIONS

Access or Drayage Energy Consumption. Truck movements are necessary to move grains from farms to elevators located on rail lines and rivers. However, because of the diversity of these trips, it is difficult to make generalizations about the truck portions of railroad and waterway movements. If there are substantial differences in the distances attributable to connecting truck movements, the comparisons presented earlier may be unrealistic. Drayage fuel consumption for container-on-flatcar (COFC) movements is discussed in the main report.

Issues with Railway and Waterway Comparisons. In previous studies, system-average railroad and waterway RTM/G values were compared and inferences drawn that waterways are more energy efficient than railways (Kruse, Protopapas, Olson, and Bierling, 2007). While this is true overall, the comparison is not completely relevant. The inland waterway traffic mix consists largely of bulk commodities such as coal, ore, petroleum, chemicals, aggregates, and farm products. In contrast, the railroad traffic base includes automobiles, auto parts, loaded and empty containers, and a multitude of neobulk and manufactured goods for which railways and trucks compete. For these reasons, comparisons of railway and waterway averages do not necessarily result in "apples to apples" comparisons. A different picture emerges when the commodities moved by rail are organized into two categories (1) bulk commodities and heavy manufactured goods that also move via waterways and (2) low-density, containerized, and/or time-sensitive goods for which railways and trucks compete. If the second group is excluded from the calculation, the railroads' energy efficiency increases from 457 RTM/G to 581 RTM/G. For purposes of comparison, the average river efficiency during the 2007-2009 period was 592 RTM/G. While this comparison is approximate, it indicates that railroad energy efficiency is approaching waterway efficiency levels for similar commodities. However, the comparison is lacking in several respects. There are significant differences in the ways that railroads and waterways make investment decisions. Railroads make decisions based on market priorities. In contrast, waterway investments are approved (or disapproved) by Congress through a lengthy political process. While there is no certainty that railway investments are optimized, many of the locks on the Upper Mississippi and Illinois Rivers are outmoded. The modernization of locks on these segments could affect forecasts of modal energy efficiency. Nevertheless, future waterway investment levels will not alter the fact that railroads are an efficient mode of transporting strategic bulk commodities and are critically important to national energy goals.

Additional Issues. The methods, data, assumptions and limitations of the study are discussed in greater detail in the main report. However, some interpretive issues are highlighted next. (1) The outcomes and implications of fuel efficiency comparisons may be different, depending upon whether marginal or average estimates are used. Most studies do not explicitly say which factors are being used and why. (2) Comparisons of railway and truck energy efficiencies may vary from state to state depending on the types of grandfathered trucks allowed and overweight permitting processes. (3) While fuel consumption for way train movements on Class I railways is reflected in this study, specific estimates for local and regional railroad operations are not. The fuel consumption rates for these movements are assumed to be similar to those experienced by Class I railroads within the same region. Because local railroad movements are short in duration, they should not have a strong influence on the conclusions. (4) While railroad energy efficiencies are specifically developed for individual commodities, river efficiency ratings reflect the average of all commodities moving on a river segment. While most of these movements are comprised of bulk commodities, there may be substantial differences in the net tonnage per barge among commodity groups. These potential differences are not reflected in the comparisons. As a result, railroad-barge comparisons for specific commodities may reflect averaging errors. (5) Railroad and waterway comparisons are further complicated by the periodic flooding of the Mississippi River basin. Because floods are a reality of waterway transportation, they must be reflected in the comparisons. In this study, a three-year waterway average (centered on 2008) is used to compare waterway and railway fuel efficiencies. Overall, the use of a three-year average yields a waterway efficiency rating of 592 RTM/G, which seems reasonable, given that the most recent five-year average is 588 RTM/G. In essence, the use of a longer averaging period has little or no effect on the comparisons presented in this report.

Table 1. Variables in Railroad Fuel Regression Model

Variable	Description	Type
GAL	Gallons of fuel consumed in train and yard freight service	Response
UGTMC	Thousands of gross ton-miles of cars and contents moved in unit trains	Structural
NGTMC	Thousands of gross ton-miles of cars and contents moved in non-unit trains	Structural
T	Time in years before 2008 (2008 = 0)	Control
REG	A set of regional variables {1, 2, 3}	Indicator

Table 2. Parameter Estimates from Railroad Fuel Model

Parameter	Estimate	Standard Error*	t-value*	Probability of > |t|*
Intercept	713,465,017	67,216,343	10.61	<.0001
UGTMC	0.74449	0.10696	6.96	<.0001
NGTMC	1.10767	0.11788	9.40	<.0001
T	3,339,195	581,239	5.74	<.0001
REG1	-476,171,943	29,754,620	-16.00	<.0001
REG2	-701,468,788	57,404,842	-12.22	<.0001

*Heteroscedasticity consistent estimates

Table 3. Weights of Railcars Used in the Transportation of Coal

Shipment Type	Car Type	Percent of Cars	Net Weight (Tons)	Tare Weight (Tons)	Net/ Gross Ratio
Non-Unit	Plain Gondola	1.7%	102	30	0.64
	Open Hopper- General Service	2.5%	98	30	0.62
	Open Hopper- Special Service	3.4%	112	27	0.68
Unit	Plain Gondola	49.7%	116	23	0.72
	Open Hopper- General Service	10.4%	105	29	0.65
	Open Hopper- Special Service	32.3%	115	25	0.70

Table 4. Energy Efficiency of Coal Movements

		Revenue Tons Miles per Gallon		
	Average Distance	Shipment Type		
Region	**(Miles)**	**Non-Unit**	**Unit Train**	**Average**
East (Internal)	368	460	637	611
Central (Internal)	960	511	856	848
West (Internal)	497	445	654	632
Central-East	1,280	462	767	762
East-West	1,733	448	629	629
West-Central	966	472	750	737
United States	**661**	**465**	**744**	**722**

Table 5. Car Weights and Fuel Efficiencies of Iron Ore Movements

Shipment Type	Region	Net/Gross	RTM/G
Non-Unit	East	0.61	425
	Central	0.63	513
	West	0.59	410
Unit	East	0.63	595
	Central	0.64	765

Table 6. Fuel Efficiencies of Major Commodity Movements at Two-Digit STCC Level

STCC	Product Name	Net/Gross	RTM/G
01	Farm Products	0.61	543
10	Metallic Ores	0.63	668
11	Coal	0.70	722
14	Nonmetallic Minerals, except Fuels	0.63	524
20	Food or Kindred Products	0.54	411
24	Lumber or Wood Products	0.54	397
26	Pulp, Paper or Allied Products	0.49	356
28	Chemicals or Allied Products	0.57	429
29	Petroleum or Coal Products	0.51	385
32	Clay, Concrete, Glass or Stone Products	0.62	459
33	Primary Metal Products	0.56	412
37	Transportation Equipment	0.24	177
40	Waste or Scrap Materials	0.54	389
42	Empty Containers or Shipping Devices	0.23	165
46	Miscellaneous Mixed Shipments	0.33	246

Table 7. Average Miles per Gallon by Truck Configuration and Weight

	Gross Vehicle Weight (pounds)			
Truck Configurations	60,000	80,000	100,000	120,000
Five-Axle Semitrailer	6.2	5.5	4.9	
Six-Axle Semitrailer	6.1	5.4	4.9	
Five-Axle Double Trailer	6.8	6.0	5.5	
Seven-Axle Rocky Mountain Double		5.8	5.2	5.0
Eight Axles (or more)		5.8	5.5	5.2
Triple-Trailer Combination		6.0	5.7	5.4

U.S. Department of Transportation. *Western Uniformity Scenario Analysis: A Regional Truck Size and Weight Scenario Requested by the Western Governors' Association*, April 2004. Original values indexed by 1.14.

Table 8. Weights of Combination Grain Trucks

Truck Configuration	**5-Axle 48-ft Semitrailer**	**7-Axle Rocky Mountain Double**	**9-Axle Twin Trailers**
Gross Weight (lb)	80,000	105,500	127,400
Tare Weight (lb)	26,800	34,200	45,000
Net Weight (tons)	26.6	35.7	41.2

Table 9. Ratio of Railroad to Truck Energy Efficiency in Transporting Grain

	50% Empty Truck Miles		25% Empty Truck Miles	
Truck Configuration/Train Type	**Average**	**Unit Train**	**Average**	**Unit Train**
Five-Axle Semitrailer	6.5	8.1	4.7	5.8
Seven-Axle Rocky Mountain Double	5.1	6.4	3.7	4.6
Nine-Axle Twin 48-ft Trailers	4.4	5.5	3.2	4.0

Note that Rocky Mountain Doubles operate primarily in the western United States, while nine- and ten-axle grain trucks operate largely in cross-border movements to and from Canada. A simple average of the values in any column of the table may be misleading, since most of the shipments occur in five-axle units.

Table 10. Waterway Fuel Efficiency Factors for Specific River Systems

	Revenue Ton-Miles per Gallon	
Waterway Name	2008	Average 2007-2009
Mississippi River, Mouth of Ohio to Baton Rouge	656	742
Mississippi River, Mouth of Missouri to Mouth of Ohio	584	703
Mississippi River, Minneapolis to Mouth of Missouri	348	436
Illinois River (IL)	287	348
Ohio River	603	592
Tennessee River (TN, AL and KY)	445	453
Tennessee Tombigbee Waterway	354	377

Table 11. Average Revenue Ton-Miles per Gallon for Barge Shipments from Upper Mississippi River Stations to New Orleans: 2007-2009

Station	Distance to Mouth of Missouri River	Weighted RTM/G
Minneapolis, MN	659	619
Minnesota City, MN	543	633
Dubuque, IA	388	654
Clinton, IA	327	664
Keokuk IA	169	693
Quincy, IL	130	702

Table 12. Ratio of Railroad-to-Alternate Mode Fuel Efficiency, Adjusted for Circuity

		Unadjusted Ratios			Adjusted Ratios		
Commodity and Region	**Alternate Mode**	**Non-Unit**	**Average**	**Unit Train**	**Non-Unit**	**Average**	**Unit Train**
Coal							
East Region	Truck	3.5	4.7	4.9	2.9	4.0	4.5
East Region	Barge	0.7	0.9	0.9	0.9	1.2	1.3
West Region	Truck	3.7	5.2	5.4	3.0	4.4	5.0
Grain							
All Regions	5-axle	3.8	4.7	5.8	3.1	4.0	5.3
All Regions	7-axle	3.0	3.7	4.6	2.5	3.2	4.2
All Regions	9-axle	2.6	3.2	4.0	2.1	2.7	3.7
Central Region	7-axle	3.3	4.1	5.0	2.7	3.5	4.6
Minneapolis to Gulf	Barge	0.8	1.0	1.2	1.0	1.3	1.7
Greenup, KY, to Gulf	Barge	0.6	0.7	0.9	0.7	0.9	1.0
Iron Ore							
Michigan	Truck	3.3	4.6	4.9	2.7	3.9	4.5
Minnesota	Truck	3.7	5.2	5.5	3.0	4.4	5.0
Flour (All Regions)	Truck	3.6			3.0	0.0	
Soda Ash (All Regions)	Truck	3.9	4.1	5.3	3.2	3.5	4.9
Ethanol (All Regions)	Truck	3.7	3.9	5.2	3.0	3.3	4.8

1. INTRODUCTION

The fuel efficiency of freight transportation is a critical issue in the United States in light of the price volatility of fuels and America's dependence upon foreign sources of petroleum. Moreover, fuel efficiency is important to environmental policy. The burning of fossil fuels for transportation purposes results in the emission of air pollutants such as nitrogen oxides, particulate matters, and volatile organic compounds. According to the U.S. Environmental Protection Agency (EPA), transportation is responsible for 27% of the total greenhouse gas emissions in the United States. Moreover, transportation is the fastest-growing source of greenhouse gas emissions, accounting for 47% of the net increase in U.S. emissions since 1990. Today, transportation is the largest end source of carbon dioxide (CO_2), the most prevalent greenhouse gas. Because emissions increase with gallons of fuel consumed, fuel efficiency is a necessary condition for improved environmental quality.

Perhaps the most common measure of transportation fuel efficiency is revenue ton-miles per gallon (RTM/G), which is an indication of the transportation output produced by a gallon of fuel. It measures how many miles one ton of cargo can be moved with a gallon of fuel. On the basis of this measurement, U.S. railroads increased their fuel efficiency rating from 283 RTM/G in 1985 to 457 RTM/G in 2008 (Figure 1.1), which represents a 61% increase over 24 years, or a 2.6% annual growth rate. A complementary indicator of fuel efficiency is the gross ton-miles of cars and contents (GTMC) moved with a gallon of fuel. In addition to revenue or cargo tons, this indicator reflects the weights of containers, trailers, and freight cars. As shown in Figure 1.1, the gross ton-miles of cars and contents produced with each gallon of fuel (GTMC/G) has increased from 558 in 1985 to 806 in 2008, a 45% increase in 24 years, or a 1.9% annual growth rate.

As these trends suggest, there are two primary sources of energy efficiency gains. (1) Railroad fuel savings are due in large part to technological and operational efficiencies that have enabled the movement of a given quantity of weight with fewer gallons. (2) Higher levels of revenue ton-miles per gallon are attributable, at least in part, to moving more revenue tons in a single car—i.e., increasing the net to gross weight ratio. By either measure (GTMC/G or RTM/G), railroad fuel savings have increased dramatically in the United States since 1980, when the railroads were deregulated—a policy change that has allowed greater operational flexibility and spurred innovations leading to fuel savings.

With a few notable exceptions, most of the comparisons of modal fuel efficiencies have utilized system averages. While insightful, these generalizations do not distinguish among different types of operations, such as railroad unit trains versus individual carload shipments. The average railroad revenue ton-miles per gallon reflects all types of train movements (unit trains, mixed freight trains, and way or local trains), as well as commodities (bulk, neobulk, containers, etc.). As shown later, there are wide disparities in fuel efficiencies within these classes.

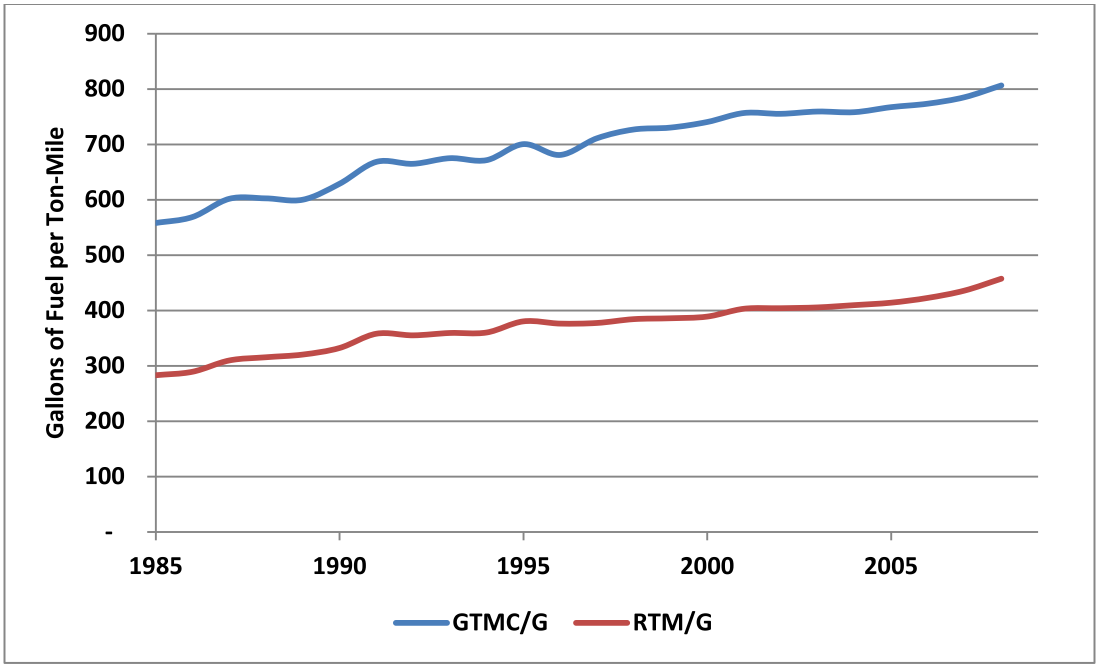

Figure 1.1 Trend in Railroad Fuel Efficiency in the United States

The main objectives of this study are to (1) conduct an analytical evaluation of movements using train resistance and fuel consumptions equations, (2) estimate a railroad fuel efficiency model that describes differences in fuel economy among classes of movements, (3) compare the results of the two methods to each other and to other studies, and (4) compare rail, truck, and waterway fuel efficiencies. Although container shipments are analyzed, the primary focus is on bulk commodity movements. The rest of the report is organized as follows. (1) The most relevant previous studies are reviewed. (2) Resistance equations are used to estimate the horsepower-hour requirements (and gallons of fuel consumed) for specific train movements. (3) Statistical equations are estimated from fuel and operational data reported by railroads to the U.S. Surface Transportation Board (STB) in the R-1 report. (4) The results of the analytical and statistical methods are compared. (5) The relative fuel efficiencies of the primary commodities transported by rail are analyzed using the waybill sample. (6) The energy efficiencies of railroads, trucks, and barges are compared for bulk commodity movements.

2. BRIEF REVIEW OF RAILWAY ENERGY STUDIES

A series of studies were conducted in the 1970s to provide simplified estimation techniques and generalized values for use in state rail planning in the United States (Table 2.1). Although outdated, these factors illustrate two key points. (1) Railroad fuel consumption is greatest for branch line or way train operations (e.g., short hauls). (2) The fuel efficiencies of unit trains are significantly greater than those of other trains. In another study from the same era, the Congressional Budget Office (CBO, 1982) synthesized the results of individual analyses conducted by railroads and concluded that the typical fuel efficiencies were 139 RTM/G for trailer-on-flatcar (TOFC) trains and 375 RTM/G for unit coal trains.

Table 2.1 Fuel Consumption Factors Used in State Rail Planning (1978)

Type of Train Service	Gallons of Diesel Fuel per 1,000 Net Ton Miles	Revenue Ton Miles per Gallon
Short-Haul Rail	24.90	40
Through Train	5.05	198
Unit Train	2.38	420
Trailer-on-Flatcar (TOFC)	5.77	173

Source: Federal Railroad Administration (FRA). Rail Planning Manual, Volume II, 1978.

In 1999, Gervais and Baumel used computer simulations provided by two Class I railroads to analyze unit grain train movements from Boone, IA, to New Orleans and Los Angeles. The hypothetical movements consisted of 100-car trains for two different car load factors: 100 and 110 tons (Table 2.2). A 110-car movement from Sioux City, IA, to Tacoma, WA, was also evaluated in the study. Each trip was simulated with three different types of locomotives.

Table 2.2 Simulated Fuel Efficiency of Unit Grain Trains Movements from Iowa

Origins-Destinations	Simulations	Cars per Train	Loads per Car	RTM/G Range
Boone, IA, to Los Angeles	6	100	100, 110	513-585
Boone, IA, to New Orleans	6	100	100, 110	688-802
Sioux City, IA, to Tacoma	2	110	110	554-664

Source: Gervais and Baumel. *Fuel Consumptions for Shipping Grain Varies by Origin, Destination*. Feedstuffs, Vol. 71(36).

All of the values shown in Table 2.2 reflect the empty movements of covered hopper cars before and/or after the loaded movements. While all movements are energy efficient, there are substantial variations in the results. For the most part, rail shipments from Iowa to New Orleans travel over flat or gentle terrain. As a result, the estimated fuel efficiencies of these movements (688 to 802 RTM/G) are significantly greater than the efficiencies of movements from Iowa to the Pacific Coast, which must cross the Rocky Mountains.

A recent study by ICF International for the Federal Railroad Administration (ICFI, 2009) focused on the comparative efficiencies of rail and truck transportation for a select set of truck-competitive commodities hauled by railroads. The 2009 report is actually an update of a 1991 study by Abacus Technology Corporation. In the ICFI study, truck fuel efficiencies for 23 movements were analyzed using the Physical Emission Rate Estimator (PERE) model developed by the U.S. Environmental Protection Agency. Line-haul railroad fuel consumption was estimated for the movements by “two participating railroads with in-house train simulators” (ICFI, 2009, p 56). The simulations were based on “actual rail routes with their grade profile, curvature, and speed limit changes" (ICFI, 2009, p 57). However, because of data inconsistencies, the effects of speed limit changes and curvature were not reflected in the analysis.

The estimates for the 12 intermodal movements analyzed in the ICFI study are shown in Table 2.3. For the most part, these are heavy double-stack container-on-flatcar (COFC) shipments with a median lading of 49 tons. The estimated fuel efficiencies of the movements range from 226 RTM/G to 512 RTM/G. According to ICFI, these movements are 3.5 to 5.1 times more fuel efficient than comparable truck movements.

Table 2.3 Range of Movement Factors and Fuel Efficiencies of Double-Stack Container Movements

Variable	N	Minimum	Median	Mean	Maximum
Cars per Train	12	27	66	60	85
Distance (miles)	12	294	1,225	1,231	2,232
GTMC	12	4,243	5,629	5,922	8,107
Tare Weight (tons)	12	21	31	32	48
Net Weight (tons)	12	15	49	47	70
GTMC/G	12	523	646	669	849
RTM/G	12	226	379	384	512

ICF International. Comparative Evaluation of Rail and Truck Fuel Efficiency on Competitive Corridors. Published by Federal Railroad Administration, Washington, D.C., 2009

Motorized vehicles and TOFC shipments were also analyzed by ICFI. The estimated fuel efficiencies of the three selected automobile shipments are 156, 157, and 164 RTM/G, while the estimated fuel efficiency of the lone TOFC simulation is 273 RTM/G. The authors conclude that the rail TOFC movement is 3.2 times more efficient than a comparable truck movement, while the automobile shipments are 1.9 to 2.2 times more fuel efficient than highway trailer movements.

Although useful, the ICFI study addresses only one element of freight flows: truck-rail competitive movements in select corridors. Bulk commodity movements are not analyzed. While the truck fuel consumption estimates from the PERE model can be independently verified, the estimates from the in-house train simulations cannot. With the exception of the two previous quotes, no descriptions are provided of the methods used in estimating railroad fuel consumption or the fundamental underlying relationships.

3. ANALYTICAL MODELS OF RAILROAD FUEL CONSUMPTION

Analytical methods of modeling railroad fuel consumption are described in this section of the paper. In section 3.1, forces and resistance equations are introduced. In section 3.2, procedures for estimating locomotive requirements and the energy expended during train movements are outlined. In section 3.3, the procedures are applied to uniform train movements of bulk, neobulk, and container shipments. The usefulness and limitations of the approach are summarized in section 3.4.

3.1 Resistance Forces and Equations

The energy requirements of a freight movement are a function of speed, weight, and resistance, which includes (1) axle (bearing) resistance, (2) wheel (rolling) resistance, (3) flange resistance, (4) air resistance, (5) track resistance, (6) curve resistance, and (7) grade resistance. Rolling resistance results mostly from friction between wheel treads and the running surfaces of rails, while flange resistance results from contacts between wheel flanges and the inside heads of rails. Track resistance is a function of deflection. Collectively, the first five forces are referred to as train resistance (R). Train resistance (which is measured in pounds per ton) refers to rolling, flange, axle, track, and air resistance on level tangent track. Curve resistance represents the additional work needed to overcome wheel-rail friction in curves. Without lubrication, curve resistance is assumed to be 0.8 pounds/ton per degree of curvature (AREMA, 2008). Grade resistance is 20 pounds/ton per percent of grade. A general model of train resistance is

(1) $R = A + BV + CV^2$

Where

R = Train resistance in pounds per ton
V = Train speed or velocity in mph
A = Resistance component that is independent of speed (e.g., axle resistance)
B = Resistance that varies with speed
C = Resistance that varies with the square of speed

Axle resistance is primarily reflected in A, while B reflects flange friction and dynamic flange impacts, which increase with speed. Rolling and track resistances are reflected in A and B. C is a streamlining coefficient that captures many aerodynamic effects such as frontal air pressure, rear drag, the swirling of air in open top cars, and turbulence between cars. Curve and grade resistance are added to the value of R to derive total train resistance (TR) for a specific segment.

Several resistance equations are used in train performance simulators, including the Davis equation, the modified Davis equation, and the Canadian National (CN) equation. These equations are defined in Volume 4, Chapter 16, Section 2.1 of the Manual for Railway Engineering, published by the American Railway Engineering and Maintenance of Way Association (AREMA, 2008). According to this manual, the CN formula "has given reliable results in train performance calculator programs or similar applications" (AREMA, 2008, p. 16-2-4). Therefore, it is used in this paper to analyze a broad mix of equipment types. In the CN formula (which is shown in Equation 2), B is equal to 0.03.

(2) $R = 1.5 + \frac{18N}{W} + 0.03V + \frac{CaV^2}{10000W}$

Where

N = Number of axles
W = Total weight in tons of locomotive or car
a = Cross-sectional frontal area of vehicle in square feet

The streamline coefficient (C) is 24 for a lead freight locomotive. However, it drops to 5.5 for trailing power units and to 5.0 for a mixture of freight cars. The C coefficients and dimensions of the equipment analyzed in this study are shown in Table 3.1. These values can be used to estimate train resistance for unit trains of like cars—i.e., coal, grain, COFC double stack, and multilevel ("autorack") trains. Understandably, empty open top cars generally have the poorest aerodynamics. The aerodynamic resistance of intermodal trains varies with the composition. Uniform double-stack trains are aerodynamically superior to intermodal trains with mixtures of containers and trailers, and to trains with unfilled slots—i.e., mixed double-stack and single container-on-flatcar movements.

Table 3.1 Typical Values of C and Frontal Areas for Freight Equipment

Type of Equipment	C*	Area (Sq. Ft.)
Gondola (loaded)	4.2	105
Gondola (empty)	12.0	105
Covered Hopper	7.1	125
Loaded Intermodal Flatcar (average)	5.0	125
Enclosed Multilevel Flatcar (autorack)	7.1	170
Leading Freight Locomotive	24.0	160

Source: American Railway Engineering and Maintenance of Way Association. Manual for Railway Engineering, 2008. Volume 4, Chapter 16, Section 2.1.
*Streamline coefficient

3.2 Estimating Procedures

3.2.1 Car and Locomotive Resistance Factors

Calculating fuel consumption from train resistance models is a multi-step process. In the initial step, resistance factors for locomotives and freight cars on tangent level track are computed for a specific velocity. Two examples are shown in Table 3.2 — a lead locomotive and a loaded gondola car. Both are traveling at 40 mph. The resistance of the loaded car is approximately 3.7 lb/ton, while the resistance of the empty car is 15.2 lb/ton. The resistance of the locomotive is 6.4 lb/ton. In the final step of the calculation, grade and curve resistance are added to the initial train resistance to arrive at the total resistance for the route. For example, the calculation of a total resistance factor (TR) for a 5-degree curve is illustrated in Table 3.2.

Figure 3.1 illustrates the relationships between velocity (in miles per hour) and resistance (in pounds per ton) for empty gondola cars, loaded gondola cars, and double-stack flatcars. The resistance factor for a loaded gondola car increases from 2.95 lb/ton at 25 mph to 4.92 lb/ton at 60 mph. Over the same interval, the resistance of an empty gondola car increases from 9.1 to 27.3 lb/ton, while the resistance of a double-stack car increases from 3.8 lb/ton to 7.5 lb/ton.

Table 3.2 Example of Train Resistance Factors for Lead Locomotive and Gondola Car

Input/Result	Locomotive	Loaded Car	Empty Car
W (tons)	195	143	21.9
N (axles)	6	4	4
a (cross-section frontal area)	160	105	105
V (velocity in mph)	40	40	40
B	0.03	0.03	0.03
C	24	4.2	12
Resistance (R from Equation 2)	6.4	3.7	15.2
Degree of curvature	5	5	5
Curve factor (lb/ton)	0.8	0.8	0.8
Curve resistance per ton	4	4	4
Total resistance (TR)	10.4	7.7	19.2

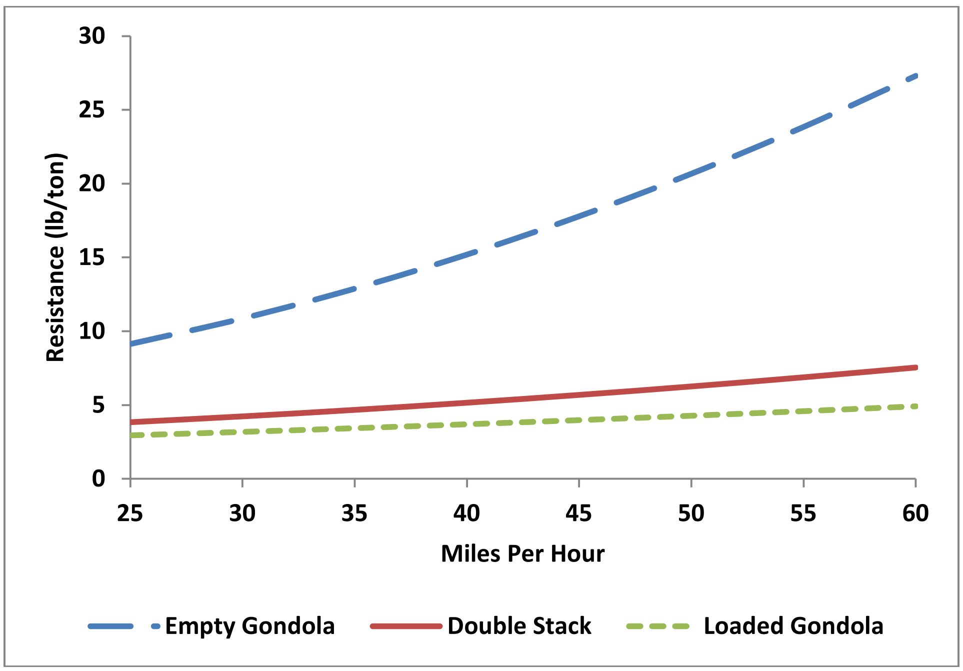

Figure 3.1 Variations in Resistance with Velocity for Select Car Movements

3.2.2 Locomotive Requirements

Once the resistance factors are calculated, the number of locomotives required for the movement is estimated. There are six major steps in this process. (1) The resistance factors for the freight car and locomotive at the fastest (target) speed are determined. (2) The tractive effort of the locomotive (i.e., its propulsive force in pounds) is computed for the same speed as 308 × horsepower / speed (in miles per hour). However, the locomotive's tractive effort is constrained to the adhesion limit. (3) The tractive effort required to overcome the locomotive's own resistance is computed. (4) From this result, the drawbar pull of the locomotive is estimated—i.e., the tractive effort available to move the train after the tractive effort needed to move the weight of locomotive is considered. (5) Using the drawbar pull and the resistance factor of the freight car, the number of trailing tons that can be moved by the locomotive (e.g., its tonnage rating) is computed. (6) In the final step, the tonnage rating is divided into the trailing tons of the train (e.g., the total weight of all freight cars) to arrive at the number of locomotives needed for the speed, equivalent grade, and train composition.

The calculations needed to determine the locomotive requirements of a train of loaded 143-ton gondola cars are illustrated in Table 6 for a 0.25% grade and a velocity of 25 mph. The illustrations are based a locomotive with 4,400 horsepower (hp) and 82% efficiency. The total resistance of the freight car (in pounds per ton) is shown in line 5 of Table 3.3, while the total resistance of the locomotive (in pounds) is calculated in lines 6-10. The tractive effort of the locomotive is computed in line 12 as 308 × 4400 / miles per hour (mph). The drawbar pull of the locomotive is shown in line 13, while the tonnage rating is computed in line 14. In this example, three 4,400-hp locomotive units will be needed if the target speed on the grade is 25 mph.

Table 3.3 Illustrations of Locomotive Tonnage Ratings and Power Requirements

Line	Factor	Denomination/ Source	Input or Computed Value
1	Target Speed	Mph	25
2	Equivalent Grade	Percent	0.25
	Freight Car Resistance		
3	Rolling Resistance	lb/ton	2.95
4	Grade Resistance / Ton	20*L2	5
5	Total Resistance/ Ton	L3+L4	7.95
	Locomotive Resistance		
6	Rolling Resistance	lb/ton	4.03
7	Locomotive Weight	Tons	195
8	Locomotive Rolling Resistance	L6*L7	786.8
9	Locomotive Grade Resistance	20*L2*L7	975
10	Total Locomotive Resistance	L8+L9	1,762
11	Locomotive Horsepower	per unit	4,400
12	Tractive Effort	308*L11/L1	54,208
13	Locomotive Drawbar Force	L12-L10	52,446
14	Tonnage Rating per Unit	L13/L5	6,600
15	Car Weight	Tons	143
16	Cars per Train	Units	110
17	Trailing Tons	L15*L16	15,730
18	Locomotives Units	Ceiling(L17/L14)	3

3.2.3 Total Train Resistance

Once the locomotive requirements are estimated, the resistance of the entire train (including the locomotives) is calculated. First, the total locomotive resistance is computed for the leading and trailing units. This calculation considers the fact that the aerodynamic resistance of the trailing units is less than the lead. Once computed, locomotive resistance is then added to the total resistance of all freight cars to derive the total resistance for the train, including grade and curve resistance. The next step is to determine the energy required to overcome total resistance, and convert these requirements to gallons of fuel. Initially, railroad energy requirements are expressed in horsepower-hours (hp-hr).

3.2.4 Horsepower-Hours and Gallons of Fuel Consumed

The energy required to move each ton of the loaded gondola car described in Table 3.2 one mile over straight level track at 40 mph is 3.7 lb × 5,280 ft / 1.98E6 ft-lb = .01 hp-hr per ton-mile. In this expression, 1.98 million ft-lb is a measure of the work performed during a horsepower-hour (i.e., 33,000 ft-lb per minute times 60 minutes). Continuing this example, it requires 1.41 hp-hr to move a loaded gondola car one mile (0.01 × 143) and 155 hp-hr to move a train of 110 gondola cars one mile. The hp-hr needed to overcome grade and curve resistance are derived in a similar manner. In the final step of the calculation, hp-hr is converted to gallons of fuel using conversion factors published by the U.S. Environmental Protection Agency (EPA, 2009). These conversion factors are 20.8, 18.2, and 15.2 horsepower-hours per gallon for large line-haul locomotives, small line-haul locomotives, and switching locomotives, respectively.

3.3 Uniform Train Simulations

The methods described previously are used to estimate gallons of fuel consumed and RTM/G for uniform trains of like cars. The car weights used in the analysis are shown in Table 3.4. The first scenario consists of a coal gondola car with an empty (tare) weight of 23 tons and a gross weight of 139 tons. The second scenario involves a grain hopper car with a gross weight of 138 tons and a tare weight of 31 tons. The third scenario reflects a double-stack COFC movement of articulated cars. The weights shown in Table 3.4 correspond to one unit of an articulated car (e.g., a well). The intermodal train consists of 100 such units. The gross weight of the intermodal flatcar includes the weights of two marine containers (approximately 9 tons). Each container is assumed to be loaded with manufactured goods weighing 12.5 tons per container. This load factor is representative of commodities such as computers and electronic components, which have densities of 16 to 20 lb/ft^3. It is also the average from the waybill sample (STB, 2008).

Table 3.4 Equipment Types and Weights Used in Uniform Train Simulations

Equipment Type	Tare	Net	Gross
Coal Gondola Cars*	23	116	139
Covered Hopper Cars*	31	107	138
Intermodal (COFC) Flatcars*	31	25	56
Multi-Level Flatcars*	53	20	73

* Values computed from the 2008 waybill sample (STB, 2008)

In these scenarios, the railcars are assumed to travel the average number of empty miles for the car type. For example, intermodal flatcars average 13% empty miles, while the empty-loaded ratio of a covered hopper car is approximately 1.0 (STB, 2009). The fuel consumed during the empty movement is reflected in each calculation. The analysis entails six major steps: (1) determine the number of locomotives needed for the train's cruising speed, (2) construct a speed profile based on track speed limits, (3) estimate the fuel consumed at each steady-state speed corresponding to a speed limit, (4) estimate the additional fuel consumed by accelerating from limit to limit within the profile, (5) estimate the fuel consumed during switching at origin and destination, and (6) include fuel consumed during idling or waiting time as a result of traffic control delays and/or congestion. A set of observed train speeds serves as a starting point for the analysis.

3.3.1 Average Train Speeds

Class I railroads publish weekly performance measures on their websites, including the average speeds of various types of trains. The average speeds for a 95-week period starting in January of 2009 and ending in May of 2011 are shown in Figure 3.2. These speeds (which represent the average of all seven Class I railroads) reflect train priorities based on commodity values. The average speeds for container and auto trains are the highest, while coal trains are the slowest.

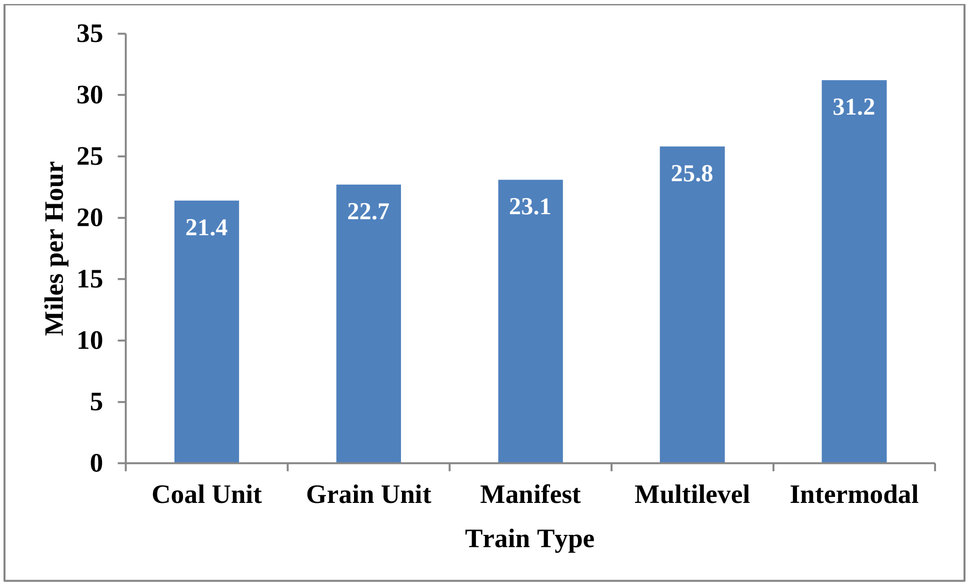

Figure 3.2 Average Train Speeds: Jan. 2009-May 2011

3.3.2 Train Speed Profile

While average speeds are insightful, train resistance varies in a non-linear manner with speed (Equation 2). For this reason, deviations in fuel consumption attributable to speed variations are important. Although the speed limits of individual track segments are not published in a central directory, the grade crossing inventory (which includes 65,535 public crossings) lists the maximum timetable speed of the track segment on which the crossing is located. While train speeds through grade crossings may be restricted to less than the timetable speed, the inventory provides a cross-section of railroad speed limits throughout the United States. According to the inventory, only 3% of track segments have timetable speeds of 80 mph or greater. For trains to travel at these speeds, an advanced track-train communication system must be installed that allows distant signals to be displayed in the cabs of locomotives.

Because the intent of this analysis is to focus on movements that reflect a large percentage of the train population, a speed profile is developed that excludes segments with speed limits > 79 mph. As shown in Figure 3.3, 14.6% of the remaining segments have speed limits of 79 mph. Other important limits are evident in the figure. The peaks centered at 10, 25, 40, and 60 mph denote the maximum speeds of FRA track classes 1-4, respectively. Similarly, the peak at 49 mph is a function of regulation. For trains to operate at speeds of 50 mph or faster, the line must be equipped with a block signal system.

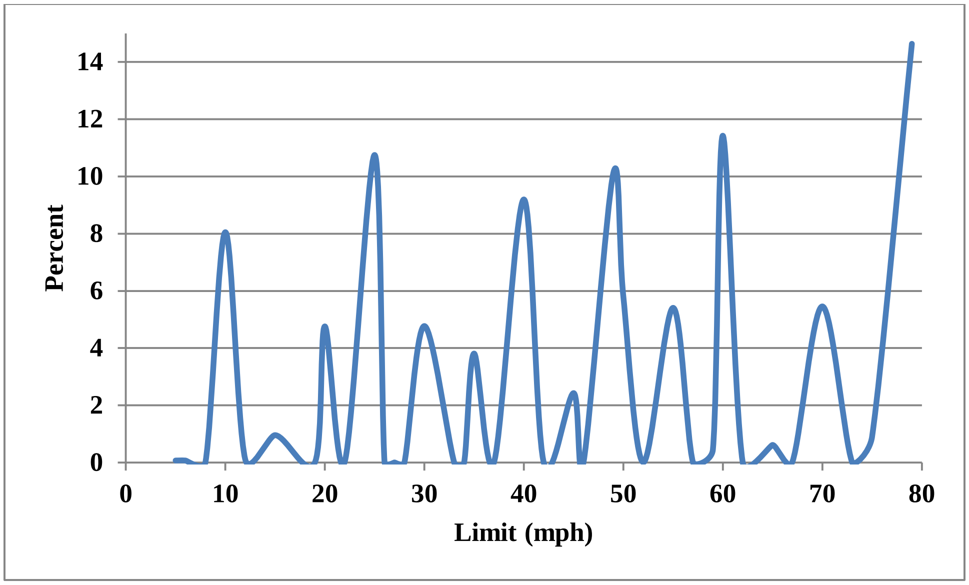

Figure 3.3 Profile of Railroad Speed Limits in the United States
Computed from the National Grade Crossing Inventory by including segments with at least one main track and one through train per day with a maximum timetable speed ≤ 79 mph

For reasons illustrated in Figure 3.1, freight trains may be restricted to speeds beneath the limit when incremental locomotive and fuel requirements become prohibitive. This is especially true of heavy bulk trains of low-value commodities, for which additional speeds are relatively unimportant. To reflect cost-effective operations, maximum practical cruising speeds are estimated that result in realistic assignments of locomotive power (Table 3.5). Increasing these speeds significantly will result in the allocation of additional locomotives to the trains.

3.3.3 Fuel Consumed During Acceleration

Train acceleration is a function of horsepower, tractive effort, and train resistance. The additional tractive effort required to accelerate a train from an initial velocity (V_i) to a final or new velocity (V_f) is shown in Equation 3 (Hay, 1980).

$$(3) \quad F_a = 95.6W \frac{V_f - V_i}{t}$$

Where

W= Weight of train in tons
V= Velocity in miles per hour (mph)
A= Rate of acceleration (mph/sec)
F_a = Tractive effort in pounds required to accelerate from the lower to higher velocity

Table 3.5 Cruising Speeds for Unit Trains on Flat Terrain Based on Locomotive Requirements

Train	Top Cruising Speed (mph)	Number of 4,400-hp Locomotives
Coal gondola (empty) – 120 cars	45	2
Coal gondola (loaded) – 120 cars	45	3
Covered hopper (empty) – 110 cars	47	2
Covered hopper (loaded) – 110 cars	47	3
Double-stack COFC (empty) – 100 cars	75	2
Double-stack COFC (loaded) – 100 cars	70	4
Multilevel autorack (empty) – 50 cars	45	1
Multilevel autorack (loaded) – 50 cars	60	2

From Equation 3, it can be seen that 95.6 pounds of force are required to accelerate one ton one mile per hour per second. Since $V_f - V_i = \Delta V$, and $\Delta V/t$ is the rate of acceleration (A) in mph/sec, Equation 3 can be reduced to $95.6WA$. It follows from Equation 3 that $A = F_a/95.6W$. However, this formula is of no practical use because train resistance varies with velocity. For this reason, acceleration cannot be represented as a constant. Instead, the distance and time required to accelerate from V_i to V_f must be calculated in an iterative (computational) manner for small mile-per-hour intervals (e.g., 0.25 mph), and the fuel consumed during each acceleration interval must be summed to arrive at the total fuel consumed during the acceleration event. A speed-distance curve for a 110-car grain train calculated in this manner is depicted in Figure 3.4.

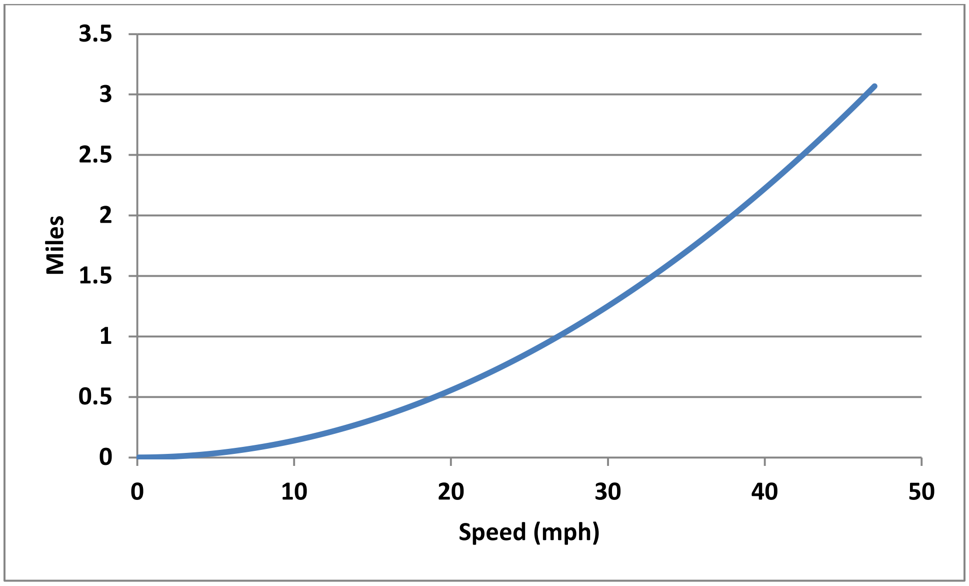

Figure 3.4 Acceleration Curve for Unit Grain Train

3.3.4 Origin-Destination Switching

According to the Surface Transportation Board (2009) the average industry switching time in the United States ranges from 7.82 minutes per car in the east to 5.24 minutes per car in the west. However, average switching times are much lower for unit train and large multicar shipments. Because a true unit train is switched as a single block, the switching time per car is 25% of the system average (STB 2009). Because large multicar blocks necessitate fewer switching moves or cuts, the average multicar switching time is 50% of the system average (STB 2009).

Container and automobile shipments are trainloads rather than unit trains. A trainload consists of several blocks of cars that are integrated into a single train at a marshaling or classification yard near the origin (e.g., a port or automobile manufacturing plant). At the marshaling yard, several blocks of cars are switched individually as the train is assembled. As this description suggests, the switching efficiencies of container and automobile shipments are more consistent with multicar operations than with unit-train loading. Nevertheless, once assembled, the container and auto trains move from origin to destination with little or no switching en route.

With the exception of intermodal trains, the spotted/pulled ratio is 2.0—i.e., the switching of a loaded car necessitates the switching of an empty car before or after. Because switching operations occur in the lower throttle positions (e.g., 2-5), a weighted fuel consumption rate of 35 gallons per hour is used. Based on this factor, the estimated gallons of fuel consumed for each train are shown in Table 3.6, using the greater of the two regional switching averages.

Table 3.6 Estimated Fuel Consumption at Origin (O) and Destination (D) for Unit Trains

			Train Type			
Line	Input or Calculated Value	Source	Grain	Coal	COFC	Auto
1	Average Minutes per Car	STB	7.82	7.82	7.82	7.82
2	Percent of Avg. Switching Time	STB	0.25	0.25	0.50	0.50
3	Adjusted Minutes per Car	L.1 x L.2	1.955	1.955	3.91	3.91
4	Cars per Train	Assumed	110	120	100	75
5	Hours per Switch: O or D	(L.3 x L.4)/60	3.6	3.9	6.5	4.9
6	Gallons per Hour	Assumed	35	35	35	35
7	Gallons per Switch: O or D	L.5 x L.6	125.4	136.9	228.1	171.1
8	Spotted/Pulled Ratio	STB	2	2	1	2
9	Gallons Consumed: O and D	L.7 x L.8 x 2	501.8	547.4	456.2	684.3

3.3.5 Average Trip Distance and Cycle Length

The origin and destination fuel estimates shown in Table 3.6 are allocated to shipments based on the average loaded trip distance for each train. These values (which are shown in column 2 of Table 3.7) are computed from the waybill sample (STB 2008). Fuel consumption during acceleration is allocated to shipments based on an assumed cycle distance (column 3, Table 3.7). Each cycle reflects acceleration of a train through the speed profile from 0 mph to cruising speed, and deceleration from cruising speed to 0 mph again.

Table 3.7 Average and Train Cycle Distances

Train	Average Shipment Distance (miles)[1]	Cycle Length (miles)[2]
Coal	743	50
Grain	1,013	75
Containers	1,007	250
Autos	911	150

[1] Computed from 2008 waybill sample
[2] Based on approximate distance between rail yards and train priorities between yards

The basis for the cycle is the approximate distance between rail yards or classification points—e.g., 250 miles. Each train must either slow to pass through a classification yard at reduced speed, stop for fuel, or stop to change crews. In between yards, lower-order trains are diverted to side tracks to allow trains with higher priorities to pass. The typical order of priorities is (1) intermodal and passenger, (2) auto, (3) grain, and (4) coal. In addition, manifest trains of mixed freight may take priority over coal trains. The cycle lengths of lower-order trains reflect the combined probability that a train will be bumped by higher-echelon trains. For example, a coal train may be diverted to a side track by a container, passenger, auto, or manifest train.

3.3.6 Estimated Speeds and Idle Time

The train speeds estimated using the methods and assumptions described above are shown in column 3 of Table 3.8. After rounding, the predicted average speed for intermodal trains matches the observed average speed of 31.2 mph (column 2). However, the predicted speeds of other trains are significantly greater than the observed speeds. This is because time spent waiting on side tracks while other trains pass is not reflected in the predicted speeds. On high-traffic lines, a lower-echelon train may be delayed for some time while higher-priority trains move through the subdivision. For auto, grain, and coal trains, the differences between the predicted and observed speeds are assumed to reflect waiting times due to traffic control delays. Fuel consumed during these intervals is estimated using an idling rate of 4 gallons per hour.

Table 3.8 Predicted and Observed Train Speeds in Miles per Hour in Flat Terrain

Train Type	Observed Average Speed	Predicted Average Speed
Coal Unit	21.4	25.6
Grain Unit	22.7	26.9
Intermodal	31.2	31.2
Auto	25.8	29.5

3.3.7 Fuel Consumed During Drayage

Automobile and container shipments often require drayage at origin and/or destination. For example, an imported container that terminates in a Chicago rail yard is delivered by truck to its final destination. Similarly, automobiles are drayed from a destination rail yard to dealers in the surrounding area. Because of these linked movements, drayage fuel requirements are estimated for automobile and containers shipments.

In the drayage analysis, each double-stack flatcar is equivalent to two individual trucks. Additional empty movements are assigned to COFC shipments to allow for the return of empty containers to the rail yard or port area. Drayage trucks are assumed to operate in shuttle service, returning to the yard for the next load until the train is empty. However, trucks may occasionally backhaul containers from industry locations to yards. In ports with on-dock rail access, origin or destination drayage may be unnecessary for import or export containers. Given these considerations, average drayage hauls of 10 and 20 miles are assumed for automobile and container shipments, respectively. Drayage is assumed at both origin and destination.

The assumptions and calculations in the drayage analysis are shown in Table 3.9. In the final calculation, 484 and 1,935 gallons of drayage fuel are added to the total energy requirements of automobile and container trains, respectively. However, no such adjustments are made for coal shipments, because loading and unloading typically occur at or near the mine and utility. Similarly, the fuel consumed in moving grain from farms to elevators is not considered because the farm-to-elevator movement occurs regardless of whether the grain moves from the elevator to market by rail, truck, or waterway.

Table 3.9 Calculation of Drayage Fuel for Automobile and Container Trains

			Train	
Line	Input or Calculated Value	Source	Auto	Container
1	Drayage Events per Loaded Move (Orig. & Dest.)	Assumed	2	2
2	Ratio: Total to Loaded Truck Movements	Assumed	2	1.5
3	Truck/Railcar Ratio	Assumed	1.5	2
4	Empty & Loaded Truck Movements per Railcar	L.1 × L.2 × L.3	6	6
5	Average Distance of Truck Movement (Mi.)	Assumed	10	20
6	Truck Miles per Railcar	L.4 × L.5	60	120
7	Average Truck Fuel Efficiency (Mi. per Gallon)	Assumed	6.2	6.2
8	Gallons of Fuel per Railcar	1/L.7 × L.6	9.7	19.4
9	Cars per Train	Assumed	50	100
10	Drayage Fuel per Train (Gallons)	L.8 × L.9	484	1,935

3.3.8 Grade Profile

Railroad grades vary widely and there is no public file containing the gradients of line segments in the United States. However, an elevation profile of the Pacific Northwest (PNW) is used to illustrate the effects of grades on fuel consumption (Figure 3.5). In this profile, trains moving from Seattle to the interior must cross two mountain ranges (the Cascade and the Rocky Mountain ranges). The grades on these routes are 2.2% and 1.8% respectively, making them severe gradients in terms of railway transportation. Because the detailed route profiles are unknown, a simplified method is used to analyze incremental energy requirements.

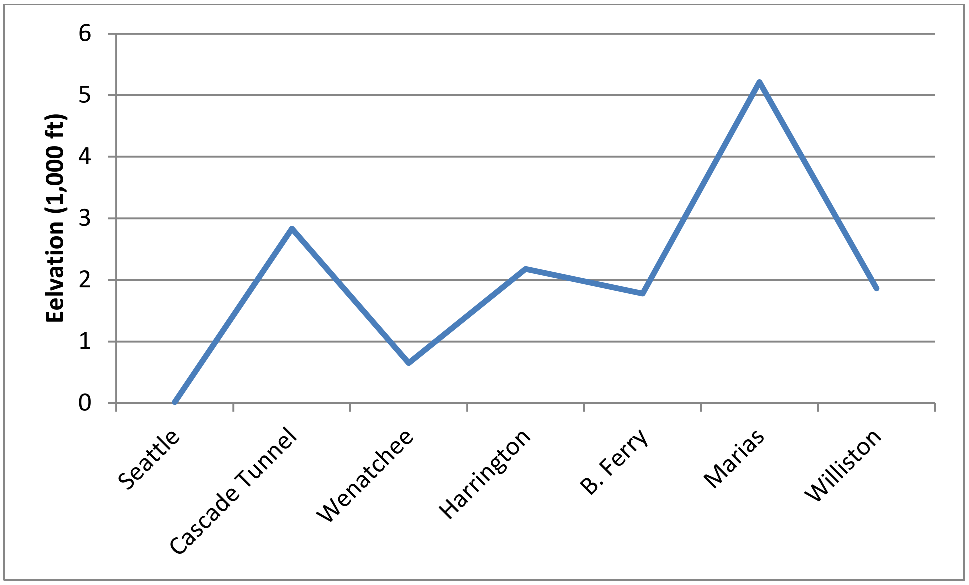

Figure 3.5 Elevation Profile in the Pacific Northwest Region of the United States

It takes 200,000 ft-lb of work to lift one ton 100 ft. As noted earlier, 1.98 million ft-lb = 1 horsepower-hour. Thus, 0.10 hp-hr are needed to lift one ton 100 ft in elevation. These incremental energy requirements are independent of speed and track profile.

A train traveling from Seattle to the interior will rise approximately 2,800 ft in elevation by the time it reaches the Cascade Tunnel. From there, it drops to an elevation of roughly 650 ft at Wenatchee, WA. However, the gradient is so steep that most or all of the potential energy of the train at the top is lost when braking down the mountain, dissipated as friction heat. From Wenatchee, the train begins to rise again as it approaches the Rocky Mountains. After a beneficial negative grade between Harrington, WA, and Bonner's Ferry, ID, (where some of expended energy is recovered), the train begins to rise again and climbs an additional 3,433 ft to the crest of Marias Pass in Montana. On the eastbound route, the total rise in train elevation with no energy recovery on the downhill gradients is approximately 6,400 ft. However, the route is kinder to westbound movements because of the beneficial negative grade from Harrington to Wenatchee. In this case, the total rise in train elevation without offsetting recoveries is 4,400 ft.

Loaded coal and grain trains are assumed to move west along this route, while empty trains travel east. The opposite flow is assumed for 75% of the auto and container trains, which are assumed to represent imports via Seattle which are destined for interior locations. Based on these assumptions, the incremental fuel consumption due to changes in elevation along this route are 4,704; 4,545; 1,892; and 1,407 gallons for coal, grain, COFC, and auto trains, respectively.

3.3.9 Predicted Results

Based on the methods and assumptions previously described, a uniform coal train is expected to achieve 976 RTM/G on flat terrain (Column 2 of Table 3.10), while a grain train generates 862 RTM/G. In comparison, an intermodal train yields 311 RTM/G. A train of automobile transporters experiences the worst fuel economy, realizing only 177 RTM/G on flat terrain.

Table 3.10 Predicted RTM/G of Uniform Train Movements

Train	Flat Terrain	PNW Route Profile
Auto	177	139
Intermodal	311	252
Grain Unit	862	649
Coal Unit	976	676

As shown in column 3 of Table 3.10, the same coal train is expected to achieve 676 RTM/G on the PNW route, after the additional fuel needed to overcome lifting resistance is added to the baseline fuel consumption for the trip. Similar estimates are shown for auto, intermodal, and grain trains.

3.4 Summary and Limitations of Analytical Method

Unlike previous studies, the methods used in this analysis have been explicitly documented and variations in speed limits and origin-destination switching have been considered. However, there are limitations to the analysis. (1) The effects of track curvature on speeds and resistance are not considered. In territories with substantial curves, trains may be unable to attain the same speeds as on tangent track. Alternatively, maintaining the same speeds in curved sections will result in additional fuel consumption. Either way, an effect is missing. (2) While realistic, the PNW route profile is one of many in the United States and may overstate or understate the energy requirements of other routes. (3) The effects of interim grades and track profiles are not considered, including train momentum and velocity head. (4) Simplified assumptions are made regarding the percentages of potential energy lost to braking on downhill grades.

While the analytical method is useful, it cannot practicably be used to develop a comprehensive picture of railroad fuel efficiency via selective application. Moreover, estimates generated from this method are not based on observed data. Rather, they are generated from deterministic resistance equations which, themselves, are generalizations of a vast number of contextual and operational factors that may affect the resistance of a train. For these reasons, an alternative method is pursued.

4. STATISTICAL MODEL OF RAILROAD FUEL CONSUMPTION

A regression model estimating railroad fuel consumption is described in this part of the paper and reflects differences in train services and terminal operations. The model is estimated from 24 years of data derived from R-1 reports submitted by Class I railroads to the U.S. Surface Transportation Board from 1985 through 2008. The database includes the reported gallons of fuel consumed for freight purposes by each Class I railroad, as well as the gross ton-miles and revenue ton-miles of operations. While many railroad mergers have occurred during this period, railroads can be organized into three geographic regions that have remained constant over time: East, Central, and West. Each railroad in the database is assigned to one of these regions (Table 4.1).

Table 4.1 Class I Railroads and Geographic Regions in the United States

Railroad	Code	Region
Atchison, Topeka, & Santa Fe	ATSF	West
Burlington Northern	BN	West
Burlington Northern-Santa Fe	BNSF	West
Chicago & Northwestern	CNW	West
Conrail	CR	East
CSX Transportation	CSX	East
Grand Trunk Corporation	GTC	Central
Grand Trunk Western	GTW	Central
Illinois Central Gulf	ICG	Central
Kansas City Southern	KCS	Central
Norfolk Southern	NS	East
Soo Line	SOO	Central
Southern Pacific	SP	West
Union Pacific	UP	West

While revenue ton-miles are reported for each railroad, no distinctions are made among types of service. However, gross ton-miles of cars and contents are reported by train type. As noted earlier, GTMC include the revenue ton-miles of cargo, as well as the tare ton-miles of the cars, trailers, and containers needed to transport the cargo. The overall relationship between GTMC and fuel consumption is illustrated in Figure 4.1, in which each square represents an individual railroad and year. As the trend line suggests, there is a strong linear relationship between fuel consumption and GTMC. Indeed, a simple regression of gallons of fuel against GTMC yields an R-Square of 0.986.

4.1 Model Formulation

4.1.1 Main Explanatory Variables

Generally, railroads operate three types of trains: way, through, and unit. Single cars usually travel in way trains at origins and/or destinations. Way trains operate primarily between branch-line stations and railroad yards, stopping frequently to drop off and pick up cars en route. Through trains typically move from yard to yard, performing only limited switching en route. According to the STB (2010), unit trains are characterized by “shuttle-type service in equipment (railroad or privately owned), dedicated to such service, moving between origin and destination.” As the definition suggests, unit trains do not require intermediate yard switching. Moreover, as detailed in 3.3.4, unit train origin-destination switching is very efficient.

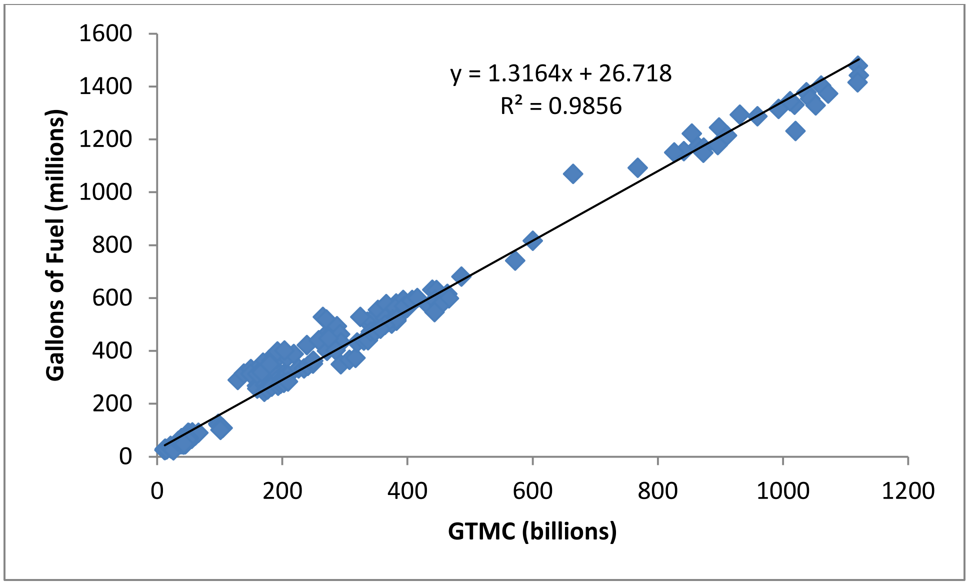

Figure 4.1 Plot of Gallons of Fuel versus Gross Ton-Miles of Cars and Contents

In 2008, way train activity comprised less than 3% of the gross ton-miles of cars and contents in the United States, while through trains accounted for approximately 55% of GTMC. The movement of a car in a way train typically precedes or follows a movement in a through train. Because way and through train movements are linked and the percentage of way train GTMC is very small, these two categories are combined to form "non-unit train" GTMC.

A non-unit train movement may consist of individual carloads, blocks of carloads moving to the same destination, or trainloads. The distinguishing characteristic is that some marshaling or gathering of cars is required at origin and/or destination, where car blocks may arrive or depart in way trains, traveling to or from nearby industry locations. In port areas, cars loaded with import or export goods may be shuttled between docks and inland classification yards. According to the STB (2009), the typical way-train trip is 14 miles in the western United States and 25 miles in the east.

4.1.2 Model Statement

Based on train definitions, a multiple regression model is formulated in which the dependent variable is gallons of fuel and the primary independent variables are unit train and non-unit train GTMC. The general form of the model is *GAL* = f(*UGTMC*, *NGTMC*, *T*, *REG*). Each variable is described in Table 4.2, along with its source—i.e., the schedule of the R-1 report from which the measure is derived. The specific form of the model is

$$(4)\quad GAL_{ij} = b_0 + b_1 UGTMC_{ij} + b_2 NGTMC_{ij} + b_3 T_j + b_4 REG_1 + b_5 REG_2 + e_{ij}$$

Table 4.2 Variables in Railroad Fuel Regression Model

Variable	Description	Source	Type
GAL	Gallons of fuel consumed in freight service during the year	R-1, 750	Response
UGTMC	Thousands of gross ton-miles of cars and contents moved in unit trains	R-1, 755	Structural
NGTMC	Thousands of gross ton-miles of cars and contents moved in non-unit trains	R-1, 755	Structural
T	Time in years before 2008 (2008 = 0)	N/A	Control
REG	A set of regional variables {1, 2, 3}	N/A	Indicator

In Equation 4, *i* denotes the region, *j* the year, and e_{ij} the error term. The predicted response is gallons of fuel consumed in region *i* during year *j*, where *j* ranges from 1 to 24 and *i* from 1 to 3. There are three possible combinations of values for REG_1 and REG_2: REG_1=1 and REG_2=0, REG_1=0 and REG_2=1, and REG_1=0 and REG_2=0. The last combination defines Region 3.

Fuel consumed in freight service includes both train and yard fuel. Thus, the dependent variable reflects three distinct operational components: (1) fuel consumed in train running or line-haul operations, (2) fuel consumed in yard switching, and (3) fuel consumed in train switching. The latter activity occurs when cars are switched at industries or tracks located outside of classification yards. While all trains perform some switching, most origin-destination switches are attributable to way and unit trains. Way trains switch cars at dispersed industries in small blocks, often less than five cars at a time. On the other hand, unit trains switch cars at one origin and destination, usually in large quantities—e.g., 100 cars or more. Because unit trains are characterized by very efficient origin-destination switching and little or no yard switching, the variable UGTMC is expected to have a smaller positive coefficient than NGTMC.

4.1.3 Time Variable

Time (T) represents the number of years prior to 2008. For example, t=1 for 2007 and 23 for 1985. This variable is important because the relationship between fuel consumption and GTMC is expected to change over time, as railroads purchase more fuel efficient locomotives and adopt energy saving practices. Because of T's inverse relationship to time, the variable is expected to have a positive sign. Because t=0 in 2008, it vanishes from the equation when values are predicted for that year.

4.1.4 Regional Variables

Each region in the R-1 database is represented by an indicator variable—e.g., Region 3. When the observation is for the western region, Region 3 equals 1. Otherwise, Region 3 equals zero. To avoid singularity, only $n - 1$ indicator variables are included in the model. The signs and magnitudes of the variables are interpreted in relation to the excluded effect, which is subsumed in the intercept. In a linear model, indicator variables shift the intercept of the regression, creating separate predictive equations for each level or classification.

The regional variables capture differences in terrain, geography, and networks that affect fuel economy. Railroads in the central or plains region do not encounter mountains. Operating primarily in gentle terrain, these railroads exhibit a decidedly north-south orientation. Heavy cars (such as grain traffic) move south via negative gradients to the Gulf. This pattern (of loads moving downgrade and empties moving upgrade) enhances fuel economy. In contrast, western railroads (which have east-west orientations) encounter substantial grades while crossing the Rocky Mountains and coastal ranges. Eastern railroads operate in the Appalachian Mountains. These geographic differences are reflected in the observed values of GTMC per gallon (GTMC/G) listed in Table 4.3.

Table 4.3 GTMC/G and RTM/G by Region in 2008

Region	GTMC/G	RTM/G
East	779	431
Central	908	501
West	809	464

4.2 Regression Results

4.2.1 Key Model Properties

The model has 71 total and 66 error degrees of freedom (DF), which should be sufficient to realize large sample properties (Table 4.4). The R-square of 0.998 suggests that the linear model explains almost all of the variation in fuel consumption. The coefficient of variation of 3.45% (which is computed as the standard error of the regression divided by the mean of the dependent variable [gallons of fuel] multiplied by 100) suggests that the model provides a very precise fit.

Table 4.4 Key Model Properties and Indicators

Observations	72
Error Degrees of Freedom	66
F Value	6,736
Prob. > F	<.0001
Coefficient of Variation	3.45
R-Square	0.9980
Adjusted R-Square	0.9979

4.2.2 Parameter Estimates and Standard Errors

The estimates from the fuel model and their corresponding standard errors are shown in Table 4.5. As shown in column 3, the standard errors of the variables are small in relation to the estimated values. This is a desirable outcome. However, the standard errors may be suspect unless the variance of the regression is consistent over the entire range of the dependent variable.

Table 4.5 Parameter Estimates from Railroad Fuel Model

Variable	Parameter Estimate	Standard Error	t Value	Prob. > |t|	Heteroscedasticity Consistent Standard Error	t Value	Prob. > |t|
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8
Intercept	713465017	58015819	12.30	<.0001	67216343	10.61	<.0001
UGTMC	0.74449	0.09710	7.67	<.0001	0.10696	6.96	<.0001
NGTMC	1.10767	0.09849	11.25	<.0001	0.11788	9.40	<.0001
T	3339195	1071017	3.12	0.0027	581239	5.74	<.0001
REG1	-476171943	29227568	-16.29	<.0001	29754620	-16.00	<.0001
REG2	-701468788	46887449	-14.96	<.0001	57404842	-12.22	<.0001

The issue of non-constant variance or heteroscedasticity is common in regression analysis. In most instances, the form of heteroscedasticity is unknown and cannot be ascertained from the data. In such cases, the variance is said to be inconsistent, meaning it is not a function of an independent variable and does not increase or decrease monotonically. The regression coefficients (i.e., the parameter estimates) are not biased by heteroscedasticity. However, there are two potential issues. (1) Regression coefficients estimated from sample data may no longer be efficient (e.g., minimum variance estimators). (2) The standard errors may be affected. As a result, hypothesis tests may be unreliable.

The first issue is not really a concern for this study because the parameters are estimated from population data. Nevertheless, as recommended by Hayes and Cai (2007), heteroscedasticity-consistent errors are used to assess the potential effects of inconsistent variance. These standard errors shown in column 6 of Table 4.5) are computed under the assumption that the variance is not constant. A comparison of the t values in columns 4 and 7 (which are computed by dividing the parameter estimates in column 2 by the appropriate standard errors) shows only modest differences, suggesting only mild inconsistency. None of the hypothesis tests are affected.

4.2.3 Probability Values and Inferences

In this study, the R-1 database constitutes the population of Class I railroads in the United States. Because population data are available, sampling variability is not an issue. However, as railroad revenues change, carriers may rise above (or fall below) the Class I revenue threshold, altering the population. For this reason, it is beneficial to envision the R-1 database as a large sample of Class I railroads that do (or could) exist. This visualization allows hypothesis tests that provide intuitive insights regarding the statistical significance of effects.

For each variable, the null hypothesis is that the partial effect attributable to the variable is statistically insignificant. For indicator variables, this means that the intercept shift attributable to the variable is not significantly different from zero. For quantitative variables, the null hypothesis is that the partial slope coefficients are not significantly different from zero. The probabilities (or p values) associated with the t statistics in column 8 of Table 4.5 are all highly significant (i.e., values of less than .0001), indicating less than a 1 in 10,000 chance of observing t values as large as those observed. The main predicted effects are (1) after controlling for time and region, an increase of 1,000 unit-train GTMC results in the consumption of 0.75 gallons of fuel, and (2) an additional 1,000 GTMC in other (non-unit) trains consumes 1.11 gallons of fuel (ceteris paribus).

The signs of the eastern and central regions are negative in relation to the west, which is characterized by challenging grades and rough terrain. The parameter estimate of time is positive, meaning that the fuel needed to transport a given quantity of gross ton-miles is less today than in previous years. There are several reasons for this trend. (1) The computerization of locomotives has resulted in the optimization of throttle settings, traction motor performance, and slip control. (2) The practice of distributed power (i.e., placing remotely controlled locomotive units at strategic locations throughout the train) has reduced slack. (3) The manufacture of higher horsepower units has reduced the number of locomotives that must be used to haul a given tonnage. With fewer locomotive axles pulling an equivalent weight, the axle resistance per ton is reduced, as well as resistance posed by the locomotives' total weights. (4) Emission control standards have encouraged manufacturers to produce more fuel efficient and cleaner locomotives.

4.2.4 Test for Serial Correlation

Serial correlation is a potential issue in panel datasets that include time-series observations. In serial correlation, the errors associated with particular time periods are related—e.g., the error term in the current period (e.g., year) may be a function of the error term in the previous year. In regression analysis, the Durbin-Watson (DW) test is used to detect potential first-order autocorrelation. This test compares the residuals (or errors) of the regression at various times (t). If the difference between the errors for observations t and t−1 is small in relation to the error at t, the errors may be correlated. As shown in Table 4.6, the DW test is not significant, supporting the notion that the error terms of the fuel model are not correlated across time.

Table 4.6 Results of Test for Serial or Autocorrelation

Durbin-Watson Test Statistic	1.692
Prob. < DW	0.1177
Prob. > DW	0.8823
Number of Observations	72
1st Order Autocorrelation Statistic	0.124

Note: Prob. < DW is the p-value for testing positive autocorrelation, and Prob. > DW is the p-value for testing negative autocorrelation.

4.3 Model Predictions

4.3.1 Level of Precision

To confirm its precision, the model is used to predict the values (i.e., gallons of fuel consumed) in each region in 2008. Because t=0 in 2008, the predictive equation for the western region is simply $b_0 + b_1$*UGTMC + b_2*NGTMC = gallons of fuel. The alternative equations are $b_0 + b_1$*UGTMC + b_2*NGTMC + b_4 and $b_0 + b_1$*UGTMC + b_2*NGTMC + b_5 for the eastern and central regions, respectively. As shown in Table 4.7, the prediction errors are 0.2%, 1.7%, and 2.5% for regions 1-3, respectively. The average prediction error for the three regions is less than 1.5%. This high level of precision is due to the very high R^2 and very low coefficient of variation.

Table 4.7 Predicted versus Observed Gallons of Fuel in 2008

Region	Gallons of Fuel Used	Predicted Gallons of Fuel	Prediction Error
East	1,027,912,283	1,029,539,077	0.16%
Central	212,893,103	209,225,598	-1.72%
West	2,645,378,417	2,712,295,930	2.53%

4.3.2 Marginal Estimates Derived from Coefficients

The coefficient of UGTMC represents the change in gallons per thousand unit train GTMC, holding all else constant—i.e., the gross ton-miles of non-unit trains, time, and region. The coefficient of NGTMC has an analogous meaning.

The gross ton-miles of cars and contents per gallon (GTMC/G) for each type of train are computed from the regression parameters as $1 / b_n * 1{,}000$, where n takes values of 1 or 2, corresponding to UGTMC and NGTMC, respectively. The resulting estimates are 1,343 and 903 GTMC/G for unit and non-unit trains, respectively. Note that the predicted marginal fuel efficiencies are greater than the average efficiency of 806 GTMC/G for 2008.

The GTMC/G values are transformed into estimates of RTM/G for specific trains using the net-to-gross car weight ratios shown in Column 2 of Table 4.8. For example, the net/gross ratio of a grain shipment is computed as the gross car weight (138 tons), plus the tare weight (31 tons) times the empty return ratio (1.0), divided by the net car weight (107 tons)—i.e., 107/(138+31 * 1.0)=0.63.

Table 4.8 Marginal Estimates of Revenue Ton-Miles per Gallon, by Train Type

Train	Net/Gross Weight Ratio	RTM/G by Train Type	
		Non-Unit	Unit
(1)	(2)	(3)	(4)
Coal	0.71/0.72*	638	962
Grain	0.63	572	850
COFC	0.42	376	N/A
Auto	0.21	193	N/A

*Difference due to higher empty/loaded ratio for non-unit train movements

As shown in Table 4.8, the marginal fuel efficiency of a unit coal train added to the railroad network is 962 RTM/G, while the marginal fuel efficiency of a unit grain train is 850 RTM/G. These interpretations presume that the addition of a single train will not substantially affect existing traffic on the network and change operating conditions or the distribution of traffic among regions. These assumptions are realistic, because the ratio of the additional GTMC of a single train to total GTMC is nearly zero. However, all fuel consumed in providing freight services is not reflected in the marginal estimates. Specifically, fuel that is not traceable to GTMC and regional variations in fuel efficiency are not considered. For these reasons, average fuel consumption factors are also considered.

4.3.3 Average Fuel Efficiency Factors

Average fuel efficiency factors for each type of train and region are estimated from the model. For Region 3, the predictive equation for unit trains is $(b_0 + b_1*GTMC) / GTMC$, where GTMC is the total GTMC in Region 3 during 2008. The predictive equation for non-unit trains is $(b_0 + b_2*GTMC) / GTMC$. Similarly, the predictive equations for unit trains are $(b_0 + b_1*GTMC + b_4) / GTMC$ and $(b_0 + b_1*GTMC + b_5) / GTMC$ for Regions 1 and 2, respectively. In each calculation, the fixed fuel requirement is added to the variable fuel component computed from the observed GTMC. In the first set of calculations, the observed GTMC is assumed to move in unit trains. In the second set of calculations, the observed GTMC is assumed to move in non-unit trains.

The predicted values are validated by computing a weighted estimate of gallons per GTMC for each region (Equation 5), and comparing these estimates to the observed regional averages. In these calculations, the estimated gallons per unit train GTMC *(Gal./UGTMC)* are weighted by the proportion of unit train GTMC *(U)*, while the estimated gallons per non-unit train GTMC *(Gal./NGTMC)* are weighted by the proportion of non-unit train GTMC *(N)*.

$$(5) \qquad \left(\frac{\widehat{Gal.}}{GTMC}\right)_i = U_i\left(\frac{\widehat{Gal.}}{UGTMC}\right)_i + N_i\left(\frac{\widehat{Gal.}}{NGTMC}\right)_i$$

The mean difference between the predicted and observed values is 2% for the three regions. While the predicted and observed values are very close, the GTMC/G estimates are scaled to the observed values in each region using the ratio shown in Equation 6. The results are depicted in Table 4.9, along with the observed values for each region.

$$(6) \qquad \left(\frac{\widehat{Gal.}}{GTMC}\right)_i \Big/ \left(\frac{Gal.}{GTMC}\right)_i$$

Table 4.9 Predicted and Observed GTMC/G Values by Train Type and Region

Region	Non-Unit Train GTMC/G (Predicted)	*Mean GTMC/G (Observed)*	Unit Train GTMC (Predicted)
East (region1)	699	*779*	944
Central (region 2)	819	*908*	1,188
West (region 3)	697	*809*	931

Several points are noteworthy. (1) The average values are substantially lower than the marginal values of 903 and 1,343 GTMC/G for non-unit and unit trains, respectively. This is because all gallons of fuel consumed in freight services are reflected in the average estimates. (2) The predicted GTMC/G estimates are substantially greater in Region 2 than in Region 1 or 3. (3) The estimated fuel efficiencies of unit trains are substantially greater than the average for all trains, irrespective of region. (4) The estimated fuel efficiencies of unit trains are 25% to 31% greater than non-unit trains.

Average revenue ton-miles per gallon (RTM/G) are derived from GTMC/G using the net/gross ratios shown in Table 4.8. The results are depicted in Table 4.10. Instead of truck drayage, way train drayage is reflected in the auto and COFC estimates. As the table shows, the fuel efficiencies of coal unit trains range from 667 to 851 RTM/G, while non-unit train coal shipments yield 493 to 579 RTM/G. The fuel efficiencies of unit grain trains range from 589 to 752 RTM/G, while other grain shipments generate 446 to 524 RTM/G. Double-stack COFC and auto shipments average 310 and 155 RTM/G, respectively, for all regions. However, the use of way train instead of truck drayage may substantially understate the total fuel requirements of these movements.

Table 4.10 Estimated RTM/G in 2008, by Train Type and Region

	Train Type					
	Coal		Grain		COFC	Auto
Region	Non-Unit	Unit	Non-Unit	Unit	Non-Unit	Non-Unit
East	494	676	443	598	291	149
Central	579	851	519	752	341	175
West	493	667	441	589	290	149

4.4 Comparisons of Predictions

In this section, estimates from the analytical method and statistical model are compared to each other and, where possible, to estimates derived from other studies.

4.4.1 Grain Shipments

The estimated revenue ton-miles per gallon of a grain unit train using the analytical method are 862 and 649 RTM/G in flat and mountainous terrain respectively. In comparison, the marginal estimate from the fuel model is 850 RTM/G, ignoring regional effects. The average fuel efficiency factors derived from the statistical model are 598, 752, and 589 RTM/G for regions 1, 2, and 3 respectively.

The only real source of comparison is the Gervais and Baumel study of 1990. There, the fuel efficiencies of 141-ton car movements in the western United States that cross the Rocky Mountains range from 585 to 664 RTM/G, while the maximum fuel efficiency of movements from Iowa to New Orleans is 802 RTM/G (Table 2.2). Presumably, these are marginal values that exclude fixed and overhead fuel requirements. If so, the most comparable estimates to the Iowa-New Orleans movement are the marginal (statistical) and flat terrain (analytical) estimates, which are 6% to 7% greater than the 1990 Gervais-Baumel estimate. In comparison, the average predicted efficiency of 752 RTM/G in the central Region (Table 4.10) is 6% less than the 1990 Iowa-New Orleans simulation. This relationship is expected, because the latter estimate excludes overhead fuel.

The analytical estimate of 649 RTM/G for the PNW route (Table 3.10) is close to the maximum value of 664 from the Gervais-Baumel study for movements from Iowa to Washington state. Moreover, the average RTM/G in the western region predicted by the statistical model (589 RTM/G) lies within the range of estimates from that study.

4.4.2 Auto Shipments

The average fuel efficiency of the three automobile shipments analyzed in the ICFI study (2009) is 159 RTM/G. According to the waybill sample (STB 2008), roughly 20% of the automobiles shipped via railroads in the United States cross the Rocky Mountains. Using this factor, the weighted marginal fuel efficiency derived from the analytical method is 169 RTM/G. The difference between the analytical results and the ICFI simulations are largely explained by differences in lading weights. The average net weight used in the analytical procedure (which was computed from the waybill sample) is 20 tons per car, while the mean lading in the three ICFI simulations is 18.7 tons. In comparison, the mean of the average efficiency ratings from the fuel model (Table 4.10) is 158 RTM/G. As these comparisons suggest, the estimates from this study are quite consistent with those of the ICFI study. As noted earlier, ICFI concluded that automobile shipments by rail are 1.9 to 2.2 times more fuel efficient than movements in highway trailers.

4.4.3 Coal Shipments

Coal shipments are not analyzed in the ICFI study or in any recent study, for that matter. Therefore, comparisons can only be made among estimates developed using different methods—i.e., analytical, marginal, and average.

According to the waybill sample (STB, 2008), roughly 10% of coal shipments move within the Rocky Mountain-Pacific Coast region. Using this percentage, the weighted estimate from the analytical method is 946 RTM/G, as compared to the marginal estimate of 962 RTM/G from the model. The average efficiency factors of 676, 851, and 667 RTM/G (from Table 4.10) reflect variations among regions due to gradients, networks, and operational factors.

4.4.4 General Inferences

The marginal estimates from the statistical model are quite similar to the estimates from the analytical procedure. However, only one elevation profile is reflected in the analytical model. More comparisons are needed before it can be concluded that the two approaches yield essentially the same results. Nevertheless, the initial comparison is encouraging.

The average fuel efficiency measures generated from the model are significantly less than the marginal estimates. However, they indicate significant differences among regions and are consistent with observed values. Moreover, the train efficiency factors within each region show substantial differences between unit and non-unit train movements and agree very closely with observed values when weighted.

5. NATIONAL ANALYSIS OF RAILROAD FUEL EFFICIENCY

Thus far, railroad fuel efficiencies have been estimated for a limited number of movements by specifying car tare and net weights. While these illustrations are realistic and descriptive of actual movements, they represent only a few of the many potential net/gross ratios of movements in the United States and do not necessarily reflect the average for any particular commodity. In this section of the paper, average fuel efficiency factors are estimated for a broader set of movements using the coefficients of the regression model and the 2008 railroad waybill sample.

5.1 Overview of Waybill Sample

The public waybill sample identifies commodity flows within and among five territories. Two of these territories lie in the eastern region. Two lie in the central region. The fifth lies in the western region, and includes the Rocky Mountains and Pacific Coast.

In the waybill sample, the commodity represented by each sample movement is identified by the Standard Transportation Commodity Code (STCC). In addition to the origin and destination territories and the commodity, the car type, net weight, and tare weight are identified for each sample movement, as well as the expanded (or population) carloads represented by the movement. While the waybill sample has limitations, it is the only comprehensive source of railroad movement information in the United States. Using this sample, six intra- or inter-regional flows are analyzed: (1) flows within the eastern region, (2) flows within the central region, (3) flows within the western region, (4) flows between the eastern and central regions, (5) flows between the eastern and western regions, and (6) flows between the western and central regions.

The waybill sample does not indicate whether a movement is a true unit train or a large multicar shipment. In costing the waybill sample, the STB assumes that 50-car shipments have the characteristics of unit trains. However, the minimum tariff volume for a shuttle train often exceeds 100 cars. For this reason, a higher threshold is used. A shipment of 75 cars or more is assumed to move as a unit train that requires no marshaling of cars at origin, or intermediate yard switching. This is obviously a blunt delineation that mischaracterizes some shipments.

5.2 Empty/Loaded Mile Ratios

Although empty/loaded car-mile ratios cannot be derived from the waybill sample, they can be calculated from the R-1 report for each car type and region, and merged with the waybill sample. The empty/loaded ratios used in this analysis are shown in Table 5.1. By definition, a shuttle train has an empty/loaded ratio of 1.0, since it cycles between an origin and destination.

Table 5.1 Empty/Loaded Car-Mile Ratios by Region

Car Code	Description	Region		
		East (1)	Central (2)	West (3)
37	Plain Boxcar	0.819	0.791	0.561
38	Equipped Boxcar	0.961	0.876	0.755
39	Plain Gondola	0.926	1.017	1.134
40	Equipped Gondola	0.931	1.044	0.953
41	Covered Hopper	0.976	1.044	1.006
42	Open Hopper – General Service	0.961	0.969	1.025
43	Open Hopper – Special Service	0.975	0.996	1.046
44	Mechanical Refrigerator	0.751	3.632	0.734
45	Non-mechanical Refrigerator	0.965	0.625	0.801
46	Flatcar – TOFC/COFC	0.133	0.099	0.132
47	Flatcar – Multi-Level	0.547	0.353	0.298
48	Flatcar – General Service	1.276	1.864	1.365
49	Flatcar – Other	0.990	1.026	0.994
50	Tank Car < 22,000 Gallons	1.018	1.074	1.072
51	Tank Car ≥ 22,000 Gallons	1.014	1.049	1.096
52	All Other Freight Cars	0.061	0.289	0.735

Computed from 2008 R-1 Reports

5.3 Estimation Procedure

The calculation process is essentially as follows: (1) The average net/gross weight ratio is computed for each combination of commodity type, regional or interregional flow, and shipment type (e.g., a unit train of coal moving within the eastern region). In each calculation, the tare weight of the car is multiplied by (1.0 + the empty/loaded ratio). This interim value is added to the net weight of the car to derive the gross weight per loaded mile. This value, in turn, is divided into the net tons to yield the net/gross ratio. (2) Once calculated, the net/gross ratio is multiplied by the GTMC/G values (by train type and region) from Table 4.9 to yield RTM/G estimates. For interregional flows, the empty/loaded and GTMC/G inputs are averaged for the origin and termination regions. The results for major commodities which comprise at least 1% of the total tons moved in 2008 are shown in Table 5.2.

5.4 RTM/G Estimates for Major Commodity Movements

As Table 5.2 shows, movements of coal, metallic ores, farm products, non-metallic minerals, and building materials are the most energy efficient flows. In particular, railroads are very efficient in moving coal from mines to utilities, averaging 722 RTM/G. This finding is important to national energy policy, because the energy consumed in transporting coal to power plants must be subtracted from the energy output of utilities to estimate net energy gains to the economy. Other key findings are: (1) Ore movements, which are critical to steel-making and heavy manufacturing, generate 668 RTM/G. (2) Movements of farm products and food and kindred products, which are critical to food supplies and prices, average 543 and 411 RTM/G, respectively. (3) Movements of chemicals and allied products average 430 RTM/G. In addition, railroads are an energy-efficient mode of transporting waste and scrap materials (averaging 390 RTM/G). The fact that some of these materials are used in recycling or in place of raw materials has an additional environmental benefit.

Table 5.2 Weighted-Average RTM/G for Major Commodity Groups

STCC	Product Description	Net/Gross	RTM/G
11	Coal	0.70	722
10	Metallic Ores	0.63	668
01	Farm Products	0.61	543
14	Nonmetallic Minerals, except Fuels	0.63	524
32	Clay, Concrete, Glass or Stone Products	0.62	459
28	Chemicals or Allied Products	0.57	430
33	Primary Metal Products	0.56	412
20	Food or Kindred Products	0.54	411
24	Lumber or Wood Products	0.54	397
40	Waste or Scrap Materials	0.54	390
29	Petroleum or Coal Products	0.51	385
26	Pulp, Paper or Allied Products	0.49	356
37	Transportation Equipment	0.24	177

Computed using the 2008 Waybill Sample

5.5 Validation of Modeling Process

The railroad modeling process described above produces very reasonable results. The overall (predicted) net/gross ratio using the statistical model and 2008 waybill sample is 0.55. In comparison, the actual net/gross ratio from the R-1 report is 0.57. The overall fuel efficiency rating predicted from the statistical model and waybill sample is 456 RTM/G. In comparison, the observed 2008 fuel efficiency rating is 457 RTM/G. In effect, the predicted and actual values are nearly identical. As these comparisons suggest, procedures based on the statistical model and waybill sample slightly underestimate the observed net/gross ratios and efficiency ratings. However, on a national scale, the estimates are quite accurate and do not overstate railroad fuel efficiencies. The next step in the analysis process is to estimate truck and waterway fuel efficiency ratings so that railroad estimates can be placed in a multimodal context**.**

6. TRUCK FUEL EFFICIENCY MODEL

During the nine-year period from 2000 to 2008, the average fuel efficiency of combination trucks (i.e., tractors pulling trailers or semitrailers) ranged from 5.1 to 5.9 mpg (Figure 6.1). The average for the period was 5.4 mpg. However, there is no apparent trend. Fluctuations in fuel economy during the period may be due to factors other than engine technology and emission controls (i.e., demand, highway congestion, tractor selection, and variations in truck travel patterns).

According to Kruse, et al. (2008), the average fuel economy of a heavy duty diesel truck with a gross weight of more than 60,000 pounds is 6.2 mpg. This value is derived from the Environmental Protection Agency's MOBILE6 model. However, because a particular weight is not specified, the estimate may be applicable to trucks weighing more than 60,000 pounds. In a comparative sense, the value derived from the EPA model is greater than the largest observed value in recent history—i.e., 5.9 mpg in 2003 and 2004 (Figure 6.1)—and substantially greater than the average of 5.4 mpg for the 2000-2008 period.

While single efficiency factors are useful, a wide range of truck configurations are used to transport freight in the United States. Because of grandfather clauses, the weights of many trucks exceed the federal 80,000-pound gross vehicle weight limit. In a 2004 study that focused on the uniformity of regulations in the western United States, the U.S. Department of Transportation estimated fuel efficiency factors for a wide range of trucks, including longer configuration vehicles (LCVs). The factors used in that study were originally developed in the late 1990s and do not reflect the more stringent 2004 emission regulations of the Environmental Protection Agency. While these values are outdated, the relative fuel efficiencies should be similar to those that existed in 2008, since improvements in engine technology and fuel economy are applicable to most (if not all) heavy duty tractors.

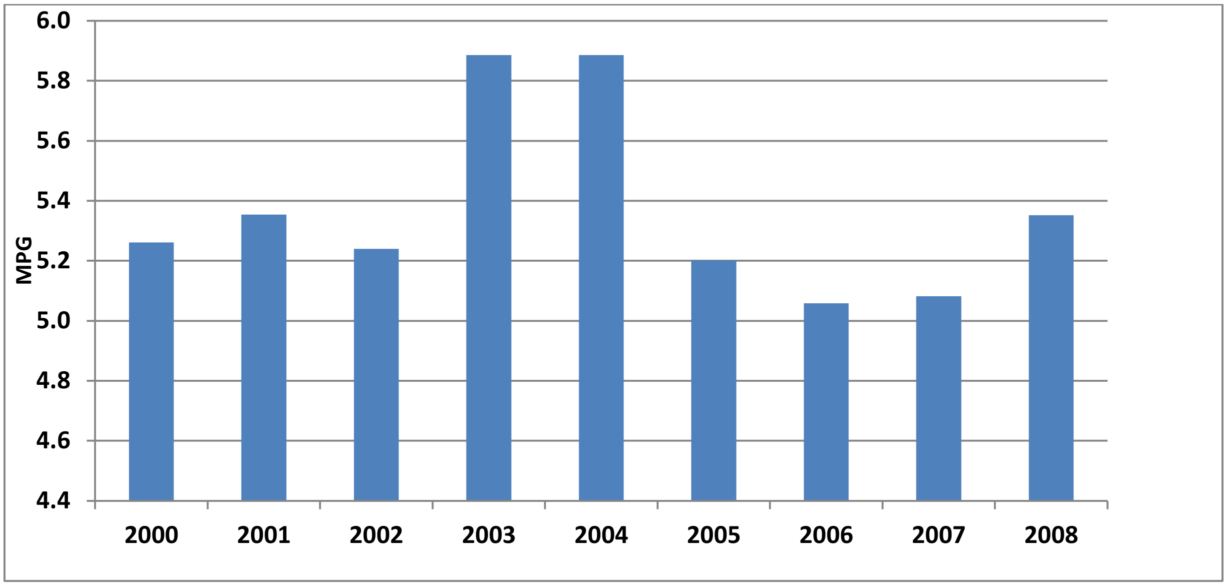

Figure 6.1 Combination Truck Fuel Efficiencies

Based on this assumption, a table of fuel efficiency factors is developed (Table 6.1) by taking the 2008 value from the EPA model (6.2 mpg) and attributing it to a five-axle tractor-semitrailer operating at a gross weight of approximately 60,000 pounds. The rest of the table is filled in by assuming that the ratio of the fuel economy of this truck to all other trucks has remained the same since the USDOT's study. This calculation is equivalent to indexing each value in the original table by 1.14 to account for improvements in tractor fuel economy since the late 1990s.

As shown in Table 6.1, fuel economy decreases as weight increases. According to Delorme et al., the fuel economy of a five-axle tractor semitrailer increases by roughly 0.06% with each thousand pounds of weight reduction (2009). However, fuel economy also varies with tractor performance and the aerodynamics of truck configurations. Because of these variances, relationships among LCV and semitrailer fuel economies are not based solely on weight.

Table 6.1 Average Miles per Gallon by Truck Configuration and Weight

	Gross Vehicle Weight (pounds)			
Truck Configurations	60,000	80,000	100,000	120,000
Five-Axle Semitrailer	6.2	5.5	4.9	
Six-Axle Semitrailer	6.1	5.4	4.9	
Five-Axle Double Trailer	6.8	6.0	5.5	
Seven-Axle Rocky Mountain Double		5.8	5.2	5.0
Eight Axles (or more)		5.8	5.5	5.2
Triple-Trailer Combination		6.0	5.7	5.4

U.S. Department of Transportation. *Western Uniformity Scenario Analysis: A Regional Truck Size and Weight Scenario Requested by the Western Governors' Association*, April 2004. Original values indexed by 1.14.

6.1 Variations in Fuel Economy with Speed

According to Peterbilt Motors Company (2011), the power necessary to overcome aerodynamic drag at speeds of 50 mph is equal to roughly half the power needed to overcome rolling resistance and the energy consumed by accessories. At 75 mph, the power needed to overcome aerodynamic drag is roughly 2.5 times the power needed to overcome rolling resistance and accessory drain (Ibid). According to Goodyear (2008), each mile per hour increment above 55 mph increases fuel requirements by 2.2%.

6.2 Empty Truck Miles

Railroad empty/loaded ratios are reflected in the RTM/G estimates presented earlier. However, there is no comprehensive source of empty/loaded ratios for trucks, because the Vehicle Inventory and Use Survey (VIUS) has been discontinued. In their report, ICFI summarized data from the latest (2002) VIUS survey and, in doing so, discovered that the percentages of empty miles attributable to van trailers range from 26% for trip distances of 200-500 miles to 19% for trip distances greater than 500 miles (2009). In comparison, the percentages of empty miles incurred by tanker trailers range from 43% at distances of 200-500 miles to 31% at distances > 500 miles. The percentages of empty miles for dump trucks range from 41% at distances of 200-500 miles to 38% at distances > 500 miles. Because more specific information is not available for this study, van trailers are assumed to incur 25% empty miles. A similar assumption is made for hopper trailers hauling grain. However, backhauls are much more difficult to obtain for specialized trailers such as hopper and dump trailers.

6.3 Fuel Attributable to Empty Truck Miles

According to simulations in Delorme et al. (2009, Fig. 24), the fuel efficiency of an empty five-axle tractor semitrailer is 23% to 27% greater than the fuel efficiency of the same truck loaded to 80,000 pounds, at speeds ranging from 50 to 70 mph. These estimates seem reasonable, given the fact that a large percentage of the fuel consumed at higher speeds is attributable to aerodynamic resistance rather than weight. Based on the aforementioned simulations, a liberal assumption is made that allows for potential energy savings during acceleration and speed change cycles. Empty truck fuel consumption (in gallons per mile) is assumed to be 70% of loaded consumption. The same percentage of fuel savings is applied to Rocky Mountain Doubles and twin-trailer trucks, even though the empty aerodynamics of these trucks is worse than the aerodynamics of a tractor-semitrailer. Because of these liberal assumptions, the allowances made for empty-mile fuel savings in this study should not understate the benefits of reduced weights.

7. WATERWAY FUEL EFFICIENCY MODEL

Waterway fuel consumption rates are estimated from the River Efficiency Model (REM) developed by the Tennessee Valley Authority (TVA). REM uses vessel and lock performance models to estimate horsepower and speed for each river segment, as well as average processing and delay time at each lock. Fuel usage is derived from speed, horsepower, lock time, and other performance data. All of the individual computations for river segments are added to determine the total fuel consumption in gallons for each waterway. At the same time, revenue ton-miles are estimated so that RTM/G values can be computed from the results. REM is described in greater detail by Bray, Dager, Henry, and Koroa (2002).

7.1 Revenue Ton-Miles per Gallon by River System

REM cannot be used to analyze fuel consumption for specific commodity movements. Nevertheless, average fuel efficiency factors can be estimated for particular waterway systems. These factors (shown in Table 7.1) reflect both loaded and empty barge movements and fuel consumed during lock transits and queuing.

Table 7.1 Waterway Fuel Efficiency Factors for Specific River Systems

	Revenue Ton-Miles per Gallon	
Waterway Name	2008	2007-2009
Mississippi River, Mouth of Ohio to Baton Rouge	656	742
Mississippi River, Mouth of Missouri to Mouth of Ohio	584	703
Mississippi River, Minneapolis to Mouth of Missouri	348	436
Illinois River (IL)	287	348
Ohio River	603	592
Tennessee River (TN, AL and KY)	445	453
Tennessee Tombigbee Waterway	354	377

While railroad energy efficiency has increased consistently over time, waterway fuel efficiency has fluctuated from year to year. Moreover, there are considerable differences among river segments (Table 7.1). In 2008, the average efficiency from Minneapolis to the mouth of the Missouri River was 348 RTM/G. The average efficiency on the Illinois River was 287 RTM/G. However, down-river fuel efficiencies were much greater—e.g., 656 RTM/G for the open river segment from the mouth of the Ohio River to Baton Rouge, LA. In 2009, the estimated fuel efficiencies were 482 and 771 RTM/G for the Minneapolis to Missouri River and Ohio River to Baton Rouge segments, respectively. Moreover, the estimated efficiency of the Illinois River was much greater in 2009 than in 2008—i.e., 395 RTM/G instead of 287. These differences are partly explained by the major flood that occurred on the Mississippi River in 2008, resulting in the second highest crest ever recorded for stations such as Quincy, IL. Because of the flood, a three-year average of waterway fuel efficiency (centered around 2008) is used in the comparison (column 3, Table 7.1). While averaging has a minimal effect on Ohio River fuel efficiency, it significantly alters the values used for the Mississippi and Illinois Rivers.

In addition to floods, the fuel efficiencies of the Upper Mississippi River-Illinois Waterway segments are constrained by small aging locks, many of which are programmed for replacement in the future. At many of these locks, barge operators must separate a tow into two components, and move the blocks through separately. Afterward, the tow must be reassembled. This process may be repeated at several locks as a shipment travels on the Upper Mississippi River or Illinois Waterway. Queuing and double locking maneuvers significantly increase fuel consumption on these river segments.

7.2 Illustrative Waterway Movements

Barge movements from upper river stations to final markets or export locations often travel on several waterway systems. For this reason, origins and destinations must be specified before fuel estimates can be generated. After the distance on each system is stipulated, weighted performance measures can be calculated.

The first illustrative river movement is from Minneapolis to the northern limits of the port district of New Orleans. The approximate distances of the main river segments are 659 miles from Minneapolis to the mouth of the Missouri River near St. Louis, 195 miles from the mouth of the Missouri River to the mouth of the Ohio River near Cairo, IL, and 852 miles from the mouth of the Ohio River to the port of New Orleans. The revenue ton-miles per gallon for these river segments (Table 7.1) are weighted by the river distances. The resulting average is 619 RTM/G.

The revenue ton-miles per gallon for shipments from additional Mississippi River stations are shown in Table 7.2. The distance from each station to the mouth of the Missouri River is shown in the second column of the table, while the average revenue ton-miles per gallon for movements to New Orleans is shown in column 3. For these stations, values range from 633 to 702 RTM/G.

Table 7.2 Average Revenue Ton-Miles per Gallon for Barge Shipments from Upper Mississippi River Stations to New Orleans

Station	Distance to Mouth of Missouri River	Weighted RTM/G
Minnesota City, MN	543	633
Dubuque, IA	388	654
Clinton, IA	327	664
Keokuk IA	169	693
Quincy, IL	130	702

The average revenue ton-miles per gallon on the Ohio River (592 RTM/G) is considerably higher than on the Upper Mississippi River. As a result, the weighted RTM/G estimates for shipments to New Orleans are significantly higher from Ohio River stations. To illustrate, it is 640 river miles from Greenup, KY (which is located near Ashland, KY) to the mouth of the Ohio River, and a total 1,492 miles to New Orleans. The average fuel efficiency of shipments from Greenup to New Orleans is 678 RTM/G. In comparison, the average fuel efficiency for shipments from Louisville, KY (which is located 374 miles from the mouth of the Ohio River) to New Orleans is 696 RTM/G.

Several patterns are apparent from the data. (1) Open river fuel efficiencies are the greatest. Propulsive energy is minimized when loaded barges travel downstream with the current. (2) Shipments that travel the shortest distances on the Upper Mississippi or Illinois Rivers are more efficient than shipments originated farther upstream. Movements originated in the northernmost reaches of the river must transit more locks en route to New Orleans and, thus, consume more fuel in queuing and lock transits. As noted earlier, many of these locks are antiquated and in need of replacement.

8. COMPARISONS OF MODAL ENERGY EFFICIENCY

Procedures for estimating rail, truck, and waterway energy efficiency have been described in previous sections of the report. In this section, the emphasis shifts from describing analysis methods and assumptions to making efficiency comparisons among modes. These comparisons reflect specific commodities and movements within and between regions. Because waterway transportation is not feasible for all flows, certain comparisons are restricted to railroads and trucks.

8.1 Grain

According to the AAR (2011A), railroads transport roughly one-third of the grain tonnage moved in the United States. Grain is included in the farm products category in Table 5.2, along with other field crops; fresh fruits and vegetables; and livestock and poultry products. More specific information can be developed using the 0113 STCC header. Based on this classification, the average fuel efficiency of all railroad grain shipments (as computed from the 2008 waybill sample) is 556 RTM/G. However, the fuel efficiency of grain unit trains (693 RTM/G) is substantially greater than the average for all farm products. The unit train estimate (Table 8.1) reflects an average net weight of 107 tons per car and a tare weight of 31 tons. The median size of a grain unit train is 108 cars.

Table 8.1 Grain Car Weights and Net/Gross Ratios of Grain Unit Train Shipments

Net Tons per Car	107
Tare Weight (tons)	31
Net/Gross	0.63
RTM/G	693

8.1.1 Truck-Rail Comparisons

Grain is moved from farms to elevators in many types of trucks (single unit and combination). However, grain shipped from elevators to markets, transfer locations, or export facilities moves in larger commercial trucks. The two most common types are the five-axle tractor semitrailer and the seven-axle tractor semitrailer-trailer combination, also known as the Rocky Mountain Double—which consists of a 40- to 48-ft semitrailer followed by a smaller "pup" trailer with two single axles. Both trucks have two sets of tandem axles. However, the Rocky Mountain Double has three single axles, whereas the tractor-semitrailer has one. A third truck configuration (which is used primarily in cross-border movements between the United States and Canada) has four sets of tandem axles and nine axles, altogether. All three trucks are equipped with hopper trailers with top loading and bottom (gravity) discharging capabilities.

Typical weights and capacities of these trucks are shown in Table 8.2, where the gross weight of the twin-trailer truck is an average of individual state weight limits that range from 105,500 to 137,800 pounds. The percentages of grains moved in each truck are unknown. Movements in nine-axle trucks are confined to limited geographic areas near the northern border under special permit. Movements in Rocky Mountain Doubles are common in the western United States under grandfather clauses, but are rare east of the Mississippi River. However, the tractor-semitrailer combination is legal nationwide and is therefore the dominant truck used in grain transportation.

Because of their specialized nature, the empty/loaded mile ratios are higher for hopper trailers than for van trailers. If the trailers are used to backhaul fertilizers, they must be thoroughly sanitized before being used to haul grain again—a fact that limits their backhaul potential. If half of the truck's miles are empty (e.g., zero backhaul), the estimated fuel efficiencies are 86, 109, and 126 RTM/G for the five-axle, seven-axle, and nine-axle trucks, respectively. If 25% of the truck's miles are empty (e.g., the trucker procures a backhaul for one of every two return trips), the estimated fuel efficiencies are 119, 150, and 174 RTM/G for the five-axle, seven-axle, and nine-axle trucks, respectively.

Table 8.2 Weights and Capacities of Combination Trucks

Truck Configuration	5-Axle 48-ft Semitrailer	7-Axle Rocky Mountain Double	9-Axle Twin Trailers
Gross Weight (lb)	80,000	105,500	127,400
Tare Weight (lb)	26,800	34,200	45,000
Net Weight (tons)	26.6	35.7	41.2

The railroad energy factors used in the comparison (computed from the 2008 waybill sample) are 693 and 464 RTM/G for unit and non-unit trains, respectively, and 556 RTM/G, overall. As these factors suggest, grain movements by rail are 6.5 times more fuel efficient, on average, than grain shipments in five-axle tractor-semitrailer trucks with no backhaul (Column 2 of Table 8.3), and 5.1 and 4.4 times more fuel efficient than movements in Rocky Mountain Doubles and twin-trailer trucks, respectively, with no backhaul. The relative fuel advantages are even greater for grain unit trains, which are 8.1, 6.4, and 5.5 times more efficient than highway movements in five-axle tractor-semitrailers, Rocky Mountain Doubles and twin-trailer trucks, respectively (column 3). If truckers experience 25% empty miles, grain unit trains are 5.8, 4.6, and 4.0 times more fuel efficient than highway movements in five-axle tractor-semitrailers, Rocky Mountain Doubles and twin-trailer trucks, respectively (column 5).

Table 8.3 Relative Fuel Efficiency of Railroads to Trucks in Transporting Grain

	50% Empty Truck Miles		25% Empty Truck Miles	
Truck Configuration/Train Type	Average	Unit Train	Average	Unit Train
Five-Axle Semitrailer	6.5	8.1	4.7	5.8
Seven-Axle Rocky Mountain Double	5.1	6.4	3.7	4.6
Nine-Axle Twin 48-ft Trailers	4.4	5.5	3.2	4.0

Note that Rocky Mountain Doubles operate primarily in the western United States, while nine- and ten-axle grain trucks operate largely in cross-border movements to and from Canada. A simple average of the values in any column of the table may be misleading, since most of the shipments occur in five-axle units.

8.1.2 Rail-River Comparisons

The railroad energy efficiency factors used in the waterway comparisons are computed from the regression model and 2008 waybill sample (Table 8.4). They represent weighted-average net/gross ratios within each region.

Upper Mississippi River to the Gulf. The weighted average fuel efficiency of a waterway movement from Minneapolis to New Orleans is 619 RTM/G. This is higher than the average for a non-unit train movement within the central region, as computed from the 2008 waybill sample (497 RTM/G). However, the typical waterway fuel efficiency is less than that of a grain unit train (748 RTM/G) traveling in the same region. Moreover, a unit train movement in the central region is more fuel efficient than movements from all of the Upper Mississippi River stations shown in Table 7.2.

Table 8.4 RTM/G Estimates for Grain Shipments Used in Rail-Waterway Comparisons

Region	Shipment Type	Net/Gross	RTM/G
East	Non-Unit	0.62	431
	Unit Train	0.63	596
Central	Non-Unit	0.61	497
	Unit Train	0.62	748
West	Non-Unit	0.61	428
	Unit Train	0.64	598

Computed from regional GTM/G values derived from the regression model (Table 4.9) and net/gross car weight ratios computed from the 2008 waybill sample.

Ohio River to the Gulf. As noted earlier, the average fuel efficiency of barge shipments from Greenup, KY, to New Orleans is 678 RTM/G. In comparison, a non-unit train grain movement within the eastern region yields 431 RTM/G (Table 8.4), while a grain unit train movement generates 596 RTM/G. In this example, Ohio River barge movements offer greater energy efficiency than railways.

Linked Truck Movements. Truck movements are necessary to move grain from farms to elevators located on rail lines and rivers. In some cases, grain moves initially to a local elevator and, from there, is transshipped to a shuttle-train facility. Similarly, grain may be shipped from an inland elevator to one located on a river. The diversity of these potential movements makes it difficult to generalize about the truck portions of railroad and inland waterway movements. If there are substantial differences in the truck distances attributable to these intermodal shipments, the comparisons presented above may be unrealistic.

8.2 Flour

Railroads transported more than 10 million tons of flour and related grain mill products in 2008. All of these shipments moved as individual carloads. About 86% of this tonnage moved in covered hopper cars with an average load factor of 93 tons. The average trip length was 784 miles. The overall efficiency rating was 429 RTM/G. Because final demand sites (such as bakeries) are distributed throughout the United States and because of the protective needs of the cargo, truck transportation is the only feasible alternative to rail. While it is possible for bulk flour to be transported in LCVs, flour is more likely to move in five-axle tractor semitrailers. With 25% empty miles, the typical efficiency of a flour movement by truck is 118 RTM/G. On average, railroad movements of bulk flour are 3.6 times more fuel efficient than highway movements on a per mile basis. However, this ratio may not be applicable to bagged flour movements in van trailers and boxcars, or other bagged or packaged grain mill products.

8.3 Ethanol

Movements of ethanol are important to clean fuel programs in several states, including California. According to the American Association of Railroads (AAR, 2011B), railroads account for 70% to 75% of ethanol transportation. Ethanol is transported primarily in large tank cars with an average load factor of 93 tons. With a net/gross ratio of 0.58, these movements realize an efficiency rating of 443 RTM/G and are 3.9 times more fuel efficient than movements in five-axle tractor semitrailers with 25% empty miles. Because of the east-west orientations of these movements, river transportation is infeasible on a broad scale.

8.4 Iron Ore

Iron ore is critical to steel-making and the manufacture of durable goods. Approximately 59.1 million tons of iron ore were mined in the United States in 2008 (U.S. Geological Survey, 2008) Seventy-seven percent of this total originated from the Mesabi Range in Minnesota. Another 23% was mined in the Upper Peninsula of Michigan. According to the waybill sample, railroads moved approximately 53 million tons of iron ore in 2008, which equals 90% of the tonnage mined. Approximately 75% of this tonnage moves in unit trains. The average unit train consists of 132 cars, each weighing approximately 25 tons empty, 116 tons loaded, and hauling 91 payload tons. More than 98% of the tons moved by rail are transported in open top hopper cars.

8.4.1 Car Weights and RTM/G Values

The average car weights and revenue ton-miles per gallon are shown in Table 8.5. In 2008, the average energy efficiency of an ore unit train was 740 RTM/G. Unit train shipments in the central region (where most of the traffic is concentrated) are even more efficient, averaging 765 RTM/G (Table 8.5). The overall efficiency of ore movements in the United States (irrespective of train service and region) is 668 RTM/G.

Table 8.5 Car Weights and Fuel Efficiencies of Iron Ore Movements

Shipment Type	Region	Net/Gross	RTM/G
Non-Unit	East	0.61	425
	Central	0.63	513
	West	0.59	410
Unit	East	0.63	595
	Central	0.64	765

Computed from the 2008 Waybill Sample

8.4.2 Rail-Truck Comparison

Minnesota does not allow LCVs. So, the heaviest vehicle that can operate with a routine permit is a six-axle tractor-semitrailer that weighs 90,000 pounds. With a tare weight of 13.5 tons and 25% empty miles, this truck can achieve 138 RTM/G. The maximum weight of a double-trailer combination in Michigan with typical axle spacing and no special permit is 109,000 pounds. At 25% empty miles, this truck can achieve 157 RTM/G. As noted earlier, the efficiency of an ore unit train in the central region is 765 RTM/G. Thus, on a per-mile basis, an ore unit train is 4.9 and 5.5 times more fuel efficient than highway movements in Michigan and Minnesota, respectively, in the heaviest combination trucks routinely allowed in those states. With these ratios, it is not surprising that iron ore in the central region moves almost exclusively by rail and water.

8.5 Soda Ash

Soda ash (or sodium carbonate) is an important industrial compound. In addition to being used for flue gas desulfurization and water treatment, soda ash is essential to the manufacture of glass, soaps and detergents, pulp and paper, and various chemicals.

In 2008, approximately 12.5 million tons of soda ash were produced in the United States, mostly in Wyoming and California (Ibid). Most of this soda ash is transported long distances (e.g., an average of 1,300 miles) to manufacturers located throughout the United States by railroads in covered hopper cars with an average load factor of 104 tons. The covered hopper cars protect the ash from contamination during transit. Moreover, pneumatically-assisted gates provide for rapid discharge of ash and complete removal of fines.

The average efficiency of soda ash movements by rail is 479 RTM/G. Because of the west to east orientations of these movements, river transportation is not feasible. Moreover, because of the nationwide distribution of soda ash, the only practical truck option is the five-axle tractor semitrailer which, with 25% empty miles, can achieve 118 RTM/G. In effect, soda ash movements by rail are 4.1 times more energy efficient than movements by truck on a per mile basis.

8.6 Coal

According to the Energy Information Administration (EIA), 93% of the coal mined in the United States is used to generate electricity. Approximately 71% of this coal is delivered by railroads (Table 8.6). Trucks deliver less than 14% of the coal needed to generate electricity.

Table 8.6 Distribution of Coal Mined in the United States, by Destination Mode (2009)

Transportation Mode	Percentage
Great Lakes	0.06%
Railroad	71.02%
River	9.73%
Tidewater Piers	0.07%
Tramway, Conveyor, and Slurry Pipeline	5.23%
Truck	13.78%
Unknown	0.10%

Source: Energy Information Administration

Roughly 42% of the coal mined in the United States originates from the Powder River Basin (PRB) of Wyoming. Although anthracite and bituminous coals generate more BTUs per ton, PRB subbituminous coal possesses relatively low levels of sulfur and ash. In order to comply with stricter sulfur emission regulations, many utilities throughout the United States burn PRB coal. Because the mines are located far from navigable rivers and lakes, western coal is moved primarily to utilities and transloading facilities by rail.

8.6.1 Car Weights

As shown previously in Table 5.2, coal is one of the heaviest loading commodities with a net/gross ratio of 0.70. However, this aggregate ratio reflects a wide range of car weights and ratios for individual cars and train types. As shown in Table 8.7, cars used in unit train service have higher net/gross ratios than cars used in carload service. In particular, special service open top hopper and gondola cars in unit train service have the highest net/gross ratios (0.72). In addition, there are substantial differences in the size of shipments within and among classifications. A non-unit train coal shipment consists of 25 cars, on average, while the average unit train includes 115 cars. A typical gondola train consists of 120 cars.

Table 8.7 Coal Car Weights and Net/Gross Ratios by Car Type and Shipment Type

	Non-Unit Train			Unit Train		
Car Type	Net	Tare	Net/Gross	Net	Tare	Net/Gross
Plain Gondola	102	30	0.64	116	23	0.72
Open Hopper- General Service	98	30	0.62	105	29	0.65
Open Hopper- Special Service	112	27	0.68	115	25	0.70

Computed from the 2008 Waybill Sample

8.6.2 Rail-Truck Comparisons

Most of the competition for coal between railroads and trucks occurs in the eastern United States where several states have increased their truck weight limits for movements on designated highways, allowing trucks to weigh as much as 60 tons, with some overweight tolerance. Three varieties of trucks are widely used to transport coal in these states (1) three-axle trucks with tandem rear axles, (2) five-axle tractors with semitrailers, and (3) six-axle tractor-semitrailer combinations with triple or tridem rear axles. The maximum allowable gross weights for these trucks are 40 tons, 45 tons, and 60 tons, respectively, on designated roads.

The six-axle tractor semitrailer is the most economical truck for longer hauls from mines to river transfer facilities and utilities and is therefore used in this analysis. With a tare weight of roughly 15 tons, this truck can haul approximately 45 tons in a single trip. Because coal trucks often operate in shuttle service and have limited backhaul opportunities, the empty/loaded ratio is assumed to be 1.0. Because of its greater weight (60 tons instead of 40 tons), the fuel efficiency of a coal truck is less than the fuel efficiency of the typical 80,000-lb tractor-semitrailer shown in Table 6.1 — i.e., 4.9 mpg versus 5.5 mpg. Based on this fuel consumption rate and the assumed empty/loaded ratio of 1.0, the average energy efficiency of a six-axle coal truck is 130 RTM/G. In comparison, the average efficiencies of non-unit and unit train coal movements in the eastern United States (as predicted from the regression model and waybill sample) are 460 and 637 RTM/G, respectively (Table 8.8). As these comparisons suggest, non-unit and unit train coal shipments in the eastern United States are 3.5 and 4.9 times more fuel efficient than movements in the heaviest truck approved for travel on designated state highways.

Table 8.8 RTM/G Estimates for Coal Shipments Used in Rail-Waterway Comparisons

Shipment Type	Region	Net/Gross	RTM/G
Non-Unit	East	0.66	460
	Central	0.62	511
	West	0.64	444
Unit	East	0.68	637
	Central	0.72	856
	West	0.70	654

Computed from regional GTM/G values derived from regression model (Table 4.9) and net/gross car weight ratios computed from the 2008 waybill sample.

While most western coal is moved to the central and eastern United States, some movements occur within the western region. In several western states, coal is moved in LCVs under exceptions to the 80,000-pound vehicle weight limit. In some areas, coal is moved in double-trailer combinations with gross weights or 129,000 pounds or more. With a tare weight of 22.5 tons, these trucks can haul 42 tons in a single trip. With a fuel efficiency rating of 5.2 mpg (Table 6.1) and no backhaul, these trucks can achieve 128 RTM/G. In comparison, the average fuel efficiencies of non-unit and unit train movements in the western United States (as predicted from the regression model and waybill sample) are 444 and 654 RTM/G, respectively (Table 8.8). In effect, non-unit and unit train coal shipments in the western United States are 3.7 to 5.4 times more fuel efficient than movements in the heaviest truck allowed under grandfather clause exemptions.

Because of variations in truck sizes and weights, a standard comparison across the United States is not possible. The only comparison that can be made is for travel on the interstate highway system, where the maximum truck weight is 80,000 pounds without a special permit. When constrained to this limit, a coal truck with a tare weight of 14 tons is able to haul 26 net tons per trip. If the truck experiences 25% empty miles, the average fuel efficiency rating is 116 RTM/G. If the trucker always has a backhaul (i.e., 0% empty miles), the average fuel efficiency rating is 143 RTM/G. If the trucker never has a backhaul (i.e., 50% empty miles), the average fuel efficiency rating is 84 RTM/G. However, the last two scenarios are unlikely.

As shown previously in Table 5.2, the overall efficiency of coal movements by rail is 722 RTM/G. This value reflects both unit and non-unit train movements throughout the United States. Using this factor, it can be said that railroad shipments are 6.2 times more efficient than coal shipments at the interstate weight limit in trucks that incur 25% empty miles.

8.6.3 Rail-Waterway Comparison

As shown in Table 7.1, the average fuel efficiency of shipments on the Ohio River is 592 RTM/G. In comparison, the average efficiency of non-unit train coal shipments in the eastern United States is 460 RTM/G, while the average efficiency of unit train coal shipments in the east is 637 RTM/G. A precise comparison is difficult because the comparative distances from mines to rail and river transfer facilities are unknown. Nevertheless, it appears that the energy efficiency of unit train coal shipments in the eastern region is at least comparable to barge shipments on the Ohio River.

As noted earlier, coal mined in the western United States is often railed from the Powder River Basin to the Great Lakes or Upper Mississippi River Valley. Because these movements are intermodal in nature, direct modal comparisons are not as relevant as for movements in the eastern part of the country.

9. TRANSPORTATION CIRCUITY

The comparisons developed in this study are based on the energy efficiencies of railroads, trucks, and waterways per mile of operation. However, each mode may not move the same product the same number of miles between a given origin and destination. Therefore, the concept of transportation "circuity" is important in modal comparisons. There are essentially three types of circuity: (1) network, (2) route, and (3) total. Total circuity is the sum or aggregation of network and route circuity factors. A circuity factor or multiplier is equal to 1 plus the circuity estimate or proportion.

9.1 Network Circuity

Network circuity is a function of the built transportation network and how much it deviates from great circle distances. According to CBO (1982), the average network circuity factors for intercity carriers are 1.83 for barges, 1.32 for railways, and 1.15 for trucks. In effect, railroad network circuity is 1.15 times greater than highway network circuity. In comparison, river network circuity is 1.59 times greater than highway network circuity, and 1.39 times greater than railroad network circuity.

Great circle distances can be approximated for a given origin-destination combination using direct air miles. In this approach, network circuity factors can be derived by comparing the distance of the shortest path within the network to the imputed great circle distance. The comparison is complicated by the fact that there may be multiple feasible paths between an origin and destination. Consequently, all such paths must be enumerated and compared. Before the widespread development of Geographic Information Systems, the calculation of network circuity factors was a very intensive process. For this reason, only a few estimates are available.

9.2 Route Circuity

Route circuity is a measure of the extent to which shipments do not take the most direct path between origin and destination. In some cases, a longer alternative path with a shorter travel time may be selected. In other cases, a longer path may be followed to avoid congestion, severe gradients, or hazards. The consolidation and distribution of freight at origin and destination may contribute to circuity. For example, an individual carload that is picked up by a way train is typically hauled to the home yard for classification regardless of the direction in which the shipment is headed. This type of circuity occurs in the airline's hub-spoke system, as well as in the less-than-truckload sector.

Because there is rarely more than one feasible water path between a river origin and destination, barge route circuity is assumed to be zero. According to the CBO (1982), the route circuity multipliers for railroads and trucks are 1.15 and 1.06, respectively. The truck factor may still be applicable, since most of the interstate and intercity arterial highway network was in place in 1982. However, the latest railroad estimate was 1.135 in 1983 (STB, 2009).

The railroad circuity factor reflects both unit and non-unit train traffic. Unit trains typically travel the shortest path between origin and destination, because out-of-line routing for purposes of yard classification is not required. In the Uniform Railroad Costing System, the STB assumes a circuity factor of 1.0 for unit trains. According to R-1 reports, approximately 16% of all car miles in 1983 occurred in unit trains. If the unit train circuity factor is 1.0, this means that the circuity factor for the remaining (non-unit train) traffic must have been 1.16.

The percent of car miles in unit trains has since increased from 16% in 1983 to 42% by 2008. If the non-unit train circuity factor has remained constant over time, the weighted-average circuity factor in 2008 was 1.09. If these assumptions hold true, railroad route circuity is roughly 1.03 times greater than truck route circuity.

9.3 Total Circuity

Based on the foregoing analysis, the total circuity factors used in this study are 1.21, 1.41, and 1.83 for trucks, railroads, and barges, respectively. In effect, total railroad circuity is 1.17 times greater than total highway network circuity. In comparison, total river circuity is 1.3 times greater than railroad circuity. More specifically, the ratio of total railroad-to-truck circuity for non-unit train movements is 1.22. For unit train movements, the ratio of total rail-to-truck circuity is 1.09. For unit train movements, the total ratio of barge-to-rail circuity is 1.24.

9.4 Railroad-Truck Comparisons Adjusted for Circuity

The ratios of railroad to truck and railroad to barge energy efficiencies computed earlier are summarized in Table XII of the overview, along with a set of ratios that have been adjusted for circuity. As expected, the railroads' energy advantages over trucks drop after the adjustments. However, railroads still hold substantial energy advantages for all of the commodities analyzed. For example, coal unit trains are still 4.5 and 5.0 times more energy efficient than truck movements in the largest vehicles allowed under grandfather clauses in the eastern and western regions, respectively. Unit grain train movements in the central region are still 4.6 times more fuel efficient than movements in Rocky Mountain Doubles.

9.5 Effects of Circuity on Railroad and Barge Energy Comparisons

While the railroad-to-truck efficiency ratios drop when circuity is considered, the railroad-to-barge ratios increase. The Minneapolis to New Orleans movement is an interesting example. The shortest railroad distance is 1,273 miles. In comparison, the river distance is 1,706 miles. In this example, the actual ratio of barge-to-rail circuity is 1.34, instead of the 1.24 factor computed earlier. However, this relationship reflects only network circuity. If another railroad route to New Orleans is selected, the rail distance will be greater and the barge-to-rail circuity ratio will be much smaller.

10. CONCLUSION

In conclusion, some of the limitations of the analysis are discussed, including interpretive issues involved in railway-waterway comparisons.

10.1 Issues with Railway-Waterway Comparisons

In previous studies, system-average railroad and waterway RTM/G values were compared and inferences drawn that waterways are more energy efficient than railways (Kruse, et al., 2008). While this is true overall, the comparison is not completely relevant. As shown in Table 10.1, the inland waterway traffic mix consists largely of bulk commodities such as coal, ore, petroleum, chemicals, and aggregates. In contrast, the railroad traffic base includes automobiles, auto parts, loaded and empty containers, and a multitude of neobulk and manufactured goods for which railways and trucks compete. For these reasons, comparisons of railway and waterway averages do not necessarily result in "apples to apples" comparisons. A different picture emerges when the commodities moved by rail are organized into two categories (1) bulk commodities and heavy manufactured goods that also move via waterways and (2) low-density, containerized, and/or time-sensitive goods for which railways and trucks compete. If the second group is excluded from the calculation, the railroads' energy efficiency increases from 457 RTM/G to 581 RTM/G. For purposes of comparison, the average river efficiency during the 2007-2009 period was 592 RTM/G. While this comparison is approximate, it indicates that railroad energy efficiency is approaching waterway efficiency levels for similar commodities. However, the comparison is lacking in several respects. There are significant differences in the ways that railroads and waterways make investment decisions. Railroads make decisions based on market priorities. In contrast, waterway investments are approved (or disapproved) by Congress through a lengthy political process. While there is no certainty that railway investments are optimized, many of the locks on the Upper Mississippi River and Illinois Waterway System are outmoded. The modernization of locks on these segments could affect forecasts of modal energy efficiency. Nevertheless, future waterway investment levels will not alter the fact that railroads are an efficient mode of transporting strategic bulk commodities and are critically important to national energy goals.

Table 10.1 Percentages of Tons Transported by Barge on Inland River Systems in 2008

	River System	
Commodity Group	Mississippi	Ohio
Coal	37.4%	57.8%
Petroleum and Petroleum Products	16.5%	6.6%
Chemicals and Related Products	7.2%	3.6%
Crude Materials	20.0%	22.0%
Primary Manufactured Goods	4.9%	4.5%
Farm Products	13.6%	5.4%
Manufactured Equipment	0.3%	0.0%
Other	0.1%	0.1%

Institute for Water Resources. Waterborne Commerce of the United States, Calendar Year 2009, Part 5–National Summaries, U.S. Army Corps of Engineers, Alexandria, Virginia, 2009.
Reflects internal river traffic only.

10.2 Additional Issues

The methods, data, assumptions and limitations of the study are discussed in greater detail in the main report. However, some interpretive issues are highlighted next. (1) The outcomes and implications of fuel efficiency comparisons may be different, depending upon whether marginal or average estimates are used. Most studies do not explicitly say which factors are being used and why. (2) Comparisons of railway and truck energy efficiencies may vary from state-to-state depending on the types of grandfathered trucks allowed and overweight permitting processes. (3) While fuel consumption for way train movements on Class I railways is reflected in the study, specific estimates for local and regional railroad operations are not. The fuel consumption rates for these movements are assumed to be similar to those experienced by Class I railroads within the same region. Because local railroad movements are short in duration, they should not have a strong influence on the conclusions. (4) The access energy for truck movements to and from river and railway stations was not quantified. (5) While railroad energy efficiencies are specifically developed for individual commodities, river efficiency ratings reflect the average of all commodities moving on a river segment. While most of these movements are comprised of bulk commodities, there may be substantial differences in the net tonnage per barge among commodity groups. These differences are not reflected in the comparisons. As a result, railroad-barge comparisons for specific commodities may reflect averaging errors. (6) Railroad and waterway comparisons are further complicated by the periodic flooding of the Mississippi River basin. Because floods are a reality of waterway transportation, they must be reflected in the comparisons. In this study, a three-year waterway average (centered on 2008) is used to compare waterway and railway fuel efficiencies. Overall, the use of a three-year average yields a waterway efficiency rating of 592 RTM/G, which seems reasonable, given that the most recent five-year average is 588 RTM/G. In essence, the use of a longer averaging period has little or no effect on the comparisons presented in this report. (7) There is some uncertainty regarding the intermodal shipment weights estimated from the waybill sample. Because of reporting practices that assign each container to a railcar even when containers are double stacked, the waybill sample overstates the number of intermodal cars moved and may yield inaccurate results (Railinc 2010). The tare weights used in this study are estimated by assuming an average utilization rate of 1.8 containers per *platform.* A three-car articulated set has three platforms. A five-car articulated set has five platforms, etc. This is equivalent to assuming that 90% of the car spaces where containers could be placed are double stacked, and 90% of TOFC shipments consist of two trailers. These estimates cannot be validated from existing data sources and, consequently, may be subject to error. Moreover, it is noteworthy that the net/gross ratios calculated in this study are much lower than those computed in the ICFI study (2009), where most of the movements analyzed were heavy double-stack shipments.

10.3 Additional Modeling Needs

While this study has provided timely new information on the relative energy efficiency of rail transportation in the United States, much more research is needed before public policies can be fully informed. The access energy consumed by truck movements to and from barge and rail facilities must be modeled before total intermodal energy requirements can be estimated. The transportation circuity factors necessary for modal comparisons are outdated and inadequate for making comprehensive energy assessments. However, the data requirements for estimating new circuity factors and access energy requirements are very extensive. Nothing short of a detailed multimodal GIS model is needed; not just for the transportation network, but for agricultural, forestry, and related land uses and manufacturing enterprises. This is most easily accomplished with crop production, where zonal production can be projected from acres under cultivation and yield forecasts. However, the zones must be small enough for accurate depiction of flows. The use of large production zones provides little benefit and, in fact, may yield misleading results. Because of the fine resolution needed for specific movement comparisons, the development of a multimodal freight GIS model is a major undertaking.

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APPENDIX

Predicted 2008 Fuel Efficiencies of Railroad Movements by Regional Flow and Shipment Type

STCC	Product Name	Regional Flow	Unit Train	Net/ Gross	RTM/G
01	Farm Products	East	0	0.61	424
01	Farm Products	East	1	0.63	594
01	Farm Products	Central	0	0.60	494
01	Farm Products	Central	1	0.63	748
01	Farm Products	West	0	0.61	425
01	Farm Products	West	1	0.64	598
01	Farm Products	East-Central	0	0.61	463
01	Farm Products	East-Central	1	0.63	672
01	Farm Products	East-West	0	0.46	319
01	Farm Products	West-Central	0	0.55	416
01	Farm Products	West-Central	1	0.64	677
08	Forest Products	East	0	0.55	382
08	Forest Products	West	0	0.43	300
08	Forest Products	East-Central	0	0.53	404
08	Forest Products	West-Central	0	0.42	316
09	Fresh Fish or Other Marine Products	East	0	0.40	279
09	Fresh Fish or Other Marine Products	West	0	0.40	279
09	Fresh Fish or Other Marine Products	East-West	0	0.49	341
09	Fresh Fish or Other Marine Products	West-Central	0	0.34	259
10	Metallic Ores	East	0	0.61	429
10	Metallic Ores	East	1	0.63	595
10	Metallic Ores	Central	0	0.63	512
10	Metallic Ores	Central	1	0.64	765
10	Metallic Ores	West	0	0.60	419
10	Metallic Ores	West	1	0.60	563
10	Metallic Ores	East-Central	0	0.60	458
10	Metallic Ores	East-Central	1	0.62	664
10	Metallic Ores	East-West	0	0.53	368
10	Metallic Ores	West-Central	0	0.60	458
10	Metallic Ores	West-Central	1	0.59	625
11	Coal	East	0	0.66	460
11	Coal	East	1	0.67	637
11	Coal	Central	0	0.62	511
11	Coal	Central	1	0.72	856
11	Coal	West	0	0.64	445
11	Coal	West	1	0.70	654
11	Coal	East-Central	0	0.61	462
11	Coal	East-Central	1	0.72	767
11	Coal	East-West	0	0.64	448
11	Coal	East-West	1	0.67	629
11	Coal	West-Central	0	0.62	472
11	Coal	West-Central	1	0.71	750
13	Crude Petroleum, Natural Gas, etc.	East	0	0.16	112
13		Central	0	0.56	462
13		West	0	0.53	371
13		East-Central	0	0.53	405
13		East-West	0	0.41	289
13		West-Central	0	0.49	375
14	Nonmetallic Minerals, except Fuels	East	0	0.64	444
14		East	1	0.64	603

Predicted 2008 Fuel Efficiencies of Railroad Movements by Regional Flow and Shipment Type

STCC	Product Name	Regional Flow	Unit Train	Net/ Gross	RTM/G
14		Central	0	0.63	512
14		Central	1	0.64	766
14		West	0	0.62	430
14		West	1	0.39	360
14		East-Central	0	0.61	461
14		East-Central	1	0.63	666
14		East-West	0	0.52	363
14		West-Central	0	0.61	464
19	Ordnance or Accessories	East	0	0.36	249
19		Central	0	0.37	301
19		West	0	0.21	144
19		East-Central	0	0.41	314
19		East-West	0	0.46	323
19		West-Central	0	0.25	186
20	Food or Kindred Products	East	0	0.54	378
20		East	1	0.63	591
20		Central	0	0.57	464
20		Central	1	0.69	818
20		West	0	0.53	369
20		East-Central	0	0.51	386
20		East-Central	1	0.63	671
20		East-West	0	0.46	320
20		West-Central	0	0.51	389
20		West-Central	1	0.61	648
22	Textile Mill Products	East	0	0.30	208
22		Central	0	0.27	218
22		East-Central	0	0.26	198
22		East-West	0	0.31	215
22		West-Central	0	0.32	244
23	Apparel or Other Finished Textiles	East	0	0.31	214
23		Central	0	0.38	312
23		West	0	0.40	276
23		East-Central	0	0.27	205
23		East-West	0	0.34	237
23		West-Central	0	0.36	272
24	Lumber or Wood Products	East	0	0.53	368
24		Central	0	0.53	435
24		West	0	0.56	389
24		East-Central	0	0.54	413
24		East-West	0	0.56	394
24		West-Central	0	0.56	427
25	Furniture or Fixtures	East	0	0.28	194
25		Central	0	0.31	250
25		West	0	0.29	201
25		East-Central	0	0.28	209
25		East-West	0	0.27	188
25		West-Central	0	0.29	220
26	Pulp, Paper or Allied Products	East	0	0.48	334
26		Central	0	0.51	419
26		West	0	0.55	380
26		East-Central	0	0.50	382
26		East-West	0	0.50	349
26		West-Central	0	0.44	330

Predicted 2008 Fuel Efficiencies of Railroad Movements by Regional Flow and Shipment Type

STCC	Product Name	Regional Flow	Unit Train	Net/ Gross	RTM/G
27	Printed Matter	East	0	0.36	253
27		Central	0	0.44	359
27		East-Central	0	0.24	182
27		East-West	0	0.37	259
27		West-Central	0	0.42	319
28	Chemicals or Allied Products	East	0	0.57	397
28		East	1	0.59	559
28		Central	0	0.57	465
28		Central	1	0.58	692
28		West	0	0.59	411
28		West	1	0.63	588
28		East-Central	0	0.56	422
28		East-Central	1	0.61	649
28		East-West	0	0.55	387
28		West-Central	0	0.56	426
28		West-Central	1	0.64	677
29	Petroleum or Coal Products	East	0	0.50	349
29		East	1	0.51	482
29		Central	0	0.51	418
29		Central	1	0.64	756
29		West	0	0.49	341
29		East-Central	0	0.51	385
29		East-West	0	0.51	359
29		East-West	1	0.70	656
29		West-Central	0	0.52	395
30	Rubber or Misc. Plastics Products	East	0	0.33	233
30		Central	0	0.35	290
30		West	0	0.54	375
30		East-Central	0	0.28	214
30		East-West	0	0.34	235
30		West-Central	0	0.33	254
31	Leather or Leather Products	East	0	0.29	206
31		Central	0	0.30	247
31		West	0	0.44	307
31		East-Central	0	0.28	216
31		East-West	0	0.29	204
31		West-Central	0	0.37	283
32	Clay, Concrete, Glass or Stone Products	East	0	0.62	436
32		East	1	0.62	581
32		Central	0	0.63	515
32		Central	1	0.68	803
32		West	0	0.64	445
32		East-Central	0	0.60	455
32		East-West	0	0.57	400
32		West-Central	0	0.58	438
33	Primary Metal Products	East	0	0.57	398
33		East	1	0.58	548
33		Central	0	0.55	449
33		Central	1	0.21	245
33		West	0	0.59	412
33		West	1	0.70	648
33		East-Central	0	0.54	411
33		East-West	0	0.55	381

Predicted 2008 Fuel Efficiencies of Railroad Movements by Regional Flow and Shipment Type

STCC	Product Name	Regional Flow	Unit Train	Net/ Gross	RTM/G
33		West-Central	0	0.53	401
34	Fabricated Metal Products	East	0	0.30	212
34		Central	0	0.38	312
34		West	0	0.17	117
34		East-Central	0	0.32	245
34		East-West	0	0.34	237
34		West-Central	0	0.33	252
35	Machinery, except Electrical	East	0	0.35	245
35		Central	0	0.32	261
35		West	0	0.39	274
35		East-Central	0	0.38	289
35		East-West	0	0.34	241
35		West-Central	0	0.34	261
36	Electrical Machinery, Equipment, etc.	East	0	0.25	175
36		Central	0	0.29	236
36		West	0	0.41	287
36		East-Central	0	0.21	162
36		East-West	0	0.22	153
36		West-Central	0	0.28	212
37	Transportation Equipment	East	0	0.22	155
37		Central	0	0.26	209
37		West	0	0.25	174
37		East-Central	0	0.24	180
37		East-West	0	0.22	156
37		West-Central	0	0.25	188
39	Miscellaneous Manufacturing Products	East	0	0.29	201
39		Central	0	0.40	331
39		West	0	0.40	282
39		East-Central	0	0.34	261
39		East-West	0	0.30	211
39		West-Central	0	0.31	234
40	Waste or Scrap Materials	East	0	0.57	400
40		Central	0	0.52	423
40		West	0	0.50	347
40		East-Central	0	0.55	416
40		East-West	0	0.48	334
40		West-Central	0	0.47	356
41	Miscellaneous Freight Shipments	East	0	0.22	153
41		Central	0	0.22	177
41		Central	1	0.46	552
41		West	0	0.27	185
41		East-Central	0	0.21	157
41		East-West	0	0.24	169
41		West-Central	0	0.25	191
41		West-Central	1	0.54	568
42	Empty Containers or Shipping Devices	East	0	0.28	195
42		Central	0	0.21	170
42		West	0	0.16	115
42		East-Central	0	0.31	236
42		East-West	0	0.13	92
42		West-Central	0	0.14	108
43	Mail, Express or Other Contract Traffic	East	0	0.29	202
43		Central	0	0.32	264

Predicted 2008 Fuel Efficiencies of Railroad Movements by Regional Flow and Shipment Type

STCC	Product Name	Regional Flow	Unit Train	Net/ Gross	RTM/G
43		West	0	0.41	289
43		East-Central	0	0.29	217
43		East-West	0	0.21	148
43		West-Central	0	0.32	244
44	Freight Forwarder Traffic	East	0	0.31	217
44		Central	0	0.39	321
44		West	0	0.40	276
44		East-Central	0	0.35	266
44		East-West	0	0.34	237
44		West-Central	0	0.36	273
45	Shipper Association or Similar Traffic	East	0	0.38	264
45		West-Central	0	0.35	267
46	Miscellaneous Mixed Shipments	East	0	0.31	214
46		Central	0	0.38	307
46		West	0	0.36	249
46		East-Central	0	0.29	220
46		East-West	0	0.33	228
46		West-Central	0	0.35	266
47	Small Packaged Freight Shipments	East	0	0.23	161
47		Central	0	0.32	262
47		West	0	0.29	203
47		East-Central	0	0.25	193
47		East-West	0	0.33	232
47		West-Central	0	0.29	222
48	Hazardous Wastes	East	0	0.58	408
48		Central	0	0.57	469
48		West	0	0.46	319
48		East-Central	0	0.54	413
48		East-West	0	0.60	419
48		West-Central	0	0.42	319