Steam v Diesel

A comparison of modern steam and diesel in the Class I railroad environment

John Rhodes

The steam versus diesel argument was seemingly settled about 50 years ago on US Class I railroads. But has anything changed on the steam side that would alter the outcome, even with the advancements in diesel technology over the same time period? This is the question that will be weighed here. The comparative cost of coal and diesel fuel shows that a coal-fueled locomotive would have lower fuel costs than a diesel-fueled locomotive. In 2008, the last full year information was available, Powder River Basin (PRB) coal was 15 times cheaper than diesel fuel on a unit of energy basis (one dollar of PRB coal provides 816,327 BTUs and one dollar of diesel provides 49,322 to 53,729 BTUs). The PRB coal cost is average spot market price, from the US Department of Energy with an average rail transportation cost added. The diesel fuel cost is the Class I railroad’s cost of fuel in 2008, as reported by the US Surface Transportation Board. In light of this fact, the steam versus diesel argument shouldn’t be over.

In the last 30 years of US steam (1930-1960), the typical steam locomotive had a thermal efficiency of about 6%, meaning that for every 100 BTUs of coal burned, six BTUs of horsepower were produced. A modern AC traction diesel is almost 36% thermally efficient at the drawbar, by comparison. However, starting in 1932, the Paris-Orleans (P-O) Railway of France, under the direction of André Chapelon, rebuilt locomotives of more than 12% thermal efficiency or double the efficiency of US steam. Why this wasn’t done in the US is another interesting chapter in the story of steam.
André Chapelon, who was born in 1892 and died in 1978, was a mechanical engineer specializing in the fields of thermodynamics and fluid dynamics at the University Ecole Centrale in Paris. He worked for the PLM Railway from 1921 to 1924 but was not appreciated by his superiors. In 1925, he joined the P-O, where management understood his ideas. He was the first locomotive designer to apply thermodynamics and fluid dynamics to the steam locomotive instead of using a trial and error basis for design. To double the efficiency of the steam locomotive, he used higher boiler pressure, about 290 psi, and higher steam temperatures, about 750° Fahrenheit, coupled with a larger cross section steam circuit that was approximately double the size of traditional recommendations, and a more efficient exhaust design. The best analogy is that the traditional steam locomotive was like a runner breathing through a soda straw, while Chapelon let the locomotives breathe properly, and efficiency doubled.

Even at this level of efficiency, 12%, and using PRB coal, with an average transportation cost, the steam locomotive would have a fuel cost 78% lower than the average Class I railroads. This is based on using the relative thermal efficiencies of steam and diesel locomotives and the cost of the fuel input. But improvements in steam technology did not end with Chapelon. They continued with a new generation of designers.

Born in 1922, Livio Dante Porta was an Argentinean mechanical engineer who moved the technology and performance of the steam locomotive farther than any other person. At the age of 27, he built his first steam locomotive, Argentina. Argentina was the most efficient steam locomotive of the late steam era, more than double the efficiency of a standard US steam locomotive. ‘The importance of Livio Dante Porta to the survival of the steam locomotive into the 21st century, and to any possible future large scale revival of its use, is difficult to exaggerate’, stated George Carpenter, translator of André Chapelon’s book ‘La Locomotive A Vapeur’. Porta, who died in 2003, developed three very important parts of modern steam:

- Clean high efficiency combustion – Gas Producer Combustion System (GPCS)
- High efficiency exhaust – Kylpor, Lempor & Lemprex
- Heavy-duty boiler water treatment, known as Porta Treatment (PT)

Porta (right) and David Wardale (left) stand beside one of Porta’s last projects, the Minaz 1816 of Cuba at the ECOVAPOR conference in Cuba, 1999.

Shaun McMahon

Five engineers have followed in Porta’s footsteps. The first one of them is David Wardale, who in 1981 transformed the South African Railway (SAR) Class 25NC 4-8-4 3450 into the SAR Class 26. He raised the drawbar horsepower (dbhp) from 2,500 to 4,000, a 60% increase, and increased the efficiency to double the thermal efficiency of US steam, utilizing GPCS, Lempor Exhaust and Porta Water Treatment.

Four men continue work on modern steam: Phil Girdlestone of Girdlestone & Associates of South Africa; Shaun McMahon, currently working for the Rio Turbio Railway and the National Institute of
Industrial Technology in Argentina; Nigel Day of Modern Steam Technical Railway Services of Wales; and Roger Waller of Dampflokomotiv-und Maschinenfabrik AG (DLM) of Switzerland.

The 1949 *Argentina*, was a 2,100 dbhp, 4-8-0 steam locomotive with a high power-to-weight ratio of 1 hp to 65 pounds.

Martyn Bane

South African Railways Class 26 3450, named *LD Porta* is nicknamed ‘The Red Devil’.

Martyn Bane

Porta’s two classifications for modern steam locomotives were Second Generation Steam and Third Generation Steam Locomotives. Porta’s outline for Second Generation Steam included:

- 14% thermal efficiency, more than twice traditional US steam locomotives
- 290-362 psi, 840°F steam
- Compound expansion
- Internal streamlining applied to piston valves
- Advanced valve and piston tribology (the science of rubbing surfaces)
- Advanced exhaust design
- Advanced steam circuit design
- Economizer
- Feedwater and combustion air pre-heating
- Gas Producer Combustion System (GPCS) with cyclonic flame path
- Advanced feed water treatment
- Exaggerated cylinder and boiler thermal insulation
- High rotational speed (504 rpm, American Association of Railroads [AAR] 1947)
- Elimination of dynamic augment
- Ergonomic operation
- Environmentally responsible
- Roller bearings throughout
- Piston and valve rings: no leaks 600,000 miles
- Advanced packing materials for valves
- Attention to detail design (This, since poor design greatly increases maintenance)

Porta’s outline for Third Generation Steam included all advancements of Second Generation Steam plus:

- 21% thermal efficiency, three times greater traditional US steam locomotives
- 870 psi, 1020°F steam
- Triple expansion
- Three-stage feed water and combustion air heating

Porta maintained that 27% thermal efficiency with condensing would be possible. By comparison, an EMD SD70ACe, an AC traction diesel-electric, has a drawbar thermal efficiency of almost 36%.

**Gas Producer Combustion System**

Porta developed the Gas Producer Combustion System (GPCS), which to date has been the most efficient method of solid fuel combustion in steam locomotives. In a traditional locomotive firebox, coal is burned with 90% primary air coming through the firebed and 10% secondary air entering above the fire.

To put it simply, with GPCS, the firebed becomes a gas producer by making it thick. In a GPCS firebed, coal + steam + 30% primary air react to form carbon monoxide (CO), hydrogen (H₂) and methane (CH₄). This combustible gas mixture is burned above the firebed with 70% of the air admitted as secondary air. The steam, in addition to being part of the chemical reaction, keeps the firebed below the ash fusion temperature, vastly reducing the formation of clinkers. The use of GPCS allows much higher fuel burn rates than conventional fireboxes.

The use of GPCS provides impressive environmental benefits. First, smoke disappears due to complete combustion through gasification of the fuel. Also, carbon monoxide (CO) and hydrocarbon (HC) emissions virtually disappear. In addition, oxides of nitrogen (NOX) emissions are very low. Porta asserted that with GPCS, sulphur can also be controlled by blending the fuel with a calcite-dolomite mixture. GPCS can burn essentially any reasonable combination of solid fuels, such as firewood logs, sawmill rejects, sugar cane waste, many coals, charcoal fines mixed with oil, petroleum coke, biomass and waste products. The use of wood chips from tree farms would be carbon neutral.
Porta began developing the Lempor Exhaust in 1952. It is the most efficient exhaust ejector design to date. It supplanted Chapelon’s Kylchap exhaust design of 1925 as the most efficient. The use of exhaust steam to draft the firebox has been at the heart of the steam locomotive since the time of Trevithick in 1804. The Lempor Exhaust is two or more times as efficient as the classic US design, with efficiency defined as the amount of draft it can create for each psi of backpressure on the cylinders. The successor to the Lempor, the Lemprex Exhaust, which should be more efficient, began its development under Porta in the 1980’s and is under development by Shaun McMahon and others today.
Porta Water Treatment

In 1969, Porta Water Treatment (PT) was developed as an outgrowth of advanced treatment used on the railways of France, TIA (Traitement Integral Armand) Water Treatment, (1940.) Porta developed PT for the Ferrocarril Nacional General Belgrano Railway of Argentina. In PT, the chemistry of the boiler water keeps any scale or mud-forming material in solution or suspension, which leads to high total dissolved solids. Antifoams are used to prevent boiler water carryover or priming. Controlled foaming acts as a sieve, leading to pure steam.

Important benefits can be attributed to the use of PT. It eliminates the formation of scale, which reduces fuel consumption - even a thin coating (1/8 inch) can increase fuel consumption by 25%. Boiler washouts are increased to a nine to 12-month cycle from a 10 to 30-day cycle. Boiler blowdowns, which use fuel and water, can be performed on a two-month cycle instead of every shift. If PT and GPCS are used in concert, even greater maintenance benefits can be had since PT preserves the water side of the boiler in basically ‘as built’ condition, and GPCS largely eliminates the sandblasting effect by unburned coal particles. Boiler tubes, flues, superheater elements and firebox plates can last 30 years with no replacements. The use of PT and GPCS, with a properly designed boiler, lead to a virtual elimination of boiler maintenance. The US railroads in the steam era contended that this boiler maintenance, which would be virtually eliminated, accounted for 91% of the maintenance cost of a steam locomotive.

The above facts should lead to a re-examination of the prevailing view that steam locomotives are more expensive to maintain than diesels. This observation is true when comparing 1920s design, heavily-worn locomotives utilizing poor servicing facilities to new first generation diesels, which was the case of the comparison when America dieselized. However, steam locomotives with one-piece cast steel frames, roller-bearings on all axles and motion pieces and
complete mechanical and pressure lubrication were actually cheaper to maintain than diesels. This was demonstrated by a maintenance comparison performed by the Norfolk and Western (N&W) and Southern Railways. The N&W agreed to develop a maintenance comparison of the then new Class J 4-8-4 and a then new EMD E6<sup>2</sup>. The locomotives in the test were used in similar services, and the Class J 4-8-4 had 29% lower maintenance costs versus the EMD E6 over the course of the test period. Also, H.F. Brown of the Institution of Mechanical Engineers produced a study showing that the steam locomotive was significantly cheaper than the diesel in the post World War II US period. From 1963 to 1986, the South African Railway (SAR) Class 25NC, a locomotive very similar to the N&W Class J, was 20% cheaper to maintain than the comparable diesel. In addition, the lifecycle costs of the 25NC were cheaper than the comparable SAR diesel. This evidence shows it is probable that a modern steam locomotive could have maintenance costs that are similar to or less than contemporary diesel locomotives.

In spite of this, a high efficiency, lower maintenance version of a traditional late US steam locomotive wouldn’t fulfill the requirements of modern US Class I railroads. US Class I railroads need the following attributes that are available in diesel locomotives: automated boiler controls, multiple unit capability, traction control, dynamic braking, distributed power and remote control capability and improved crew comfort versus a traditional steam locomotive. Power plants have had automated boiler controls for years, and the use of this type of control on any US locomotive would be necessary to prevent the need for a fireman and would undoubtedly be needed to meet environmental compliance. Automated boiler controls, along with electric control of throttle and cutoff, could form the heart of multiple unit (MU) capability. MU capability would allow a single engineer to control many locomotives in the normal way or through distributed power or remote control. A computerized traction control system that restricts steam being exhausted from the cylinders to prevent a wheel slip from occurring could be used on a modern steam locomotive. Diesel locomotives have dynamic brakes, and a modern steam locomotive could utilize compression or ‘water’ brakes. Steam locomotives in many other countries, as well as the Denver & Rio Grande Western Railway here, have used compression brakes. Crews must have a cab that is as comfortable as a diesel, and a cab of the same design as a diesel could be fitted to the end of the tender, allowing the same level of comfort for crews.

A modern steam locomotive would require different fueling and servicing infrastructure from that used by diesels today. The Norfolk and Western Railway had the most advanced fueling and servicing infrastructure of any railway. Their designs could form the basis of new facilities. The N&W had a 2,000-ton coaling station that could fill four locomotives facing in either direction with coal, water and sand on any of four tracks at one spotting in less than 10 minutes. These coaling stations were built by Roberts and Schafer Engineering, which still builds material handling equipment for the mining and power generation industries. On a monthly basis, locomotives would need lubricating and fire cleaning. The longer fire cleaning interval is due to GPCS combustion using steam jets underneath the firebed, which keeps the fire below the ash fusion temperature of the coal so the amount of clinker formation is minimal. Modern steam would use V-Section Anti Clinker Grinding Grates, a new type of constant rocking grates that would grind up whatever small amount of clinker forms and eject it into the ashpan. The Norfolk and Western had two hydraulic ash plants built by United Conveyor Corporation which continues to produce ash handling equipment for the power generation industry. These ash plants used water to automatically move ash from pits underneath the locomotives to dewatering bins and then finally hopper cars for disposal.

A modern steam locomotive for US Class I railroads should be comparable in performance to a General Electric (GE) ES44AC. This is a very typical locomotive in Class I service today. The ES44AC has a 4,400 hp prime mover, six powered axles, 180,000 pounds starting tractive effort
and dynamic brakes. A Third Generation steam locomotive in the form of a five cylinder, 2-8-8-2 could match the performance of an ES44AC. The steam locomotive would have a diesel type cab in the end of the tender, along with compression braking in lieu of dynamic brakes. The steam locomotive would utilize triple expansion, having one high pressure and one intermediate pressure cylinder on one engine group and three low-pressure cylinders on the other engine group. The principal specifications of this locomotive are as follows:

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal efficiency</td>
<td>21 percent</td>
</tr>
<tr>
<td>Maximum HP</td>
<td>5,900 At drawbar</td>
</tr>
<tr>
<td>Maximum tractive effort</td>
<td>180,000 Pounds</td>
</tr>
<tr>
<td>Driver diameter</td>
<td>60 Inches</td>
</tr>
<tr>
<td>Full weight</td>
<td>1,500,000 Pounds</td>
</tr>
<tr>
<td>Max speed</td>
<td>90 MPH</td>
</tr>
<tr>
<td>Grate area</td>
<td>71 Square feet</td>
</tr>
<tr>
<td>Average hourly coal</td>
<td>2.44 Tons</td>
</tr>
<tr>
<td>Average hourly water</td>
<td>2,880 Gallons</td>
</tr>
<tr>
<td>Tender:</td>
<td>4 axles</td>
</tr>
<tr>
<td>Coal capacity</td>
<td>51 Tons</td>
</tr>
<tr>
<td>Water capacity</td>
<td>10,474 Gallons</td>
</tr>
<tr>
<td>2 water tank cars</td>
<td>50,000 Gallons total</td>
</tr>
<tr>
<td>Running time</td>
<td>21 Hours</td>
</tr>
</tbody>
</table>

The 2-8-8-2 is approximately 118 feet for the engine and tender and another 120 feet for both water tank cars. The locomotive is 15.5 feet tall. The dashed line is the bottom of the coal space angled to the stoker trough.

*John Rhodes drawing*
Drawbar pull of 2-8-8-2 and ES44AC

Drawbar horsepower of 2-8-8-2 and ES44AC

All 2-8-8-2 performance data is estimated from the Porta proposed Third Generation 2-10-0 of 1978 with the assistance and concurrence of Shaun McMahon and Nigel Day.

In the past, it has been said that the cost of fuel for steam locomotives sitting at idle was high. Today this wouldn’t be the case, due to better design and low fuel cost. The 2-8-8-2 described
above would cost 10% of the cost of an Auxiliary Power Unit (APU) equipped diesel locomotive sitting at idle. Also, the 2-8-8-2 would have a fuel and water range 6% greater than the ES44AC, due to its low fuel consumption and large tenders.

US Class I railroads use a computer simulation model to simulate capacity and train performance. The Class I railroads have standardized on the Berkeley Simulation Software Rail Traffic Controller or RTC rather than on other competing simulation programs. This model was used to compare the performance and fuel consumption of the 2-8-8-2 and the ES44AC. RTC includes a train performance calculator (TPC) which was used to compare the performance and fuel consumption of modern steam and diesel locomotives in a simulated railroad environment.

The steam versus diesel simulation comparisons were made on the Norfolk Southern Pocahontas District between Bluefield and Williamson, West Virginia, and Burlington Northern Santa Fe (BNSF) Railway Clovis Subdivision (a section of the Transcon), between Clovis and Vaughn, New Mexico. The NS section has heavy grades (1.4%); many sharp curves (10+º); 25-40 mph speed limits; and heavy tonnage (20,000 ton trains). In contrast, the BNSF section has moderate grades (0.8%); few curves (1º); 60-70 mph speed limits with fast trailer and double stack trains. Current operating practices and procedures of the railroads were used in the simulations.

Screen prints from individual runs of trains on the train performance calculator are shown.
- The dark grey shaded area in the top section represents the track speed.
- The red line represents the target speed for the train. This can be less than the track speed for many reasons, such as train length, recovering from speed restrictions, or stopping to add helpers as in the case of the loaded coal trains from Williamson to Bluefield.
- The green line represents the actual speed of the train.
- The other three sections are labeled.
- The throttle section shows the throttle position during the run.
- The elapsed time and mileage are listed at the bottom.

### Diesel – Loaded coal from Williamson to Bluefield, West Virginia – Norfolk Southern.

The two places where the speed drops to 0 are where helpers and then cars are added.
Steam – Loaded coal from Williamson to Bluefield, West Virginia – Norfolk Southern.

The two places where the speed drops to 0 are where helpers and then cars are added.

Diesel – Trailers from Clovis to Vaughn, New Mexico – BNSF Railway.
Steam – Trailers from Clovis to Vaughn, New Mexico – BNSF Railway.

The RTC simulation showed that the steam locomotives had fuel consumption equating to costs 89 percent less than the diesel locomotives. In 2008, the Class Is had a diesel fuel bill of $12.2 billion, which could be reduced to a $1.3 billion coal bill, resulting in a $10.9 billion cost saving per year. In all the services modelled, the cost savings ranged from 88.2% to 90.1%, based on ton-miles per dollar of fuel consumption. The steam locomotives consumed an average of 2.44 tons of coal and 2,880 gallons of water per hour, while the diesel locomotives averaged 252 gallons of fuel per hour.

As can be seen by comparing the RTC screenshots of steam and diesel runs, the steam locomotives gave a higher level of train performance than the diesel locomotives. On heavy tonnage trains, one steam locomotive was used for each diesel. The steam locomotive had higher hp and tonnage, which allowed the steam locomotives to attain a 25% increase in ton-miles per hour and to reduce the running time by 25 minutes on the NS section from Williamson to Bluefield, West Virginia. On fast trains on the BNSF from Clovis to Vaughn, New Mexico, horsepower was equated allowing three steam locomotives to match the performance of four diesels. The steam locomotives’ higher hp at higher speed gave slightly higher average speeds and about a 3% increase in ton-miles per hour.

This leads to the question of how much money could be saved by the US Class I railroads if they converted to steam. Over the first five years, the estimated cost to install fueling and routine maintenance facilities, but not heavy maintenance facilities, is $1.7 billion. It would take $18 billion over 15 years above programmed locomotive fleet renewal costs to purchase the needed steam locomotives. The locomotive cost was estimated by Roger Waller of DLM. Even with these costs of nearly $20 billion factored out, the modern steam locomotive could produce almost $50 billion in fuel cost savings over the 15-year implementation period.

The collected evidence would show that the steam versus diesel argument is not decided, as
conventional wisdom would suggest. A more in-depth study of steam versus diesel would seem appropriate as a first step. If the feasibility study shows promise in steam, then a prototype modern steam locomotive should be built and tested. There would be three important factors that would determine the success of the prototype testing: 1) performance, 2) economics and 3) emissions.

The conclusion may be that steam locomotives should be utilized again. With the fluctuating costs of petroleum-based fuels, i.e., diesel, and the instability of Middle East governments controlling those fuels, it would seem advisable to conduct studies to see if US coal, and steam-powered locomotives, could provide the most efficient, economical and environmentally-balanced way to keep the nation’s railroads running.

Notes
1 Water treatment process for steam locomotives invented by Louis Armand.
2 A 1941 cab unit diesel electric passenger locomotive, an E-unit, uses 2 A-1-A trucks and has 2000hp from 2ea 12 cylinder 567 prime movers.

Further Reading

John Rhodes is a Transportation Analyst at the railroad consulting firm of R.L. Banks & Associates, Inc. of Arlington, VA (Virginia). This is his first Trains byline. He would like to thank Eric Wilson, owner of Berkeley Simulation Software, for allowing him to use the Berkeley model for this purpose. Additionally, he would like to thank Charles Banks, President R.L. Banks & Associates, Inc. – (his employer) for railroad information (track charts and employee timetables to create the network in RTC).