The Economics of Coal as a Locomotive Fuel on US Class I[1] Railroads

By John Rhodes, student
For Dr. Ken Button, professor

Executive Summary:

A coal-fueled locomotive could achieve a 64.2% average cost savings[2] over the current petroleum diesel-fueled locomotive. This comparison is based on ton-miles per dollar of fuel consumed in calendar year 2006. US Class I railroads burned 4.2 billion[3] gallons of diesel fuel in 2006, costing $8.1 billion[4]. The dollar value of coal that would accomplish the same amount of "work" is only $3.0 billion[5], according to calculations. This is a cost savings of $5.1 billion[6] in the single year of 2006. That is an incredible cost savings over the use of diesel fuel, which is largely imported, compared to coal, which is mined locally in the US. Those 4.2 billion gallons of diesel fuel comprise 6.6%[7] of the nation's diesel fuel use. That quantity of diesel fuel could be replaced by 72.3 million[8] tons of coal, equivalent to only 6.2%[9] of the 1.16 billion[10] ton yearly production of coal.

Use of coal-fueled locomotives would require the replacement of the US Class I's fleet of locomotives. The Class I's would need to buy an estimated 21,347 new coal-fueled locomotives[11] to replace the current fleet of diesels. That is expected to cost $3.5 billion[12] per year over each of fifteen years compared to $1.7 billion[13] spent annually on new diesels assuming a 25-year renewal rate. Also, new locomotive servicing facilities would need to be constructed. It is estimated that the cost of providing these new

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[1] AAR definition of Class I railroad is a railroad having $319.3 million or more in operating revenue. From aar.org, Class I Railroad Statistics, page 1 of 7

[2] Calculated on, "Fuel Cost TM Comparison All.xls" Sheet: "Overview Cost" Cell J25 in the file addendum.

[3] Calculated on, "Fuel Cost TM Comparison All.xls" Sheet: "Overview Fuel" Cell J24 in the file addendum.

[4] Calculated on, "Fuel Cost TM Comparison All.xls" Sheet: "Overview Cost" Cell J22 in the file addendum.

[5] Calculated on, "Fuel Cost TM Comparison All.xls" Sheet: "Overview Cost" Cell J23 in the file addendum.

[6] Calculated on, "Fuel Cost TM Comparison All.xls" Sheet: "Overview Cost" Cell J24 in the file addendum.

[7] Calculated on, "Petroleum Consumption.xls" Sheet: "Petroleum Used" Cell C4 in the file addendum.

[8] Calculated on, "Fuel Cost TM Comparison All.xls" Sheet: "Overview Fuel" Cell J25 in the file addendum.

[9] Calculated on, "Coal Production.xls" Sheet: "Coal Production" Cell C5 in the file addendum.

[10] Calculated on, "Coal Production.xls" Sheet: "Coal Production" Cell C3 in the file addendum.

[11] Calculated on, "Loco Fleet RR.xls" Sheet: "Freight Fleet Comparison" Cell I13 in the file addendum.

[12] Calculated on, "Loco Fleet RR.xls" Sheet: "Freight Fleet Comparison" Cell L13 in the file addendum.

[13] Calculated on, "Loco Fleet RR.xls" Sheet: "Freight Fleet Comparison" Cell L25 in the file addendum.

facilities would be $496.1 million[14] per year for first five years at the start of the conversion process.

It is estimated that the breakeven point, where the fuel cost savings pay for the added locomotive acquisition cost and for the installation of servicing facilities (combined coaling and watering facilities, watering facilities and servicing facilities), would be reached in the eleventh year of the conversion process to coal-fueled locomotives, under very conservative assumptions, as will be explained in the next paragraph.[15] During the fifteen-year conversion process, the cumulative net cost savings is estimated to be $9.5 billion.[16] This cost savings does not include the cost of retraining employees to run and work on and the conversion of heavy rebuilt facilities to handle coal-fueled locomotives.

These calculations are based on conservative assumptions in a number of areas. The breakeven point could easily be in the fifth year as opposed to the eleventh. One determining factor is the cost of the new locomotive fleet. At the suggestion of Roger Waller of DLM, the Swiss locomotive manufacturing and rebuilding company, the cost of the new coal-fueled locomotive was set at a cost of 50% higher than a comparable diesel electric, even though in his technical judgment he believes the locomotives in volume series production would cost the same as diesel-electrics.[17] This fact alone would reduce the time in which the breakeven would occur to during the fifth year. Also, the comparison doesn't take into account that the cost of diesel on a BTU basis is expected to rise by 8.5% between 2006 and 2030 while coal is expected to drop by 0.4% in inflation-adjusted dollars.[18] This factor alone, or coupled with expected increases in rail traffic, will greatly increase the yearly cost saving from the use of coal-fueled locomotives versus diesel-electrics. In addition, the locomotives used in this paper to drive the cost comparison are only half as fuel efficient as what is expected by L. D. Porta, as referenced later in this paper. While some level of improvement in the fuel efficiency of the diesel-electric is obviously expected, it cannot be expected that the diesel-electric will increase 100% in its fuel efficiency during the fifteen-year study term. The convergence of these many factors could make the cost savings from the use of coal-fueled locomotives even better than what is stated in this report. Also, the infrastructure costs do not include any credit for what dollars would have been spent on diesel-electric-related infrastructure that could be reallocated to coal-fueled locomotive infrastructure expense.

The main reason for this substantial cost savings is that coal is a much better energy value than diesel fuel. One dollar only bought American Class I railroads between roughly 75,000 and 91,000 BTU's using diesel fuel. Coal, on the other hand, would yield 440,000 to 670,000 BTU's for the same one dollar of fuel purchased. This

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[14] Calculated on, "Infrastructure.xls" Sheet: "Infrastructure RR" Cell K14 in the file addendum.

[15] Calculated on, "Breakeven.xls" Sheet: "Breakeven" Cell M7 in the file addendum.

[16] Calculated on, "Breakeven.xls" Sheet: "Breakeven" Cell P7 in the file addendum.

[17] Roger Waller, e-mail message to author, December 20, 2007.

[18] "Annual Energy Outlook 2008 (Early Release)," The Energy Information Administration, http://www.eia.doe.gov/oiaf/aeo/prices.html

extraordinary difference explains why the American power industry uses so much coal to generate electricity. Coal is a very inexpensive fuel comparatively.[19]

The coal-fueled locomotive would be a modern steam locomotive with a coal gasifying combustion cycle that would be environmentally friendly and low maintenance as well as be able to deliver power and use characteristics comparable to the diesel-electric locomotive.

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[19] Calculated on, “BTU Comparison” Sheet: “Comparison” Line 8 A-M in the file addendum.


Cumulative Cost Savings Steam
Cost Savings in Millions of Dollars
$60,000
$55,000
$50,000
$45,000
$40,000
$35,000
$30,000
$25,000
$20,000
$15,000
$10,000
$5,000
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$(5,000)
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Modern Steam:

The concept of the Modern Steam Locomotive stems from the fact that, "It is false that the STEPHENSONIAN steam locomotive attained the maximum possible degree of thermal efficiency, performance, productivity and financial return on investment. This is a widespread opinion shared by steam engineers who, after the war (World War II), did not produce advances in parallel with other technologies."[20] But Modern "…Steam is not a comeback of the steam locomotives which they (enthusiasts) once loved. Instead it incorporates the most advanced level of modern engineering, even if the wheels are still round, the boiler is still used to evaporate water and a bunker is still used to carry the fuel."[21]

The Mechanical Engineers:

Two mechanical engineers, now deceased, were responsible for the initiation of the Modern Steam Locomotive. Andre Chapelon can be considered the grandfather of Modern Steam. Chapelon was a French Mechanical Engineer born 1892.[22] Chapelon worked as a mechanical engineer at SNCF's, the French national railway, Steam Locomotive Design Division. He advanced the Modern Steam Locomotive by applying the principles of Thermodynamics and Fluid Dynamics to the design of the steam locomotive which had been mostly designed in an empirical nature, especially in the US. This manifested itself when Chapelon was able to use these principles to in some cases double the horsepower output of certain locomotives, such as his four-cylinder compound 4-8-0 of the Paris-Orleans Railway and the SNCF 141P class redesigned from PLM 2-8-2's. His crowning achievement was the 1946 design and construction of the three-cylinder compound SNCF 242A1, rebuilt from a three cylinder simple locomotive. He was able to raise the cylinder or indicated horsepower from 2,800 to 5,500. This high horsepower output caused the SNCF to increase the horsepower rating of a new electric locomotive designed nearly 20 years later so it would not be embarrassed by a steam locomotive. Chapelon's former boss, George Chan, from the SNCF described him as "'the man who gave new life to the steam locomotive.'" He died in 1978 at the age of 85.[23]

The other mechanical engineer was Ing Livio Dante Porta. He is considered the father of Modern Steam and was born in 1922.[24] In 1949, at the age of 27, he rebuilt his first steam locomotive, a meter-gauge four-cylinder 4-8-0 "Argentina." The Argentina

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[20] Ing. Livio D. Porta, Consulting Engineer, "XXIst Century Steam The Day of Modern Steam Traction," Buenos Aires, Dec. 15th, 1997, http://www.martynbane.co.uk/modernsteam/ldp/articlesbyldp/xxist.htm

[21] Ibid.

[22] Andre Chapelon, http://en.wikipedia.org/wiki/Andr%C3%A9_Chapelon

[23] Andre Chapelon, *La Locomotive A Vapeur*, trans. George W. Carpenter, C.Eng., M.I. Mech.E. (Great Britain: Camden Miniature Steam Service, 2000), 3, 4 and 340

[24] Ibid, 612-614, entire paragraph on Porta

had double the efficiency of the standard US steam locomotive.[25] The Argentina also recorded, along with Chapelon's 240P, the highest power to weight ratio ever recorded by a steam locomotive. Two of Porta's most significant developments in the cause of Modern Steam had their basis in this locomotive, the Gas Producer Combustion System (GPCS) and the Kylpor & Lempor exhaust systems, which will be explained in more detail later in this paper. In 1957, Porta became the manager of the Rio Turbio Railway in the southern tip of Argentina. There he perfected the use of GPCS on 20 Mitsubishi built 2-10-2's. In 1969, he started development work on the third item that is a hallmark of the Modern Steam Locomotive, heavy-duty boiler water treatment and continued his development work on steam locomotive exhaust systems. His system based on the French TIA boiler water treatment system, which has come to be known as Porta Treatment, has been found to be the best boiler water treatment ever developed, massively reducing boiler maintenance costs. Porta Treatment will be discussed in detail later in this paper. George Carpenter, who translated Andre Chapelon's seminal work on the Steam Locomotive, had this to say about L. D. Porta:

> "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. Whilst he has followed Chapelon's principles and practices, he has developed them further, and just as importantly has passed both his own and Chapelon's principles on to a new generation of steam engineers."

Porta died June 10th, 2003 at the age of 81 in his native Argentina.[26]

Five steam engineers are continuing the work of developing Modern Steam. They and their companies are: David Wardale, Wardale Engineering and Associates; Phil Girdlestone, Girdlestone and Associates; Shaun McMahon, currently employed by the Rio Turbio Railway and consultant to Ferrocarril Austral Fueguino Railway; Nigel Day, Modern Steam Technical Railway Services; and Roger Waller, Dampflokomotiv- und Maschinenfabrik DLM AG.

David Wardale began his railway career by working as a mechanical engineer with British Railways for two years after his graduation, before moving to South Africa in 1974 specifically to work on steam locomotives, since nearly 2,000 were still in use on the railway.[27] Wardale became an Assistant Engineer (Traction) in the production section of the South African Railways (SAR). Wardale, by sheer persistence, cajoled his superiors into allowing him to modify a locomotive. He was allowed to install GPCS and a Lempor exhaust on a SAR Class 19D 4-8-2, this was the first installation of a Lempor exhaust outside of Argentina. L. D. Porta was his long distance adviser for this and his next and final project with the SAR. Wardale's crowning achievement thus far was the

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[25] The Argentina had a thermal efficiency of 13% according to http://www.martynbane.co.uk/modernsteam/ldp/argentina/arg.htm. The average US steam locomotive had a thermal efficiency of 6% to 7% according to Ralph Johnson, *The Steam Locomotive* (Omaha: Simmons-Boardman, 2002), 385

[26] Livio Dante Porta Obituary, http://www.martynbane.co.uk/modernsteam/ldp/portaobituary_thegaurdian.htm

[27] Andre Chapelon, *La Locomotive A Vapeur*, trans. George W. Carpenter, C.Eng., M.I. Mech.E. (Great Britain: Camden Miniature Steam Service, 2000), 615-616

metamorphosis of a Class 25NC to a Class 26 4-8-4.[28] Wardale was able to get the grudging approval of his superiors to make another modification job on a locomotive. This time he would have more resources and a comprehensive rebuild, again with the tutoring of L. D. Porta. The locomotive was extensively modified with 33 systems or sub-systems modified to increase efficiency, power and reliability, including the application of GPCS, Lempor Exhaust, Porta Treatment and an improved steam circuit. The Class 26 reduced coal consumption by between 30% and 60% and water consumption by between 20% and 45% which corresponds to an increase in thermal efficiency of between 43% and 150% over the 25NC Class. In 1975, the 25NC could produce more than three times the amount of work as the SAR's contemporary diesel-electric per unit of fuel cost. The Class 26 would have fared even better, but the SAR management was set on dieselization anyway. Wardale went on to work on a new steam design for the Chinese, but the project was canceled due to China's desire to dieselize.

Wardale was also a part of the aborted attempt to introduce a new steam locomotive in the US in the 1980's, with L.D. Porta and Ross Rowland. This is the American Coal Enterprises' ACE3000. This project lost momentum when the spiking cost of oil in the 1980's returned to more normal levels. Currently, Wardale is working on the design and construction of an advanced 2,500 HP, 125 MPH, 4-6-0 for the British leisure train industry. Calculations show that this locomotive will have greater efficiency than even his Class 26 project.[29] The project can be seen at http://www.5at.co.uk/.

Phil Girdlestone entered the profession of steam locomotive mechanical engineer in 1978. He began his career working at the Ffestiniog Railway in the UK. He worked with David Wardale and L.D. Porta, learning Modern Steam technology. He has rebuilt and modernized five locomotives on three continents. He has also installed Lempor Exhausts and oil firing systems on a handful of other locomotives. He built Ferrocarril Austral Fueguino (FCAF) Railway No. 5, a new 2-foot gauge 0-4-0+0-4-0 Garratt for Argentina. His company, Girdlestone & Associates, is based in South Africa and specializes in the modernization and construction of steam locomotives.[30]

Shaun McMahon also started on the Ffestiniog Railway, but in 1979. He then moved to South Africa to work on the Alfred County Railway for Phil Girdlestone on the modernization of two Class NGG16, 2-6-2+2-6-2 Garratt type locomotives. McMahon has also been associated with Porta since they met in 1990. He also worked with Nigel Day modernizing locomotives under the name of Day & McMahon Steam Technical Services. In the late 1990's, he became Tranex Turismo's Technical Manager overseeing the operations of the FCAF Railway. He, along with Porta, modernized the two FCAF Steam locomotives of the fleet. He managed the new locomotive purchase for the FCAF, bought from Girdlestone & Associates. McMahon has become increasingly involved with the application of Porta Treatment along with Martyn Bane of the UK. In 2004

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[28] David Wardale, *The Red Devil and Other Tales from the Age of Steam* (Scotland: Highland Printers, 2002), 146, 217, 46, 413, 375

[29] 21st Century Steam - The 5AT Project http://www.5at.co.uk/

[30] Andre Chapelon, *La Locomotive A Vapeur*, trans. George W. Carpenter, C.Eng., M.I. Mech.E. (Great Britain: Camden Miniature Steam Service, 2000), 617, 618

McMahon was hired by the Rio Turbio Railway in Argentina to convert it to steam traction. He is now in the process of modernizing the 2-10-2's that were first under Porta's care. The coal hauling Rio Turbio will also be extended through Chile to the coast to be a transcontinental railway. This is the first railway to be in the process of converting from diesels to Modern Steam Locomotives.[31]

Nigel Day is self-taught in Modern Steam; his career started in 1977. He worked with Shaun McMahon for a time and has modernized locomotives on about a dozen railroads. His modernizations have centered on the installations of Lempor exhausts and light oil (diesel fuel) firing systems. His most recent project was the installation of a Lempor exhaust on Union Pacific's Challenger No. 3985, a locomotive in their steam program. This modernization will reduce the operating cost and increase the power output.[32]

Roger Waller, a Swiss locomotive mechanical engineer, first became acquainted with Modern Steam when he worked as an assistant to Wardale on the Red Devil in South Africa. He became convinced that a market for the Modern Steam Locomotive exists today. Through Swiss Locomotive and Machine Works and now his company DLM, six new rack steam locomotives were produced for Switzerland and Austria, having lower emissions than the diesel locomotives they replaced. DLM, with the help of Porta, modernized the German 2-10-0 No. 52 8055. The locomotive had more than 70% of the parts and systems modified or replaced in the modernization. The locomotive now has lower emissions than a diesel locomotive and is the most advanced standard gauge steam locomotive running today. DLM has produced a new marine steam engine for a paddle steamer in Switzerland. The owners chose to switch from diesel electric to steam because of the similar operating costs, lower emissions and the longevity of the power system, expected to last nearly three times as long as a diesel electric power system. DLM has two other locomotives on the drawing board as well as actively rebuilding other steam locomotives and producing component parts for the European market.[33]

The steam electric is also being studied as an alternative to the diesel electric locomotive. Tom Blasingame of the T. W. Blasingame Company has been working on the development of coal fueled steam electric locomotives since the 1980's. Matt Janssen of the Vapor Locomotive Company is also working on a steam electric, but powered by biomass.

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[31] Ibid, 618-620 and The Work of Shaun McMahon http://www.martynbane.co.uk/modernsteam/smcmahon/smcmahon.htm and http://www.martynbane.co.uk/modernsteam/smcmahon/rfirt/oct04news.htm

[32] Andre Chapelon, *La Locomotive A Vapeur*, trans. George W. Carpenter, C.Eng., M.I. Mech.E. (Great Britain: Camden Miniature Steam Service, 2000), 620 and http://www.martynbane.co.uk/modernsteam/nday/nigeldayhome.htm and personal communication with Nigel.

[33] Andre Chapelon, *La Locomotive A Vapeur*, trans. George W. Carpenter, C.Eng., M.I. Mech.E. (Great Britain: Camden Miniature Steam Service, 2000), 620-623 and http://www.martynbane.co.uk/modernsteam/dlm/dlm.htm

The Modern Steam Locomotive:

L. D. Porta described the Modern Steam Locomotive as follows. He said that, "The development of steam traction may be divided into four generations of locomotives:

- Generation 'zero,' the bulk of which was built around 1920;
- First Generation, the most recently built steam locomotives: the NIAGARA 4-8-4 (of the New York Central Railroad), the South African 25 and 25NC, the post-war British and German standard locomotives, the 141 P, 141 R, the Union Pacific BIG BOY, etc.;
- Second Generation, the locomotives which it is possible to build today, incorporating the technological advances from 1950 to date;
- Third Generation, yet-to-be developed engines, the prototypes of which would cost the $100 million to develop and build."[34]

Porta developed this basic summary of what "the Second Generation locomotives as an immediate answer to the challenges faced today"[35] would be:

- "Cycle improvements: 20 to 25 bar (290 to 362psi) steam pressure, 450°C steam temperature;
- Compound operation without simple expansion and without direct injection into the receiver;
- Utmost internal streamlining of which perhaps the most significant is that applied to the piston valves;
- Advanced valve and piston tribology (the science of rubbing surfaces);
- Advanced draught ejector design (halved back pressure for a given draught as compared to the KYLCHAP or GIESL ejectors) including the Kordina effect;
- Economizer;
- Feedwater and combustion air pre-heating by exhaust steam;
- Gas Producer Combustion System (GPCS) with cyclonic flame path;
- Advanced feed water treatment;
- 'Exaggerated' cylinder and boiler heat insulation;
- Elimination of wall effects in the cylinders;
- Virtual elimination of wall effects;
- New concepts concerning compounding;
- Elimination of the 'dynamic augment';
- High rotational speed (504 rpm, AAR standard 1947);
- Ergonomic operation;
- Compliance with environmental protection regulations, etc;
- Roller bearings throughout;

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[34] Ing. Livio D. Porta, Consulting Engineer, "XXIst Century Steam The Day of Modern Steam Traction," Buenos Aires, Dec. 15th, 1997, http://www.martynbane.co.uk/modernsteam/ldp/articlesbyldp/xxist.htm

[35] Ibid.

- Manganese axlebox rubbing surfaces;
- Piston and valve rings lasting 1,000,000 km with perfect tightness;
- Substitution of the crosshead mechanism by links;
- Grinding the tyres every month without dismantling the wheels or the motion;
- Virtual suppression of atmospheric corrosion;
- Advanced packings for valves, etc.
- Most important of all, attention to detail design: 50% of daily maintenance is devoted to details!"[36]

Porta described the Second Generation Steam Locomotive as a Stephensonian design incorporating the following:

- "A cycle in which the steam, after having worked in the cylinders, is released into the atmosphere (no condensation);
- A draughting system consisting of static, non-moving parts which keeps the steam/air ratio constant over the whole boiler operating range;
- A boiler which has a very high specific evaporation (up to 140 kg/m^{2}h);
- A direct connection between the power pistons and the wheels (the connecting rod);
- No recourse to electricity and/or gears for power transmission;
- A boiler which forms the structural backbone of the engine;
- A rigid wheelbase leading to least forces exerted on the track;
- A non-enclosed motion;
- A performance not dependent on advanced metallurgy;
- A cab for the driver/crew which is protected against collision;
- A well adapted, natural tractive effort curve;
- It is not repaired by the replacement of spare parts, but by the reconstruction of worn-out components;
- It carries the energy and water supplies with it;
- An indefinitely long life etc."[37]

Porta also described the importance of using the best available boiler water treatment as follows:

> "Perhaps the most important one is feedwater treatment. Since 1944, the French TIA system guarantees an indefinite life for the boiler to the point that it can be welded onto the frame. Pure steam (contamination < 1 ppm) also guarantees an indefinitely long life of the superheater and reduces the abrasive wear in the cylinders. The advances made by the author since 1970 are reflected in the fact that the treatment is cheap and heavy duty."[38]

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[36] Ibid.

[37] Ibid.

[38] Ibid.

The reduction in fuel and water consumption expected by Porta was one fourth of what generation zero steam locomotives show. Porta also said, “Most importantly of all, it requires an investment per hp which is about a third of that necessary for an equivalent diesel fleet, not to mention its ability to work on a wide range of fuels.”[39]

Porta also had many important things to say about thermodynamics. He noted that “a locomotive operates on the basis of extremely complex thermodynamic phenomena. This is true of most machines: an aeroplane also uses extremely complex aerodynamic phenomena. The point remains however that the following principle applies:
‘Nobody knows what he does not know until he knows it.’ The English-speaking world behaved as if thermodynamics did not exist. Yet BULLEID’s post-WWII Pacifics ran daily at 130 km/h (80 mph), and a maximum of 200 km/h (124 mph) was reached by DRG's 05 and 202 km/h (126 mph) by GRESLEY's A4. The steam locomotive was already an admirable machine before scientific thermodynamics reached the engineering community. Its development progressed mainly by trial and error on an empirical basis. Long before any quantitative analysis was possible, the British were, as early as 1895, able to run the 869 km between London and Aberdeen in 8 h 29 min with three stops made during the night. The empirical genius of those engineers was however insufficient to produce, after WWII, engines which performed significantly better than the pre-war KINGS for example, whilst at the same time their fellow engineers working on aeroplanes had invented the jet. Mention should be made of the unhappy efforts of GOSS and YOUNG in America: the former took the ‘loss of tractive effort at speed’ as inherent to the very nature of the steam locomotive, whilst the latter, after considerable theoretical and experimental work, achieved those worst ever ejectors characteristic of most American locomotives: a thundering exhaust and a 3m column of solid black smoke were far from correlating with power and efficiency!”[40]

Porta also envisioned a Third Generation Steam Locomotive. He described it as a locomotive which “could reach 21% under test conditions, of course using biomass as fuel. The improvement is on the thermodynamic cycle:

- 60 bar (870psi)/550°C steam;
- Triple expansion;
- Regenerative three stage feed water and combustion air heating;
- Other detail improvements, etc.
- All still keeping to the STEPHENSONIAN scheme.
- Should it prove to be interesting, a further advance in thermal efficiency, a condensing scheme, could be envisaged. This condensation should occur in a ‘cooling-tower’ tender like the SLM-ESCHER WISS machine (ca. 1926). The water treatment can be modified to accept raw water as boiler feed because the condenser is of the evaporative type. Optimistically, the overall thermal efficiency could reach 27% at the drawbar.”[41]

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[39] Ibid.
[40] Ibid.
[41] Ibid.

By comparison an EMD SD70ACe, a modern AC traction motor equipped diesel-electric, has a drawbar thermal efficiency of 30.2%.[42]

Descriptions and Explanations of the Important Technologies in a Modern Steam Locomotive:

The Gas Producer Combustion System (GPCS)

Porta describes his GPCS this way, "It essentially consists in transforming the firebed into a gas producer by making it very thick. Only 30% (20% in the case of biomass) of the combustion air passes as primary air through the grate, thus leading to an almost negligible particle entrainment. The secondary air makes up the lion's share of the air needed for combustion and creates an intense turbulence in the flame space so that the gas phase combustion can proceed to the degree of completeness required to meet pollution laws. While it appears to have that extreme simplicity characterizing great inventions, its thermodynamics are extremely complicated – after all just an intellectual problem!"[43]

Porta began developing the GPCS in 1958 in connection with coal burning steam locomotives at the Rio Turbio Railway in Argentina, but Porta had successfully used the GPCS concept to burn a wide variety of solid fuels, which is the underlying strength of the external combustion engine, as in the steam locomotive. He has used, "firewood in logs, sawmill rejects, bagasse (sugar cane waste), a wide variety of coals, bagasse-oil briquettes, charcoal fines mixed with oil, etc. In the near future, rice husks, orange peels, bark, and dry peat will be tested."[44]

The Environmental Benefits of GPCS

Porta had the following to say about the emissions levels concerning the coal burning GPCS: "One of the blessings of the system is that smoke disappears. CO and HC emissions virtually disappear, and NOX emissions are very close to their theoretical minimum. The expectancy is that, by simply blending the fuel with a calcite-dolomite mixture, sulphur can also be controlled to a large extent."[45] Also, the use of wood chips as a fuel source from tree farms for this purpose would make the Modern Steam Locomotive a carbon neutral means of transportation since the carbon in wood is fixed out of the atmosphere.

The Particulars of GPCS

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[42] Calculated on, "Diesel Thermal Efficiency" Sheet: "Diesel" Cell: B8 in the file addendum.

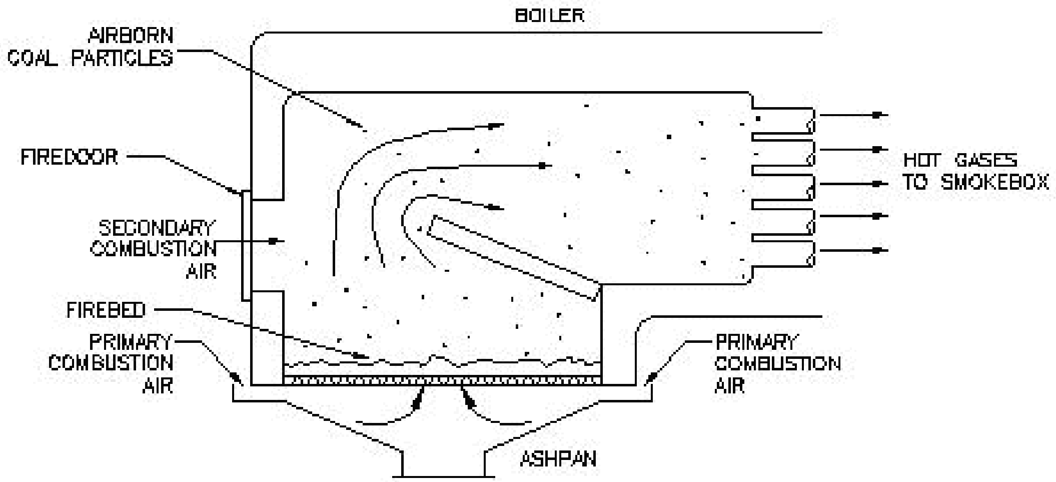
[43] Ing. Livio D. Porta, Consulting Engineer, "XXIst Century Steam The Day of Modern Steam Traction," Buenos Aires, Dec. 15th, 1997, http://www.martynbane.co.uk/modernsteam/ldp/articlesbyldp/xxist.htm

[44] Ibid.

[45] Ibid.

Below is an excerpt from a page on Hugh Odom's website on the Modern Steam Locomotive:

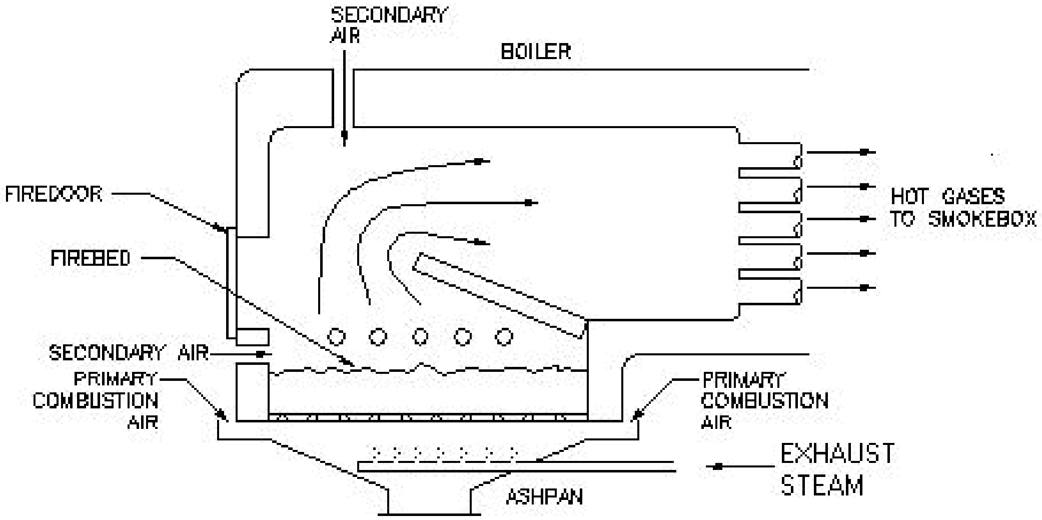
"This drawing shows a simplified cross-sectional view of a typical steam locomotive firebox. Most of the air required to burn the coal (about 90%) enters through the ashpan and comes up through the grate. A much smaller amount of air (about 10%) enters the firebox through holes in the firedoor, and sometimes through openings installed in the sides of the firebox (such as over-fire jets).



CONVENTIONAL FIREBOX

"Coal particles act much like sand-blast grit as they fly through the boiler at high velocity. This causes wear on the surfaces in the boiler, including the rear tube sheet, rear tube ends, superheater ends, and internal parts of the smokebox. The cinders, if of sufficient size, can ignite line-side fires along the railroad tracks. A conventional steam locomotive firebox is illustrated below.

"Another problem with conventional coal combustion was clinker formation. All coal contains non-combustible components. Some of these components can melt at the temperatures attained in the coal bed. When this happens, the molten substance flows together to form a clinker. Since the clinker can't burn, it blocks off a portion of the firebed, reducing the engine's output (sometimes by extreme amounts). The fireman has to attempt to break it up manually using a steel rod and then shake the engine's grates to get the broken pieces to drop into the ash pan. This was a laborious task, especially on a moving train.



GAS PRODUCER FIREBOX

“The illustration above demonstrates the same firebox after conversion to a GPCS configuration. The coal grates are replaced with grates having smaller air openings, so that only about 30% of the air (primary air) required to completely burn the coal enters through the grates. For proper operation, the grates must fit tightly when closed to prevent uneven air flow up through the firebed. A number of air admission ducts are installed through the walls of the firebox, along the sides, back, top, and/or front. These ducts are sized to admit about 70% of the air (secondary air) required to completely burn the coal. Finally, dispersion tubes are installed below the grates to admit steam to the fire. This steam comes from the exhaust nozzle (3-4% of the exhaust flow from the cylinders) and from various other steam-powered accessories on the locomotive. The steam must be evenly distributed and mixed with the primary air to ensure proper operation. The firebed is maintained much deeper than in a conventional firebox.”[46]

The Lempor Exhaust:

The Lempor Exhaust is the most efficient design to date for using exhaust steam from the cylinders to create a draft on the fire. This principle is the heart of the steam locomotive going back to Richard Trevithick in 1804.[47] The Lempor Exhaust has been under development by Porta since 1952. At that time it was the Kylpor, which had supplanted Chapelon’s Kylchap as the most efficient design. Currently, the Lemprex exhaust is under development by Shaun McMahon and other associates of his, which will supercede the Lempor in efficiency. The basic outline of the Lempor is listed below. The efficiency of an exhaust is characterized by how much draft (measured in inches of

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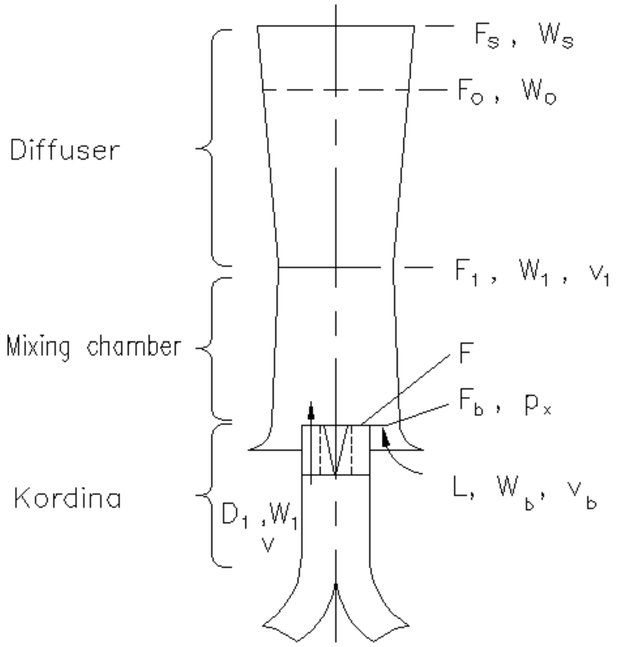
[46] Hugh Odom, *The Gas Producer Combustion System*, http://www.trainweb.org/tusp/firebox.html

[47] Nigel Day, e-mail communication, various. Graphic from Hugh Odom, *Theory of the Lempor Ejector*, http://www.trainweb.org/tusp/lempor/lempor_theory.html

water) it can create for each pound per square inch of backpressure it imposes on the cylinders. The Lempor installation on the Grand Canyon Railway produces twice the draft as the standard American type exhaust that it replaced.[48] Porta's Lempor Theory is available for download on Hugh Odom's as well as Martyn Bane's websites.



Porta Water Treatment (PT):

Beginning in the 1960's, Porta started developing a boiler water treatment regime that would keep a boiler virtually free of maintenance for a period of 30 years, basically the economic life of the locomotive. This treatment is called Porta Treatment; it was an outgrowth of the "advanced treatments used on the railways of France (TIA) and the UK (Alfloc)."[49] Porta developed this treatment for the Ferrocarril Nacional General Belgrano railway in Argentina. Martyn Bane of Porta Treatment.com, who markets the treatment outside of Argentina, explains how it works:

"Put simply, once the carbonate concentration is above a certain level all other factors fall into place. This concentration, which shows as a high pH, typically above pH11, also means a high TDS, the combination of which deal with variations in feedwater. These conditions, aided by the tannin acting as an oxygen scavenger and caustic embrittlement inhibitor, lead to the creation of protective layers of impermeable material on the water surfaces of the boiler. These layers, which are microscopically thin,

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[48] Sam Lanter, Chief Mechanical Officer, Grand Canyon Railway, e-mail communication, various.

[49] Martyn Bane, 'Porta Treatment' An Advanced Internal Boiler Water Treatment Regime emailed from author, owner portatreatment.com, p. 5

provide total protection against corrosion.

The chemistry of the boiler water keeps any scale or mud-forming material in solution or suspension and mobile at all times. In doing so fouling is prevented, with all the benefits, which flow from this. The fact that the boiler water contains a lot of suspended solids can be seen at the gauge glass when the boiler is steaming at high rates. Through very rapid circulation of the boiler water, this suspended material reaches the gauge glass turning the water almost black. In traditional terms this would indicate that heavy boiler water carryover was likely but through the use of antifoams this is not the case.

Many antifoams are described as de-foamers but, in this instance, total de-foaming is not the required phenomenon. Rather, controlled foaming is required. The foam layer is put to good use. Instead of being made up of large uncontrolled bubbles, the condition aimed at is akin to the head on a pint of Guinness, that is, a very dense layer of small bubbles. The effect of this thick layer of foam is to sieve the steam bubbles escaping from the water. In other words, solids attached to these steam bubbles are removed, thus leading to pure steam."[50]

The Maintenance and Efficiency Effects of PT

PT eliminates the formation of scale, which can reduce the horsepower output of a locomotive by 15%.[51] The boiler tubes can last 30 years with the use of PT.[52] Boiler washouts can be performed on a six month cycle instead of a 30 day cycle as in the late steam era.[53] The boiler blowdowns can be performed every other month as opposed to every shift, saving huge amounts of fuel and water.[54] Also, the firebox plates can last 30 years with no replacements.[55] In addition, the Superheater elements can last 30 years without replacement.[56] With PT and GPCS, because of the elimination of the sandblasting effects of unburned coal particles, leads to the virtual elimination of boiler maintenance, which accounted for 91% of the maintenance cost of the steam locomotive, as the chart below illustrates.[57]

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[50] Martyn Bane, Porta Treatment Internal Boiler Water Treatment for the 21st Century, from the author, p.21

[51] Martyn Bane, 'Porta Treatment' An Advanced Internal Boiler Water Treatment Regime emailed from author, owner portatreatment.com, p. 13

[52] Ibid. p. 17

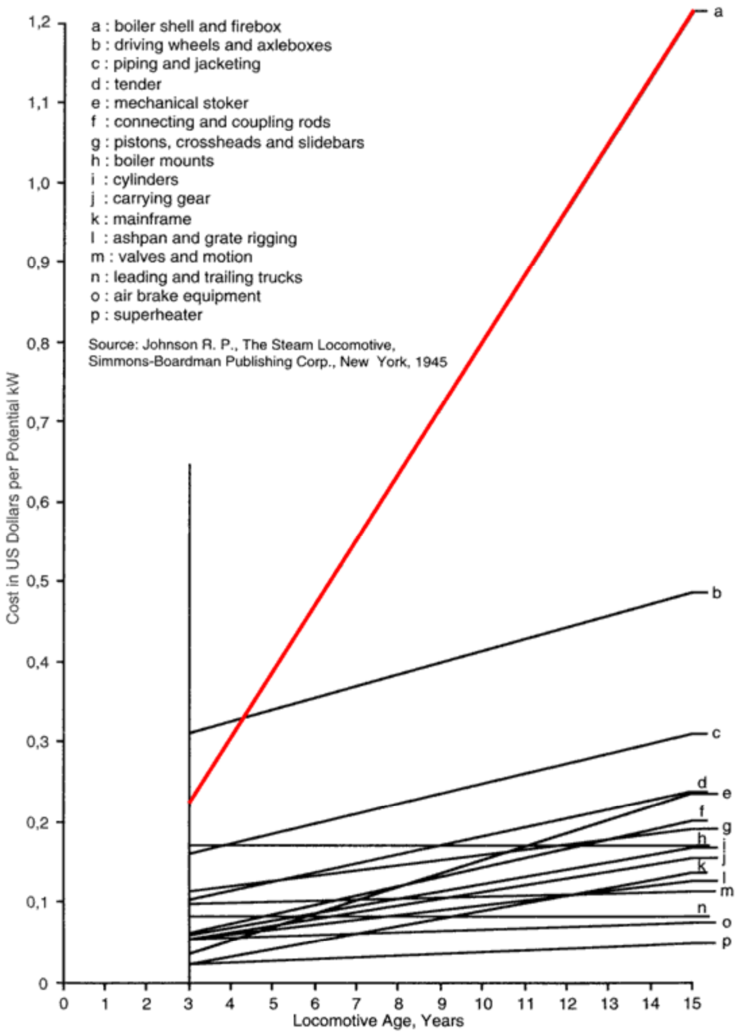
[53] Ibid. p. 18

[54] Ibid. p. 37

[55] Shaun McMahon, *The Practical Application of 'Porta Treatment'* from Martyn Bane, p. 1

[56] Martyn Bane, 'Porta Treatment' An Advanced Internal Boiler Water Treatment http://www.portatreatment.com/savings.htm

[57] Ibid.



Source: Johnson R. P., The Steam Locomotive, Simmons-Boardman Publishing Corp., New York, 1945

Maintenance Cost Trends for Locomotive Components (Classified Repairs)

"The graph to the left, taken from D. Wardale's book listed in the reference section, shows how boiler repairs (line in red) formed the greatest fraction of the overall cost of locomotive repairs in the USA over the life of a locomotive.

Whilst not all boiler repairs are due to water side causes it is not inaccurate to state the majority are. As any locomotive operator will know, water side boiler repairs are neither inexpensive nor necessarily easy tasks. Through the use of Porta Treatment line 'a' would be nearly flat throughout the entire life of the locomotive and at a much lower level in the graph."[54]

Needs for the American Class I Railroads:

- **Automated Boiler Controls –** For the Modern Steam Locomotive to work in the US, the application of automated boiler controls is a must. First of all, the economics would not work at all if the railroads had to return to a two person locomotive crew from a single person crew. From environmental and efficiency standpoints a person doesn't have the reaction time or the ability to finely tune the combustion and evaporation of a boiler to keep it at the peak of optimum operation. Also, the next item would not be possible without automated boiler controls. These are the main reasons why automated boiler controls would be a must if the Modern Steam Locomotive were to re-enter use on the American Class I Railroads.

- **Multiple Unit Capability –** First, the economics of having to put even a single person crew in each locomotive would not work. This is the main reason for the need of MU capability. This will require that the computer to actually operate the locomotive, whereas the engineer simply tells the computer to accelerate or brake in a similar manner to current diesels. The throttle that the engineer uses on a diesel is not directly connected to the prime mover; the computer makes the adjustments. This will also be the case on Modern Steam.

- **Traction Control –** Traction Control will be needed on the Modern Steam Locomotive as it is on diesel locomotives. A traction control system would use a computer to compare the speed of the driving wheels with unpowered wheels. The computer would basically restrict the steam being exhausted from the cylinders to keep a wheel slip from occurring. The computer would need to be able to sense the start of a slip in just a few degrees of the revolution of the driving wheels. Fortunately, computers are very powerful these days, and traction control has been around for decades in both locomotive and automotive applications.

- **Dynamic Braking –** Dynamic braking on diesel locomotives is a form of braking where the traction motors act as generators powering a resistance-heating grid. The more power directed to the grid, the more resistance the traction motors provide against the continued movement of the train. This reduces the use of the brake shoes on the freight cars and makes train handling easier. While not used often in the U.S. other types of brakes (compression brakes) were installed on many steam locomotives in other parts of the world. These had the same functionality as dynamic brakes do on a diesel. The most commonly used type were "water brakes," invented by Henry le Chatelier, which were used by the Denver and Rio Grande Western in the US.[58]

- **Distributed Power and Remote Control Capability –** These features are possible on a diesel because of its multiple unit capability. The same would be true of a steam locomotive. Distributed power simply uses radio signals to send the MU signals to one or more locomotives in the middle or at the end of a train. Remote Control uses a belt mounted radio transceiver to send radio signals to the locomotive from the operator(s) on the ground. These two items could be installed on a steam locomotive just as easily if the locomotive is already MU capable.

- **Crew Comfort –** A Modern Steam Locomotive must have a cab that is as comfortable as a diesel or electric locomotive. In the past, steam locomotive cabs were very hot because the boiler insulation was poor. This is one of the many reasons old steam locomotives were not very efficient. If the heat from the boiler

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[58] Brakes, http://encyclopedia.jrank.org/BOS_BRI/BRAKE.html

is going into the cab then it isn't doing useful work for the company that owns the locomotive! A Modern Steam Locomotive should include the following:

- A fully enclosed cab that is not drafty;
- Air conditioning, ventilation and heating;
- HVAC air intakes placed so exhaust gases and brake or other odors do not enter the cab;
- Advanced sound and thermal insulation (a locomotive cab of any type should not be deafening or hot);
- "Thermal" pane windows for the same reasons as stated above;
- Wipers and washers for the front and rear windows;
- A toilet, most likely located in the tender;
- Air seats similar to those on over-the-road trucks for maximum engineer and conductor comfort;
- Ample work space for the engineer as well as for the conductor;
- Ergonomically designed layout of controls with good lighting and display and/or illumination; and
- Provision for the installation of a microwave and/or coffee pot if so desired on road locomotives.

Comparisons between Modern Steam and Diesel Maintenance:

It has long been the prevailing view in the railroad industry that the steam locomotive was more expensive to maintain than the diesel. This could easily be the case when comparing worn out generation "zero" steam locomotives having World War I era construction dates, with new diesel locomotives before, during and after World War II. On the other hand, the more modern "first generation" steam locomotives, those with non-fabricated frames (i.e., one-piece cast), roller-bearings on all axles and motion, and complete mechanical and pressure lubrication, like the Norfolk and Western Railway (N&W) Class J and the South African Railways Class 25NC, were actually cheaper to maintain than diesel locomotives. The N&W and the Southern Railway carried out a maintenance comparison between the Class J and then-new E6 passenger locomotives in similar service between November 1946 and March 1947. The N&W Class J was shown to be 29% less expensive to maintain on the basis of total maintenance cost per 100 locomotive miles.[59] In H. F. Brown's presentation to the Institution of Mechanical Engineers, he showed that the steam locomotive was significantly cheaper to maintain than the diesel in the US during the postwar period.[60] During Wardale's tenure on the South African Railways, he collected the following data comparing the Class 25NC and diesel locomotives. Between 1963 and 1986 the Class 25NC was 20% cheaper to

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[59] Gordon Hamilton, "*N&W Steam vs. Southern Diesels How did the costs compare?,*" *The Arrow Norfolk and Western Historical Society Magazine,* September / October 2004, 11-12

[60] H. F. Brown, Ph.B., *Economic Results of Diesel Motive Power on the Railways of the United States of America,* The Institution of Mechanical Engineers, November 30th 1960, 14

maintain on a kilometer basis than the average SAR diesel.[61] The average maintenance cost per unit of output over the first thirteen years in service was 43% lower for the 25NC than the average diesel, and in the thirteenth year the 25NC cost 56% less to maintain than the average diesel.[62] At no time during 30 years of service life was the 25NC more expensive to maintain than the average diesel.[63] The economic life of the average diesel was 42% of that of the 25NC.[64] As stated earlier with GPCS and Porta Treatment, the maintenance costs for the boiler would be significantly reduced and almost eliminated. Also, as shown earlier, these costs accounted for a high percentage, 91% to be exact, of the total maintenance costs. Comparisons between the actual maintenance costs for Modern Steam Locomotives and current diesel locomotives are not available due to the fact there are no Modern Steam Locomotives in freight service in the US. It can be estimated from historical comparisons and increases in technology that a Modern Steam Locomotive would at least be as cheap to maintain as a diesel, if not cheaper. This possibility is not included in the projected cost savings of Modern Steam Locomotives outlined in the executive summary of this paper.

Comparisons of the Modern Steam and Diesel Locomotives for the American Class I Railroad Industry:

First to be compared will be some of the basic characteristics of Modern Steam Locomotives that could be designed to be a close match to the diesel locomotives used by the American Class I and passenger railroads today. There are currently no Modern Steam Locomotives designed for Class I railroads so the author calculated the characteristics of a group of modern steam locomotives that could replace the diesel locomotive on the Class I railroads as well as Amtrak and the various commuter agencies. The principal comparisons will be Drawbar Pull, Drawbar Horsepower, Tonnage Ratings, Full Throttle Fuel Use & Cost, Idle Fuel Use & Cost and Running Time & Characteristics of Fueling & Servicing.

The Class I railroads use four principal locomotives on freight trains, and the author has made extensive calculations concerning five modern steam locomotives that could be substitutes:

- One with high horsepower, six-axles and AC traction motors, the 4,300 HP EMD SD70ACe and the 4,400 HP GE ES44AC. This type of road locomotive is used for heavy haul type operations as on unit coal, grain or other mineral service trains, and it is also becoming popular on high speed intermodal container and trailer trains. It is replaced by a 2-8-8-4, having eight driving axles;

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[61] David Wardale, *The Red Devil and Other Tales from the Age of Steam* (Scotland: Highland Printers, 2002), 33
[62] Ibid. 37
[63] Ibid. 38
[64] Ibid. 40

- One with high horsepower, six-axles and DC traction motors, the 4,300 HP EMD SD70M-2 and the 4,400 HP GE ES44DC. This type of road locomotive is a general purpose road locomotive, which can be found on nearly any type of non-local (switching of industries) service. It is replaced by a 2-6-6-4, having six driving axles;

- One with medium horsepower, six-axles and DC traction motors, the 3,000 HP EMD SD40-2. This type of locomotive can be seen working heavier local trains, those that deliver and pick up cars from industries and other customers. They can also be seen on road freight trains when business is heavier and railroads are short on power and also as helpers on steep grades, on work trains and occasionally on switching cars in yards. It is replaced by a 2-10-2, having five driving axles and

- One with low horsepower, four-axles and DC traction motors, the 2,000 HP EMD GP38-2. This type of locomotive can be seen working local trains, on work trains and can be found switching cars in yards. It is replaced by a 2-8-2, having four driving axles.

The Class I railroads use two principle types of locomotives for the switching of train cars in freight cars. These are:

- One with low horsepower, four-axles and DC traction motors, the 1,500 HP EMD MP15 and National Railway Equipments Genset Switcher. This type of locomotive is used for switching cars in yards. Two are replaced by a 0-10-0, having five driving axles and

- One with low horsepower, twelve-axles in two or three units and DC traction motors. This locomotive is used to push cars over the “hump” in large hump-type classification yards. This type of locomotive is usually made in-house by a railroad from older four or six axle power. It consists of a “mother” which is a 2,000 HP locomotive and one or two “slugs” which have no engines but get their power from the mother. It is replaced by two of the same 0-10-0’s as above.

America’s passenger railroads use two principle types of locomotives for passenger and commuter operations. These are:

- One with high horsepower, four-axles and DC traction motors, the 4,250 HP GE P42. This locomotive, used by Amtrak, is the type used for passenger trains. It is replaced by a 4-8-4 with four driving axles and

- One with medium horsepower, four-axles and DC traction motors, the 3,600 HP MPI MP36 and 4,000 HP MPI MP40. This type of locomotive is used for commuter rail operations. It is also replaced by a 4-8-4 that is the same as above with some slight differences in the tender.

In the realm of true high speed rail, that over 110 MPH, the electric locomotive has been the only type used in America, on the North East Corridor, for this service. The Federal Railroad Administration concluded a demonstration project to develop a non-electric high speed rail locomotive in which Bombardier built a prototype gas turbine electric locomotive. Currently, only plans are being made to start high speed rail corridors, but none are actually in place yet, other than the electrified North East Corridor. A 4-4-4-4 with four driving axles could be used instead of the turbine electric.

The Locomotive Comparisons:

Drawbar Pull:

Drawbar Pull (DBPull) is related to Tractive Effort, Tractive Force or Tractive Power, which are used loosely to describe the same force.[65] E. A. Phillipson, a British Locomotive (mechanical) engineer, describes the force as "usually stated in pounds, is that force which the locomotive is capable of exerting at the treads of the coupled wheels."[66] This definition of tractive effort is the standard of describing the force created by a locomotive and has been used on all forms of locomotives, steam, diesel and electric, although the force available on the coupler face (or drawbar) of the locomotive is actually the meaningful value, as it moves the train. The DBPull of any locomotive is the tractive effort at a speed less the locomotive resistance at the same speed. The locomotive resistance is the amount of work necessary to move the locomotive at a given speed.

Drawbar Horsepower:

Drawbar Horsepower was described by Phillipson as "the net power available for the haulage of the train at the tender drawbar"[67] and comprises the horsepower created in the cylinders less the machinery resistance of the engine and the locomotive resistance of the locomotive and/or tender. Drawbar Pull can be converted into Drawbar Horsepower, and vice versa, by the use of the formula:

DBHP = (DBPull x Speed)/375
Also
DBPull = (DBHP x 375)/Speed.[68]

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[65] Ralph Johnson, *The Steam Locomotive* (Omaha, Simmons-Boardman, 2002), 137

[66] E. A. Phillipson, *Steam Locomotive Design: Data and Formulae* (Great Britain: Camden Miniature Steam Service, 2004), 12

[67] Ibid. 28

[68] Ralph Johnson, *The Steam Locomotive* (Omaha, Simmons-Boardman, 2002), 177

Tonnage Ratings:

The tonnage rating of a locomotive is developed on a district-by-district basis. It is the allowable train weight that the locomotive can successfully haul over the ruling grade and curvature of a district while meeting specified speed requirements.

Fuel Cost and Idle Fuel Cost:

The comparison of fuel costs in the following section is based on full-throttle fuel consumption. This rate of consumption is based on the production of the full rated power of the locomotive. It is understood that locomotives do not operate at full throttle all the time, and that is why a discussion of fuel costs at idle is also made for comparison purposes.

Running Time, Fuel:

In addition to the above items, a comparison of the running time between refueling will also be made.

The Modern 2-8-8-4 versus the high horsepower, six-axle, AC traction diesel:

The Modern 2-8-8-4 will be compared to the EMD SD70ACe, and it will be shown that the 2-8-8-4 is fully capable of replacing the SD70ACe in the Class I Railroad environment. The 2-8-8-4 as described below has two power output settings, referred to as “Economy” and “High Power.” These power settings equate to the power output of a single SD70ACe and 140% of the output of a SD70ACe, as will be described below. The 2-8-8-4 is derived from the Norfolk and Western Railway Y Classes. The N&W bought or built 221 of these locomotives in classes Y2 through Y6b.[69] The last one of which, Y6b No. 2200, was the last steam locomotive built in the US for road service. Its construction was completed at the N&W Roanoke Shops on April 22, 1952. The last Y class retired by the N&W was in September of 1960. For many years these locomotives were said to be the “workhorses” of the N&W.[70] The addition of one trailing axle is to facilitate moving the firebox behind the drivers so a wide deep firebox may be used in place of the wide shallow type as used on the N&W locomotives. The shallow type firebox is not compatible with the thick fire needs of GPCS operation.

Note: All numbers are calculated by the author with the explanations in the “Calculations” section of this paper.

Drawbar Pull & Drawbar Horsepower:

At five mph, the 2-8-8-4 can produce slightly more tractive effort than the SD70ACe, as can be seen in the chart and graph on the two following pages. The 2-8-8-4 produces 176,504 pounds of DBPull compared to the SD70ACe’s 174,000. Except for around ten mph, the 2-8-8-4 in Economy mode produces more DBPull than an SD70ACe, up to 50 mph. Just above 20 mph the 2-8-8-4 High Power produces more DBPull than 1.4 SD70ACe’s. The N&W Y6 is included for historical reference. The DBHP curves for the locomotives can be seen on page 29. As can be seen in this graph, the steam locomotive’s DBHP curve follows its diesel counterpart, especially between 20 and 50 mph where this type of locomotive will get the majority of use on heavy trains carrying coal, minerals and other bulk commodities.

Fuel Cost:

The following page also shows the fuel cost per hour with the locomotives at full throttle. The High and Low designators relate to the Class I Railroads with the highest and lowest average price paid for diesel fuel in 2006. The steam costs include water and

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[69] Ron Rosenberg, *Norfolk & Western Steam (The Last 25 Years)* (New York: Quadrant Press, 1973) 2 & 43

[70] Colonel Lewis Ingles Jeffries, *N&W Giant of Steam* (Hong Kong: Norfolk & Western Historical Society, 2005) 226 & 343

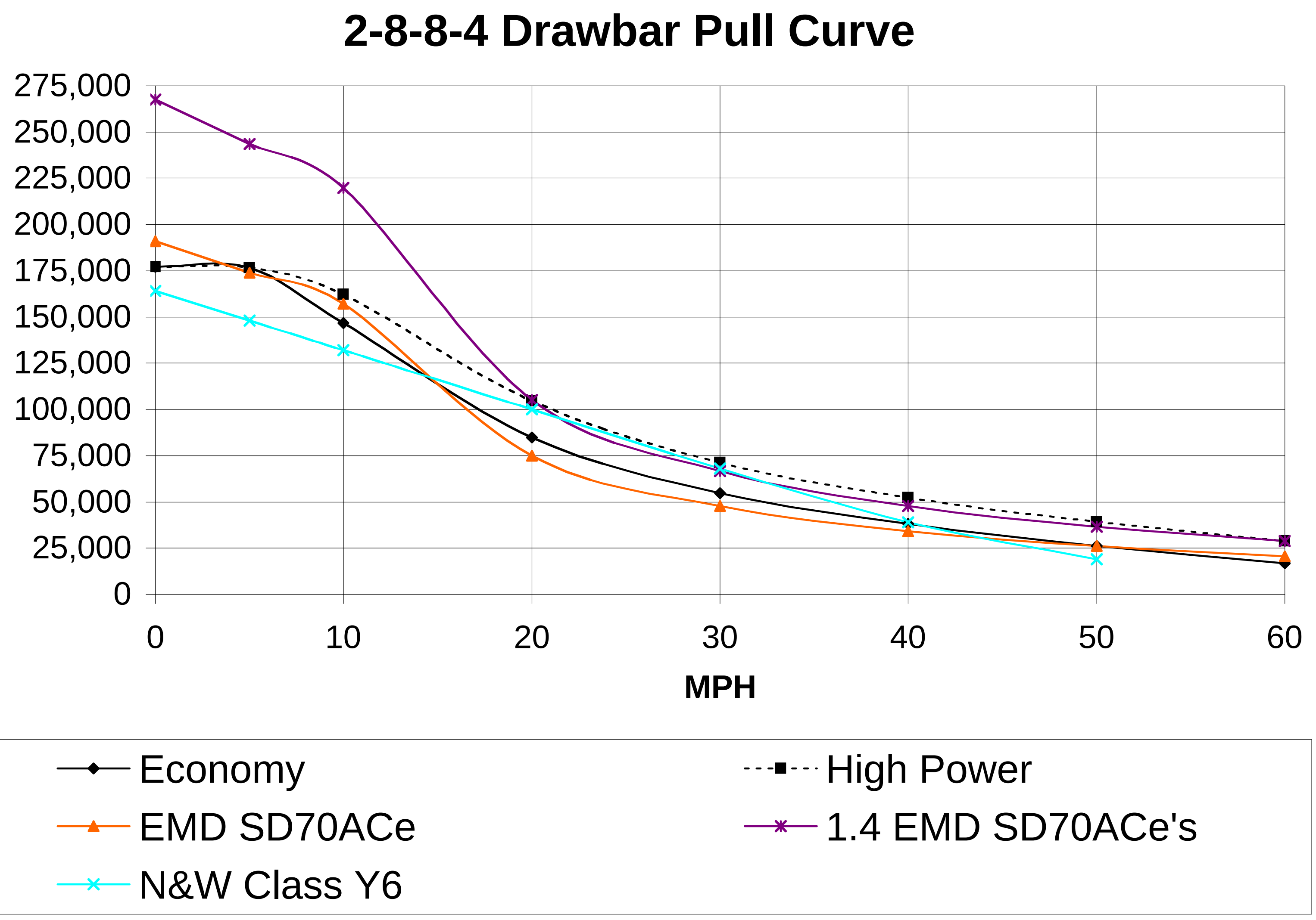
coal costs. CAP, NAP, ILB & UIB are the designators used by the US Department of Energy to describe Central Appalachian (CAP), Northern Appalachian (NAP), Illinois Basin (ILB) and Uinta Basin Coals (UIB) coals. The DOE tracks the prices of these four coals. On pages 30 and 31, the drawbar horsepower hours created per dollar of fuel cost are graphed for the 2-8-8-4 in economy as well as high power mode. As can be seen the modern steam locomotive can produce significantly higher DBHP Hours/$ than the contemporary diesel locomotive.

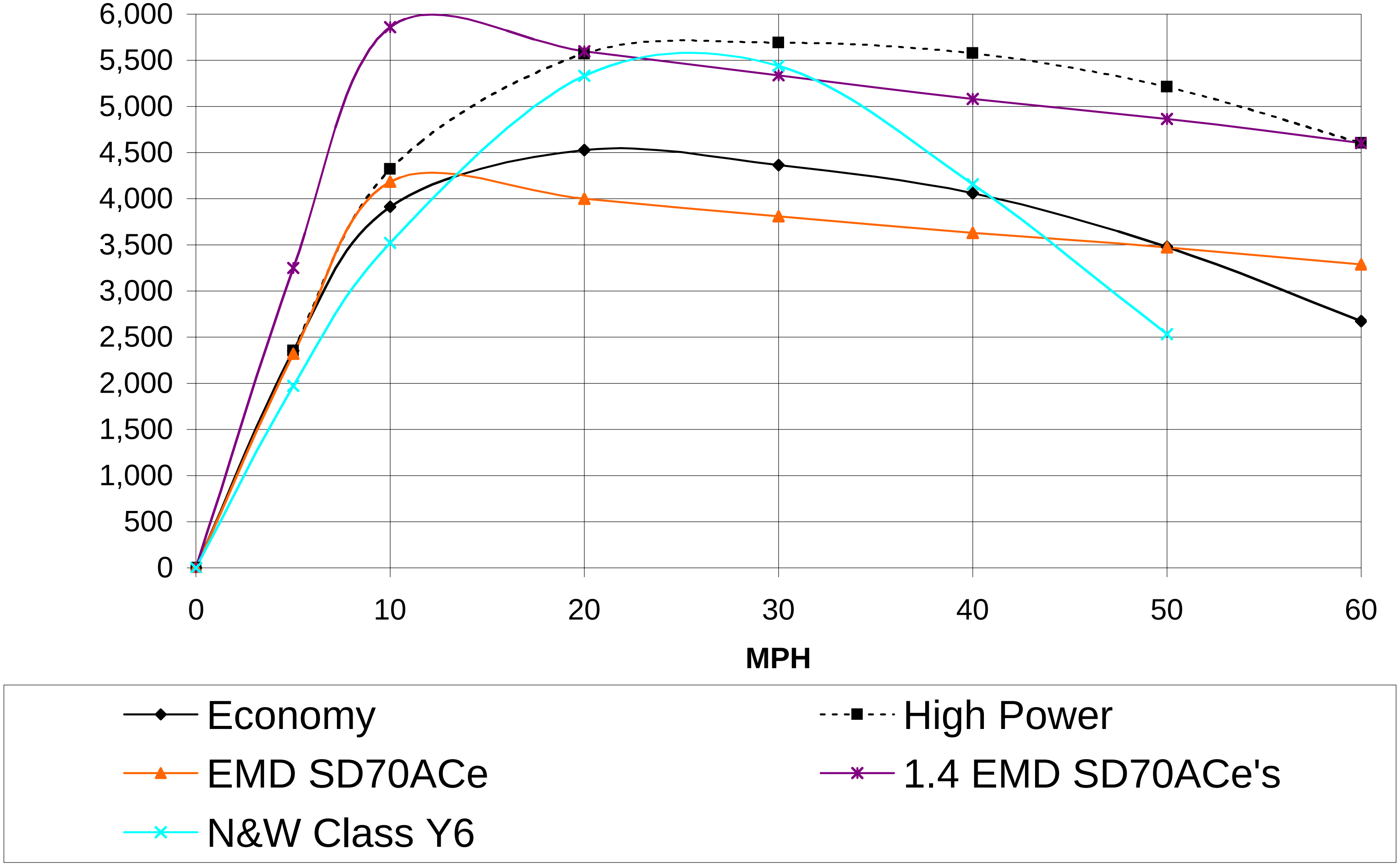
Full Throttle / Notch 8, Comparison - Modern 2-8-8-4 & EMD SD70ACe

	MPH	0	5	10	20	30	40	50	60
Economy Setting									
Drawbar pull, level track		**176,993**	**176,504**	**146,818**	**84,919**	**54,575**	**38,035**	**26,094**	**16,717**
Drawbar Horse Power, level track		**0**	**2,353**	**3915**	**4529**	**4366**	**4,057**	**3479**	**2675**
DBHP Hours per $ of Fuel Cost, CAP		0	9	15	18	17	16	14	11
DBHP Hours per $ of Fuel Cost, NAP		0	12	20	24	23	21	18	14
DBHP Hours per $ of Fuel Cost, ILB		0	14	24	28	27	25	21	16
DBHP Hours per $ of Fuel Cost, UIB		0	14	23	26	25	24	20	16
EMD SD70ACe (4300 HP)	DBPull	**191000**	**174000**	**157000**	**74981**	**47640**	**34027**	**26053**	**20560**
	DBHP	**0**	**2320**	**4187**	**3999**	**3811**	**3630**	**3474**	**3290**
DBHP Hours per $ of Fuel Cost, Low		0	6	11	11	10	10	9	9
DBHP Hours per $ of Fuel Cost, High		0	5	9	9	8	8	8	7
High Power Setting									
Drawbar pull, level track		**176,993**	**176,504**	**162,104**	**104,499**	**71,109**	**52,274**	**39,080**	**28,770**
Drawbar Horse Power, level track		**0**	**2,353**	**4323**	**5573**	**5689**	**5,576**	**5211**	**4603**
DBHP Hours per $ of Fuel Cost, CAP		0	7	13	17	17	17	15	14
DBHP Hours per $ of Fuel Cost, NAP		0	9	17	22	22	22	20	18
DBHP Hours per $ of Fuel Cost, ILB		0	11	20	26	26	26	24	21
DBHP Hours per $ of Fuel Cost, UIB		0	10	19	25	25	25	23	20
1.4 EMD SD70ACe's (4300 HP)	DBPull	**267400**	**243600**	**219800**	**104974**	**66696**	**47637**	**36474**	**28784**
	DBHP	**0**	**3248**	**5861**	**5599**	**5336**	**5081**	**4863**	**4605**
DBHP Hours per $ of Fuel Cost, Low		0	6	11	11	10	10	9	9
DBHP Hours per $ of Fuel Cost, High		0	5	9	9	8	8	8	7
	MPH	0	5	10	20	30	40	50	60
N&W Class Y6	DBPull	164000	148000	132000	100000	68000	39000	19000	
	DBHP	0	1973	3520	5333	5440	4160	2533	

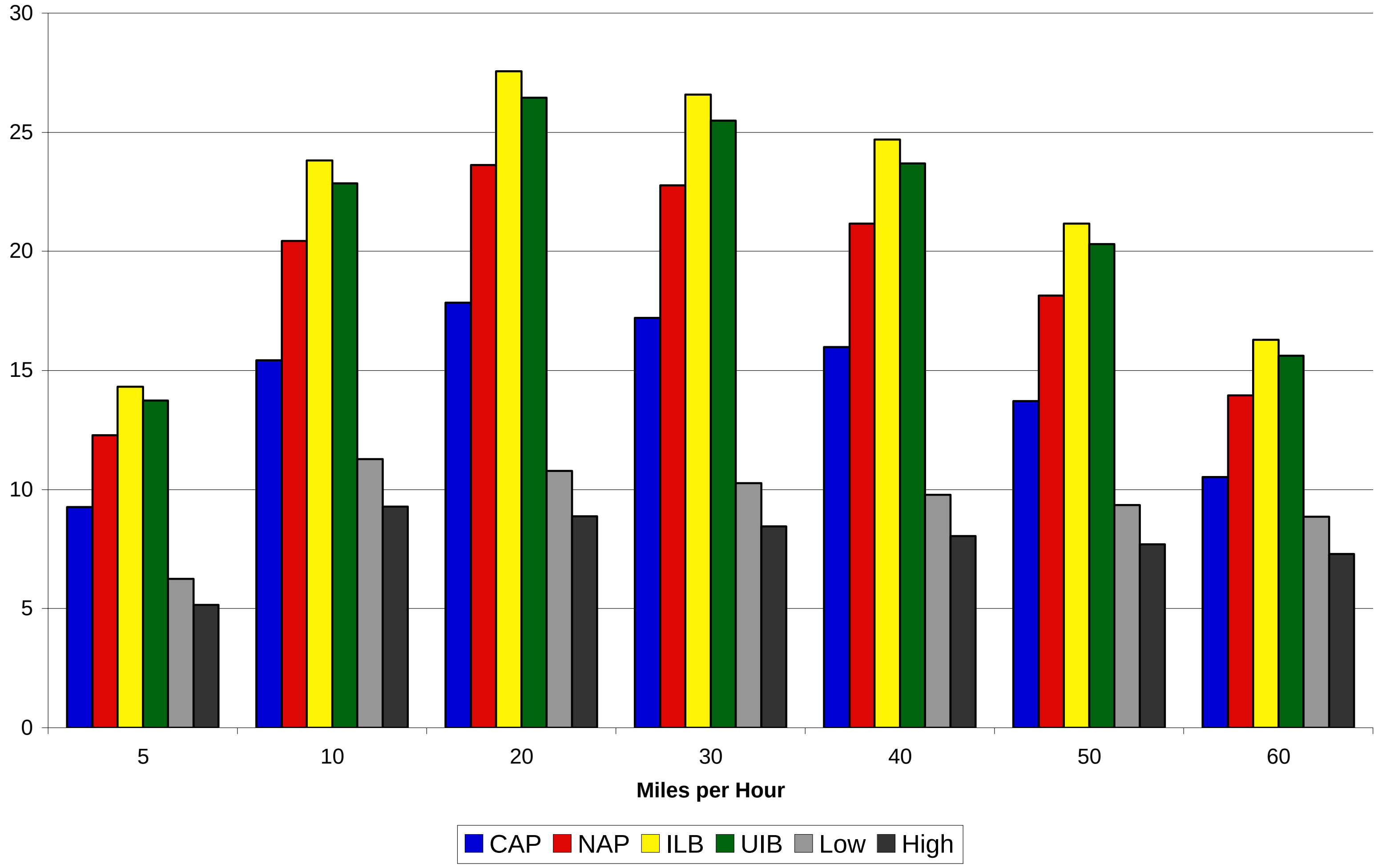
Water Cost	
Cost per 1000 gal. water	$ 0.09
Treatment cost per 1000 gals.	$ 2.35
Total cost per 1000 gals.	$ 2.44
Total cost per 1 gal.	$0.002

Full Throttle Fuel Cost / Hr.	
Coal Cost	
CAP	$56.67
NAP	$41.77
ILB	$35.20
UIB	$36.88
Diesel Cost	
Low	$1.80
High	$2.19
Economy	
CAP	$253.81
NAP	$191.68
ILB	$164.32
UIB	$171.30
High Power	
CAP	$337.39
NAP	$254.56
ILB	$218.08
UIB	$227.38
SD70ACe	
Low	$371.14
High	$450.68
1.4 SD70ACe	
Low	$519.59
High	$630.95


2-8-8-4 Drawbar Pull Curve
275,000
250,000
225,000
200,000
175,000
150,000
125,000
100,000
75,000
50,000
25,000
0
0
10
20
30
40
50
60
MPH
Economy
High Power
EMD SD70ACe
1.4 EMD SD70ACe's
N&W Class Y6

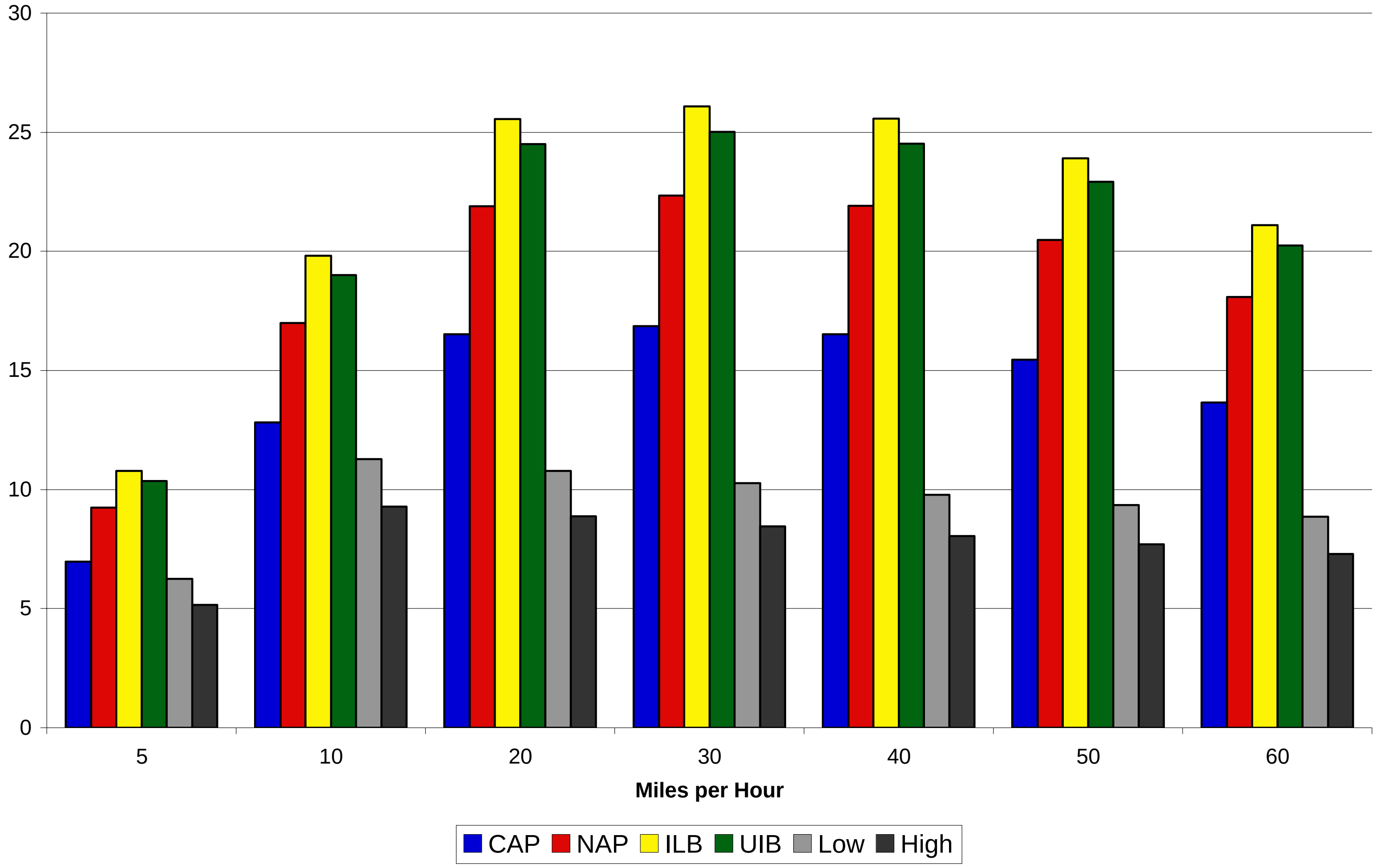


2-8-8-4 Drawbar Horsepower Curve



Drawbar Horsepower Hours per $ of fuel cost, 2-8-8-4 Economy & SD70ACe

Drawbar Horsepower Hours per $ of fuel cost, 2-8-8-4 High Power & SD70ACe



The Modern 2-6-6-4 versus the high horsepower, six-axle, DC traction diesel:

The Modern 2-6-6-4 will be compared to the EMD SD70M-2, and it will be shown that the 2-6-6-4 is fully capable of replacing the SD70M-2 in the Class I Railroad environment. The 2-6-6-4 as described below has two power output settings, referred to as “Economy” and “High Power.” These power settings equate to the power output of a single SD70M-2 and 150% of the output of a SD70M-2, as will be described below. The 2-6-6-4 is derived from the Norfolk and Western Railway Class A. The N&W built 43 of these locomotives between 1936 and 1950.[71] The N&W Class A was the most versatile locomotive on the railroad, being used on everything from slow freight like coal to time freight and even heavy passenger trains. The locomotive was used on both the flatter and hillier parts of the railroad. The locomotive type was used on fast freight or passenger trains at speeds in excess 70 mph and could handle 19,000-ton coal trains.

Note: All numbers are calculated by the author with the explanations in the “Calculations” section of this paper.

Drawbar Pull & Drawbar Horsepower:

The DBPull of the 2-6-6-4 in economy setting is higher than that of the SD70M-2 between 5 and 65 MPH. Between 30 and 75 MPH the 2-6-6-4 exceeds 1.5 SD70M-2’s. The high horsepower output of the 2-6-6-4, especially when in high power mode, is of a great benefit in Intermodal service, which as will be seen later, is quite horsepower intensive. The N&W Class A is included in the DBPull and DBHP graphs for historical reference.

Fuel Cost:

As can be seen in the following chart and graphs, the majority of the cost savings is between 20 and 60 mph, right where most freight is operated. Also, it is seen that the locomotive fuel cost is less than half the cost of the SD70M-2.

---

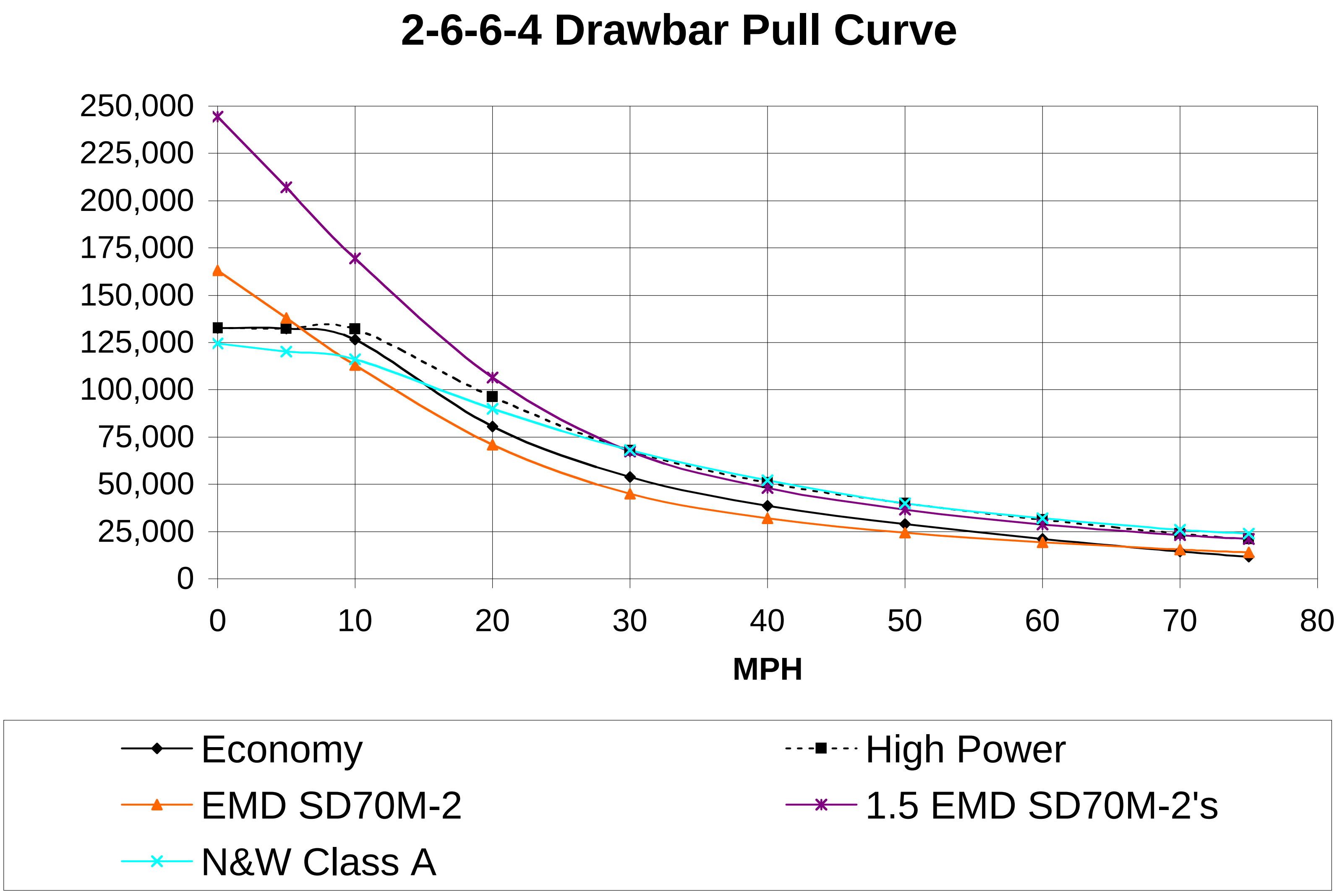
[71] Ron Rosenberg, *Norfolk & Western Steam (The Last 25 Years)* (New York: Quadrant Press, 1973) 43

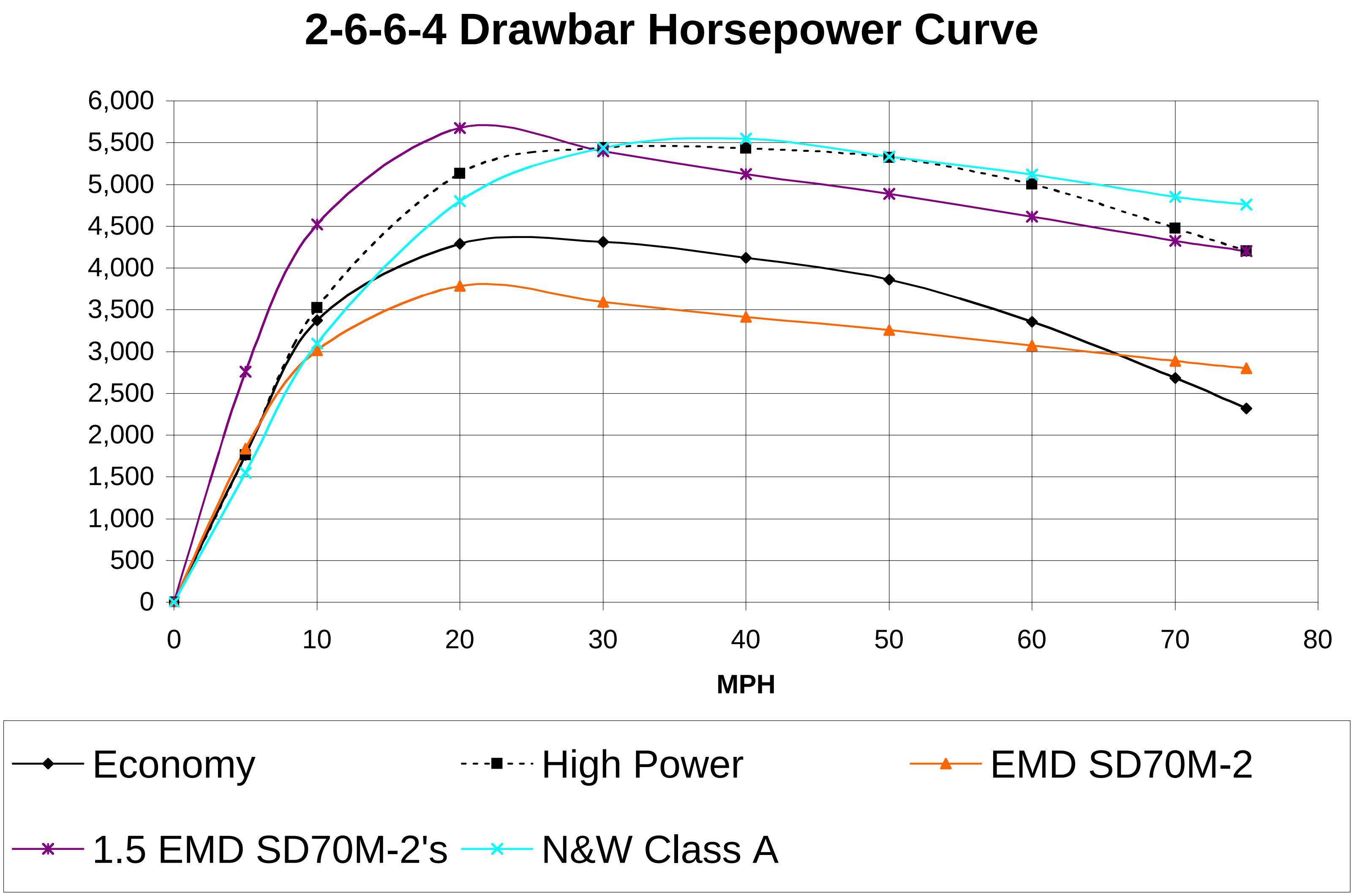
Full Throttle / Notch 8, Comparison - Modern 2-6-6-4 & EMD SD70M-2

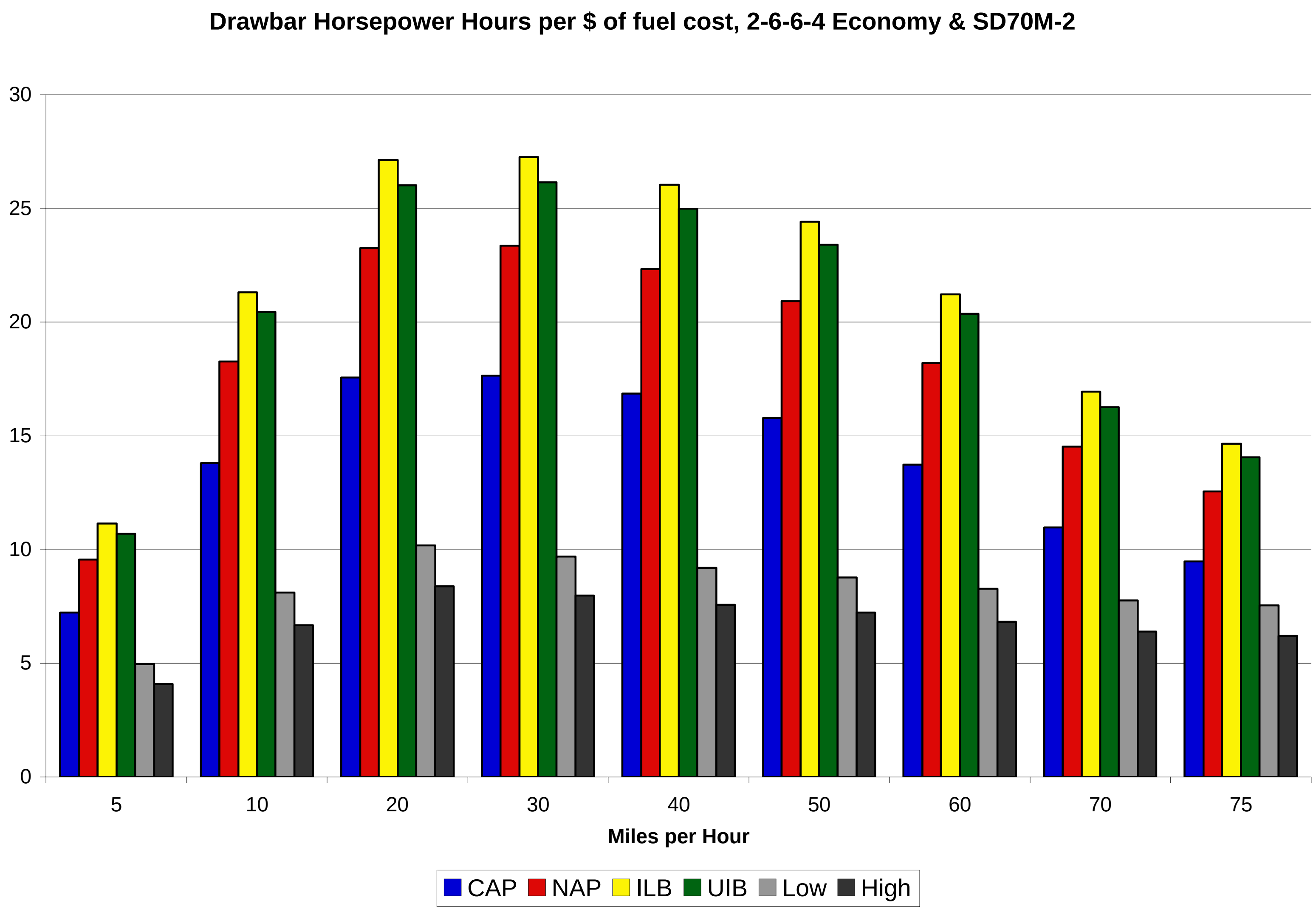
	MPH	0	5	10	20	30	40	50	60	70	75
Economy Setting											
Drawbar pull, level track		**132,637**	**132,375**	**126,491**	**80,469**	**53,919**	**38,633**	**28,957**	**20,995**	**14,368**	**11,590**
Drawbar Horse Power, level track		**0**	**1765**	**3373**	**4292**	**4314**	**4121**	**3861**	**3359**	**2682**	**2318**
DBHP Hours per $ of Fuel Cost, CAP		0	7	14	18	18	17	16	14	11	9
DBHP Hours per $ of Fuel Cost, NAP		0	10	18	23	23	22	21	18	15	13
DBHP Hours per $ of Fuel Cost, ILB		0	11	21	27	27	26	24	21	17	15
DBHP Hours per $ of Fuel Cost, UIB		0	11	20	26	26	25	23	20	16	14
EMD SD70M-2 (4300 HP)	DBPull	**163000**	**138000**	**113000**	**70950**	**44953**	**32011**	**24440**	**19216**	**15454**	**14004**
	DBHP	**0**	**1840**	**3013**	**3784**	**3596**	**3415**	**3259**	**3075**	**2885**	**2801**
DBHP Hours per $ of Fuel Cost, Low		0	5	8	10	10	9	9	8	8	8
DBHP Hours per $ of Fuel Cost, High		0	4	7	8	8	8	7	7	6	6
High Power Setting											
Drawbar pull, level track		**132,637**	**132,375**	**132,076**	**96,206**	**67,958**	**50,940**	**39,922**	**31,259**	**23,965**	**21,007**
Drawbar Horse Power, level track		**0**	**1765**	**3522**	**5131**	**5437**	**5434**	**5323**	**5002**	**4474**	**4201**
DBHP Hours per $ of Fuel Cost, CAP		0	5	11	16	17	17	16	15	14	13
DBHP Hours per $ of Fuel Cost, NAP		0	7	14	21	22	22	22	20	18	17
DBHP Hours per $ of Fuel Cost, ILB		0	8	17	24	26	26	25	24	21	20
DBHP Hours per $ of Fuel Cost, UIB		0	8	16	23	25	25	24	23	20	19
1.5 EMD SD70M-2 (4300 HP)	DBPull	**244500**	**207000**	**169500**	**106425**	**67429**	**48017**	**36661**	**28824**	**23182**	**21006**
	DBHP	**0**	**2760**	**4520**	**5676**	**5394**	**5122**	**4888**	**4612**	**4327**	**4201**
DBHP Hours per $ of Fuel Cost, Low		0	5	8	10	10	9	9	8	8	8
DBHP Hours per $ of Fuel Cost, High		0	4	7	8	8	8	7	7	6	6
	MPH	0	5	10	20	30	40	50	60	70	75
N&W Class A	DBPull	124500	120250	116000	90000	68000	52000	40000	32000	26000	23800
	DBHP	0	1547	3093	4800	5440	5547	5333	5120	4853	4760

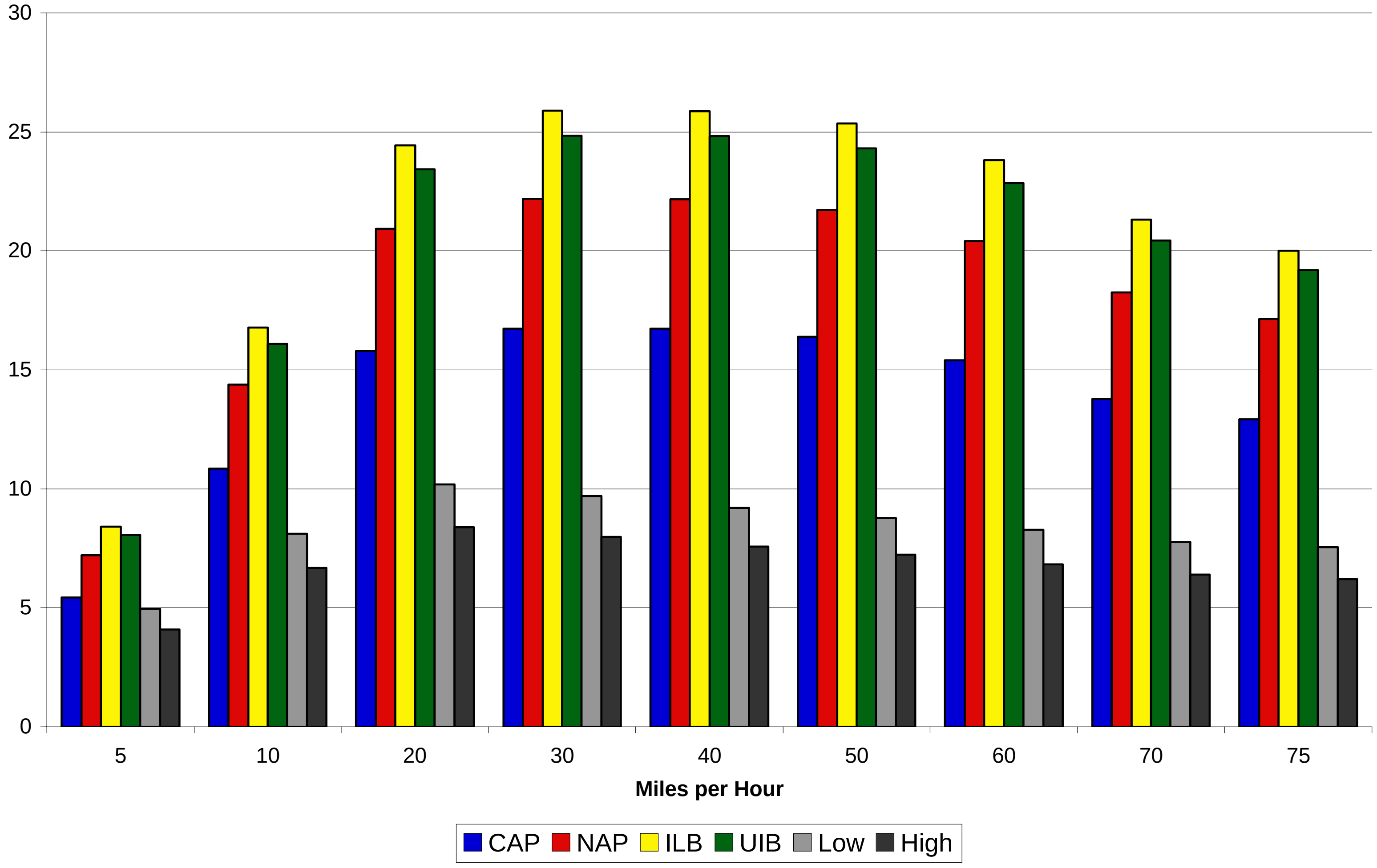
Water Cost	
Cost per 1000 gal. water	$ 0.09
Treatment cost per 1000 gals.	$ 2.35
Total cost per 1000 gals.	$ 2.44
Total cost per 1 gal.	$0.002

Full Throttle Fuel Cost / Hr.	
Coal Cost	
CAP	$56.67
NAP	$41.77
ILB	$35.20
UIB	$36.88
Diesel Cost	
Low	$1.80
High	$2.19
Economy	
CAP	$244.36
NAP	$184.54
ILB	$158.20
UIB	$164.92
High Power	
CAP	$324.85
NAP	$245.09
ILB	$209.97
UIB	$218.93
SD70M-2	
Low	$371.14
High	$450.68
1.5 SD70M-2	
Low	$556.70
High	$676.01


2-6-6-4 Drawbar Pull Curve
250,000
225,000
200,000
175,000
150,000
125,000
100,000
75,000
50,000
25,000
0
0
10
20
30
40
50
60
70
80
MPH
Economy
High Power
EMD SD70M-2
1.5 EMD SD70M-2's
N&W Class A


2-6-6-4 Drawbar Horsepower Curve
6,000
5,500
5,000
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
0
10
20
30
40
50
60
70
80
MPH
Economy
High Power
EMD SD70M-2
1.5 EMD SD70M-2's
N&W Class A


Drawbar Horsepower Hours per $ of fuel cost, 2-6-6-4 Economy & SD70M-2
30
25
20
15
10
5
0
5
10
20
30
40
50
60
70
75
Miles per Hour
CAP
NAP
ILB
UIB
Low
High


Drawbar Horsepower Hours per $ of fuel cost, 2-6-6-4 High Power & SD70M-2

The Modern 2-10-2 versus the medium horsepower, six-axle, DC traction diesel:

The 2-10-2 is a scaled up version of the 2-8-2 listed next. 2-10-2's are called Santa Fe's because the type was developed by the Santa Fe Railroad. The railroad had more than 350 2-10-2's.[72] Many railroads had large numbers of 2-10-2's including the Baltimore and Ohio Railroad and the Pennsylvania Railroad, having 788 locomotives of this style with five drive axles.[73] The Modern 2-10-2 in economy mode is targeted at the SD40-2 which is mainly used for local service. The 2-10-2 in high power mode is comparable to a SD60. This makes it much more versatile when a railroad needs to press second string power into road service when traffic volumes are heavy.

Note: All numbers are calculated by the author with the explanations in the "Calculations" section of this paper.

Drawbar Pull and Drawbar Horsepower:

Between 5 and 40 mph, the 2-10-2 economy has higher DBPull than the SD40-2. This speed range matches the intended duty of the locomotive as power for local freight operations. When the locomotive is used in road freight service the high power setting of the 2-10-2 will allow it to produce more DBHP than a SD60 from 7 to 60 mph. The graphs are located on the following pages.

Fuel Cost:

As can be seen in the following chart and graphs, the fuel cost of the 2-10-2 is less than half of the cost of the diesels. Also, the area of maximum cost savings is in the middle speed range.

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[72] Evan Werkema, "Santa Fe All-time Steam Roster," http://atsf.railfan.net/atsfstea.html

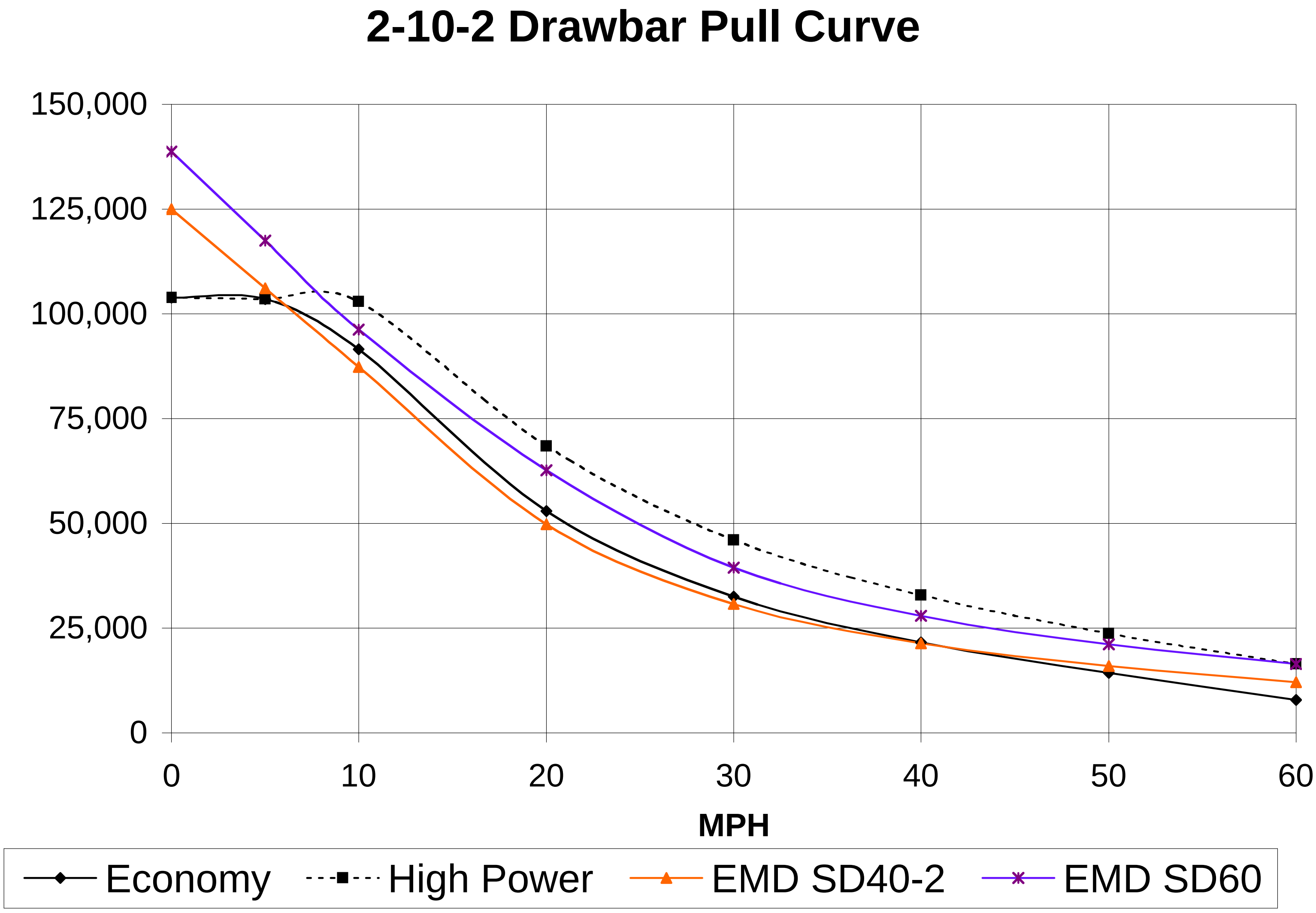
[73] Alvin F. Staufer, *Pennsy Power* (United States: Staufer, 1962), 65 & 83

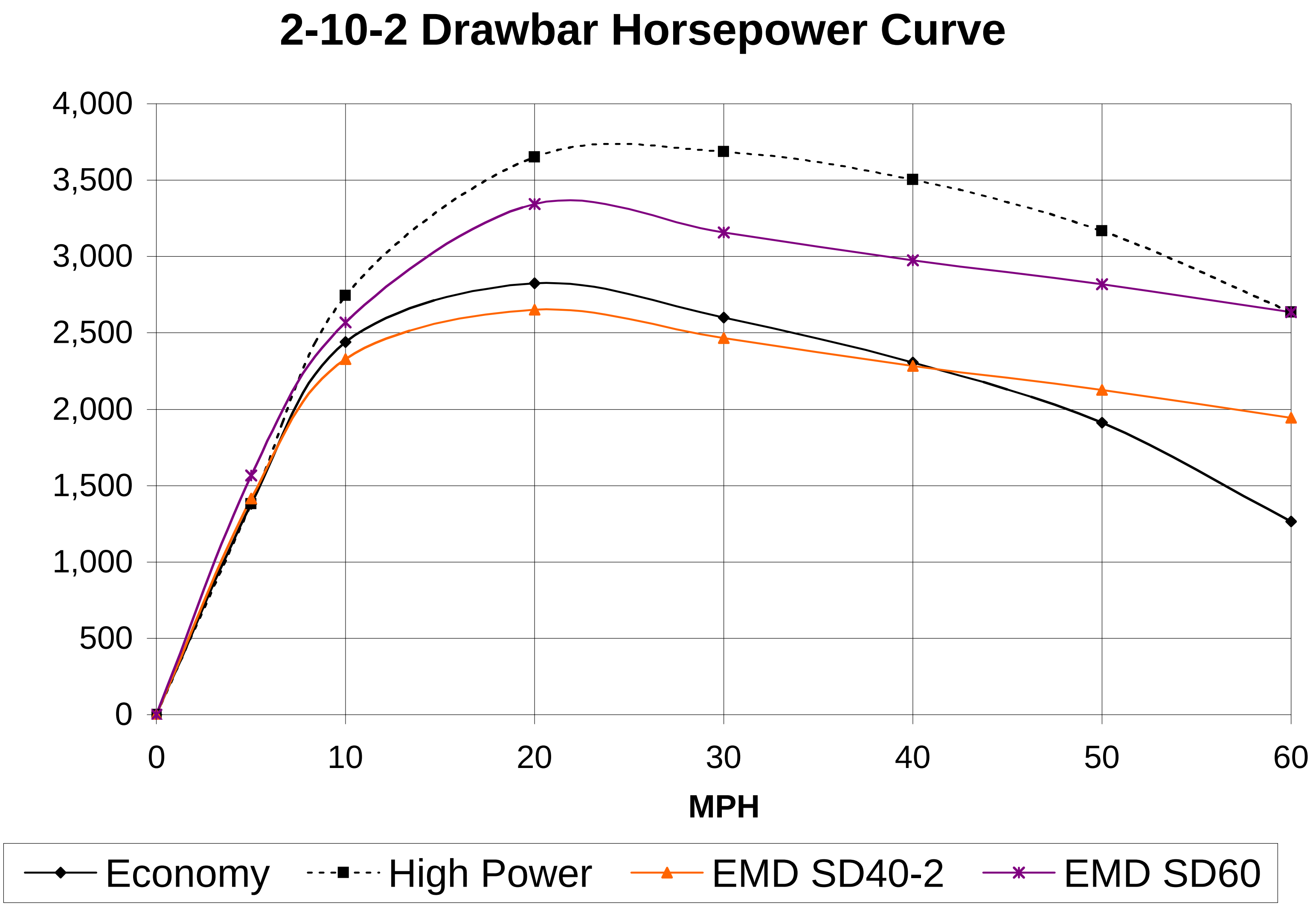
Full Throttle / Notch 8, Comparison - Modern 2-10-2, EMD SD40-2 & EMD SD60

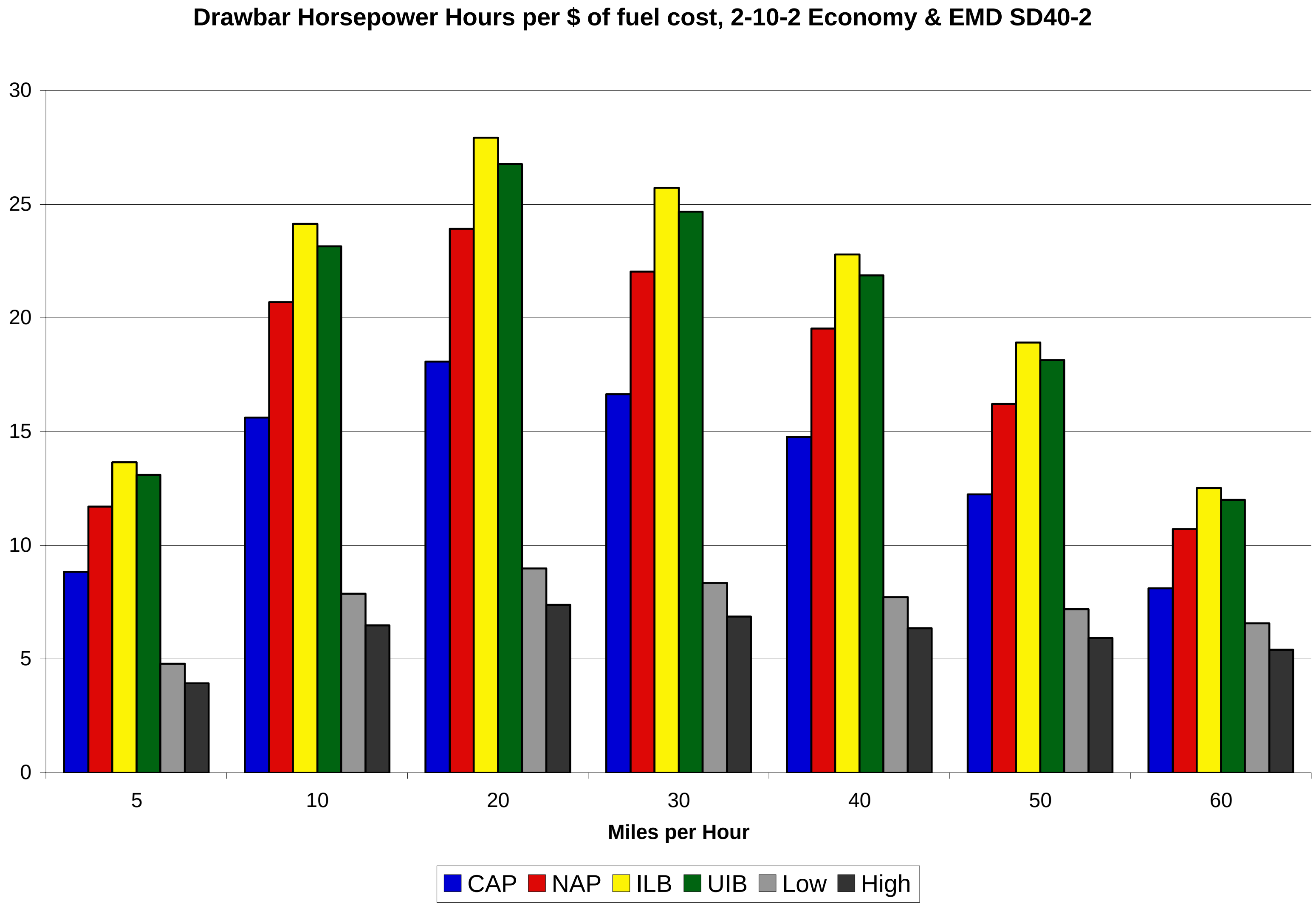
	MPH	0	5	10	20	30	40	50	60
Economy Setting									
Drawbar pull, level track		**103,907**	**103,524**	**91,571**	**52,957**	**32,521**	**21,622**	**14,351**	**7,912**
Drawbar Horse Power, level track		**0**	**1380**	**2442**	**2824**	**2602**	**2,306**	**1913**	**1266**
DBHP Hours per $ of Fuel Cost, CAP		0	9	16	18	17	15	12	8
DBHP Hours per $ of Fuel Cost, NAP		0	12	21	24	22	20	16	11
DBHP Hours per $ of Fuel Cost, ILB		0	14	24	28	26	23	19	13
DBHP Hours per $ of Fuel Cost, UIB		0	13	23	27	25	22	18	12
EMD SD40-2 (3000 HP)	DBPull	**125000**	**106150**	**87300**	**49733**	**30808**	**21402**	**15954**	**12144**
	DBHP	**0**	**1415**	**2328**	**2652**	**2465**	**2283**	**2127**	**1943**
DBHP Hours per $ of Fuel Cost, Low		0	5	8	9	8	8	7	7
DBHP Hours per $ of Fuel Cost, High		0	4	6	7	7	6	6	5
High Power Setting									
Drawbar pull, level track		**103,907**	**103,524**	**102,876**	**68,438**	**46,060**	**32,853**	**23,755**	**16,465**
Drawbar Horse Power, level track		**0**	**1380**	**2743**	**3,650**	**3,685**	**3,504**	**3167**	**2634**
DBHP Hours per $ of Fuel Cost, CAP		0	6	13	17	17	16	15	12
DBHP Hours per $ of Fuel Cost, NAP		0	9	17	23	23	22	20	16
DBHP Hours per $ of Fuel Cost, ILB		0	10	20	26	27	25	23	19
DBHP Hours per $ of Fuel Cost, UIB		0	10	19	25	26	24	22	18
EMD SD60 (3800 HP)	DBPull	**138700**	**117500**	**96300**	**62700**	**39453**	**27886**	**21140**	**16466**
	DBHP	**0**	**1567**	**2568**	**3344**	**3156**	**2975**	**2819**	**2635**
DBHP Hours per $ of Fuel Cost, Low		0	5	7	10	9	9	8	8
DBHP Hours per $ of Fuel Cost, High		0	4	6	8	8	7	7	6

Water Cost	
Cost per 1000 gal. water	$ 0.09
Treatment cost per 1000 gals.	$ 2.35
Total cost per 1000 gals.	$ 2.44
Total cost per 1 gal.	$ 0.002

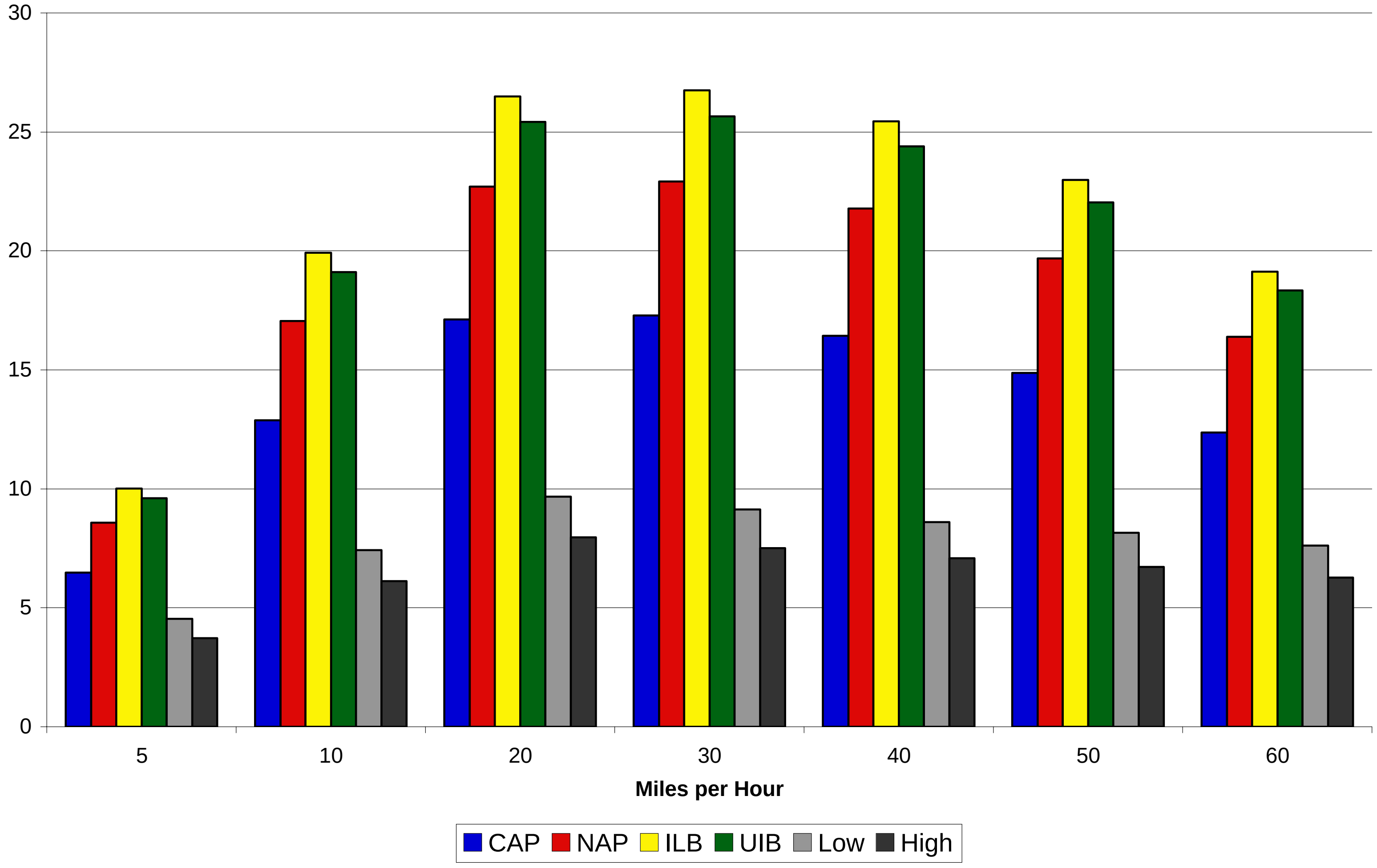
Full Throttle Fuel Cost / Hr.	
Coal Cost	
CAP	$56.67
NAP	$41.77
ILB	$35.20
UIB	$36.88
Diesel Cost	
Low	$1.80
High	$2.19
Economy	
CAP	$156.25
NAP	$118.02
ILB	$101.18
UIB	$105.47
High Power	
CAP	$213.12
NAP	$160.80
ILB	$137.76
UIB	$143.64
SD40-2	
Low	$295.47
High	$358.79
SD60	
Low	$345.73
High	$419.83


2-10-2 Drawbar Pull Curve
150,000
125,000
100,000
75,000
50,000
25,000
0
0
10
20
30
40
50
60
MPH
Economy
High Power
EMD SD40-2
EMD SD60


2-10-2 Drawbar Horsepower Curve
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
0
10
20
30
40
50
60
MPH
Economy
High Power
EMD SD40-2
EMD SD60


Drawbar Horsepower Hours per $ of fuel cost, 2-10-2 Economy & EMD SD40-2
30
25
20
15
10
5
0
5
10
20
30
40
50
60
Miles per Hour
CAP
NAP
ILB
UIB
Low
High

Drawbar Horsepower Hours per $ of fuel cost, 2-10-2 High Power & EMD SD60



The Modern 2-8-2 versus the low horsepower, four-axle, DC traction diesel:

The 2-8-2 wheel arrangement was very popular with the American railroads during the steam era. This type was in use by most railroads, with some 579 being owned by the Pennsylvania Railroad alone, for use on secondary assignments.[74] The 2-8-2 in this comparison is scaled as half of the 2-8-8-4 from the beginning of the list. The 2-8-2 in economy mode is a replacement for the EMD GP38-2, which is the standard type used by the railroads for the lightest freight duties. In high power mode, the 2-8-2 would have capabilities similar to an EMD GP59 which is an update of the GP40. This ability to have higher output when needed would be an advantage to a railroad when more road power is needed for busy times when power is short.

Note: All numbers are calculated by the author with the explanations in the "Calculations" section of this paper.

Drawbar Pull & Drawbar Horsepower:

Below 15 mph, the 2-8-2 in Economy mode would be capable of producing substantially more DBPull than the GP38-2. Between 15 and 40 mph, the 2-8-2 would produce more DBHP than the GP38-2; however, above 50 mph, the GP38-2 would be producing more DBHP, but in local service this would not be that great a handicap. Starting at five mph, the 2-8-2 in high power mode would create more DBPull than the GP59. From that speed until 60 mph, the 2-8-2 would have higher DBHP than the GP59.

Fuel Cost:

The diesels' fuel cost would be significantly more expensive, more than twice the cost of the 2-8-2. This can be seen on the following pages. The 10 to 40 mph range is where the 2-8-2 would have the highest savings in fuel used per unit of power produced.

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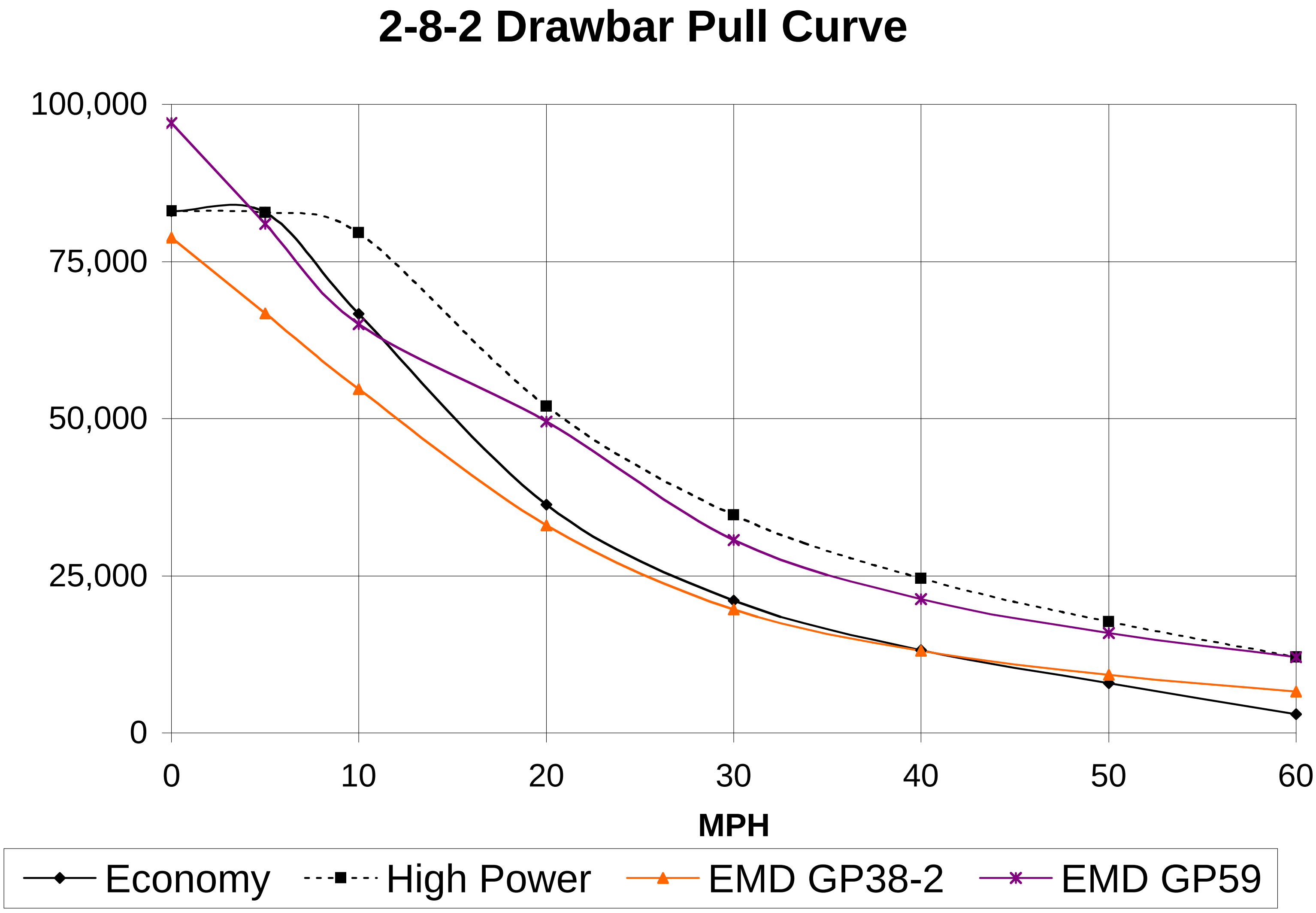
[74] Alvin F. Staufer, *Pennsy Power* (United States: Staufer, 1962), 51

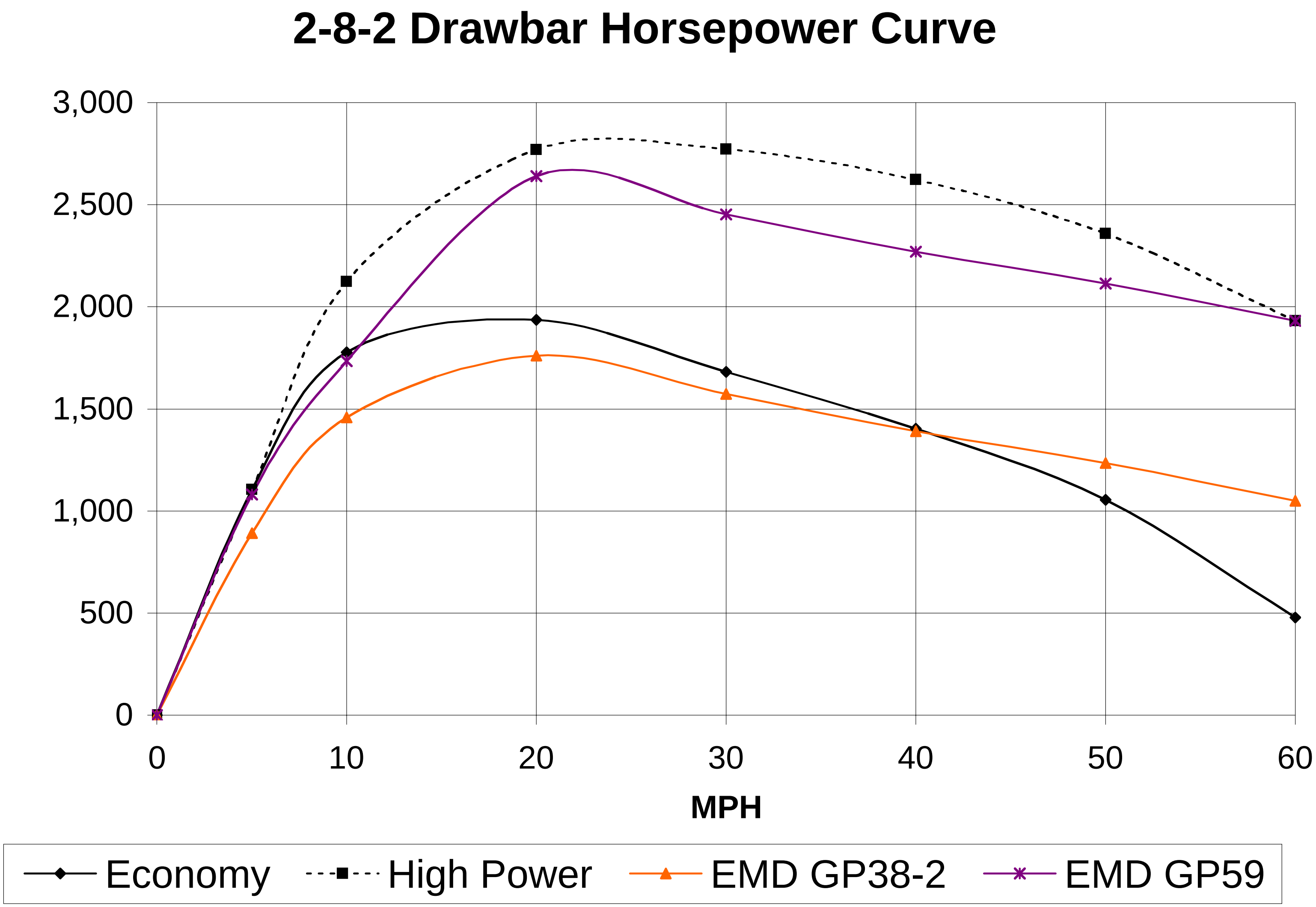
Full Throttle / Notch 8, Comparison - Modern 2-8-2, EMD GP38-2 & EMD GP59

	MPH	0	5	10	20	30	40	50	60
Economy Setting									
Drawbar pull, level track		**83,035**	**82,789**	**66,659**	**36,291**	**21,022**	**13,151**	**7,908**	**2,994**
Drawbar Horse Power, level track		**0**	**1104**	**1,778**	**1,936**	**1,682**	**1,403**	**1,054**	**479**
DBHP Hours per $ of Fuel Cost, CAP		0	10	16	18	16	13	10	4
DBHP Hours per $ of Fuel Cost, NAP		0	13	22	24	21	17	13	6
DBHP Hours per $ of Fuel Cost, ILB		0	16	25	28	24	20	15	7
DBHP Hours per $ of Fuel Cost, UIB		0	15	24	26	23	19	14	7
EMD GP38-2 (2000 HP)	DBPull	**78800**	**66750**	**54700**	**33000**	**19653**	**13036**	**9260**	**6566**
	DBHP	**0**	**890**	**1459**	**1760**	**1572**	**1391**	**1235**	**1051**
DBHP Hours per $ of Fuel Cost, Low		0	4	7	8	7	6	6	5
DBHP Hours per $ of Fuel Cost, High		0	3	5	7	6	5	5	4
High Power Setting									
Drawbar pull, level track		**83,035**	**82,789**	**79,605**	**51,948**	**34,651**	**24,599**	**17,696**	**12,068**
Drawbar Horse Power, level track		**0**	**1104**	**2123**	**2,771**	**2,772**	**2,624**	**2360**	**1931**
DBHP Hours per $ of Fuel Cost, CAP		0	7	13	17	17	16	15	12
DBHP Hours per $ of Fuel Cost, NAP		0	9	18	23	23	22	19	16
DBHP Hours per $ of Fuel Cost, ILB		0	11	20	27	27	25	23	19
DBHP Hours per $ of Fuel Cost, UIB		0	10	20	26	26	24	22	18
EMD GP59 (3000 HP)	DBPull	**97000**	**81000**	**65000**	**49500**	**30653**	**21286**	**15860**	**12066**
	DBHP	**0**	**1080**	**1733**	**2640**	**2452**	**2271**	**2115**	**1931**
DBHP Hours per $ of Fuel Cost, Low		0	4	6	10	9	8	8	7
DBHP Hours per $ of Fuel Cost, High		0	3	5	8	7	7	6	6

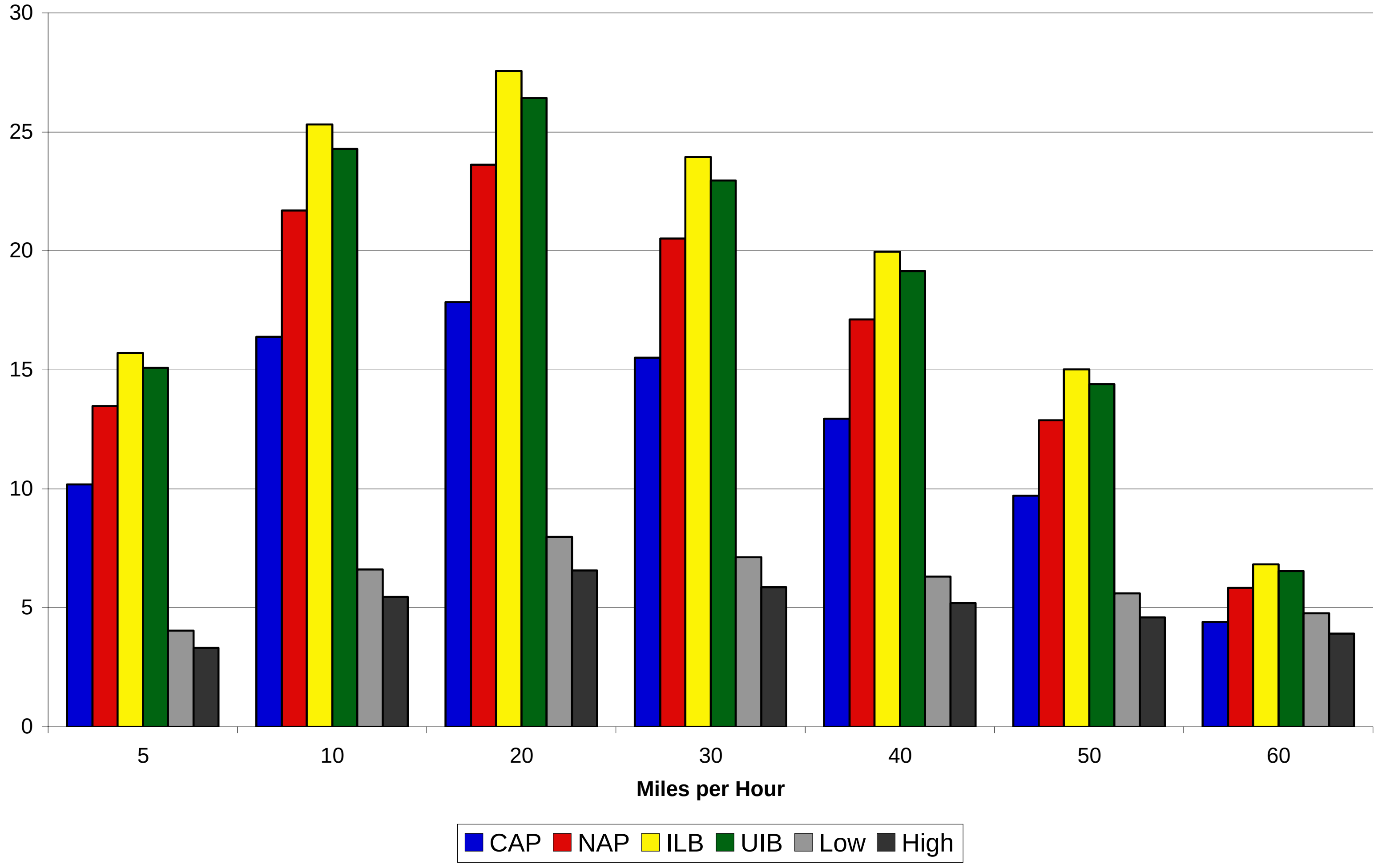
Water Cost	
Cost per 1000 gal. water	$ 0.09
Treatment cost per 1000 gals.	$ 2.35
Total cost per 1000 gals.	$ 2.44
Total cost per 1 gal.	$ 0.002

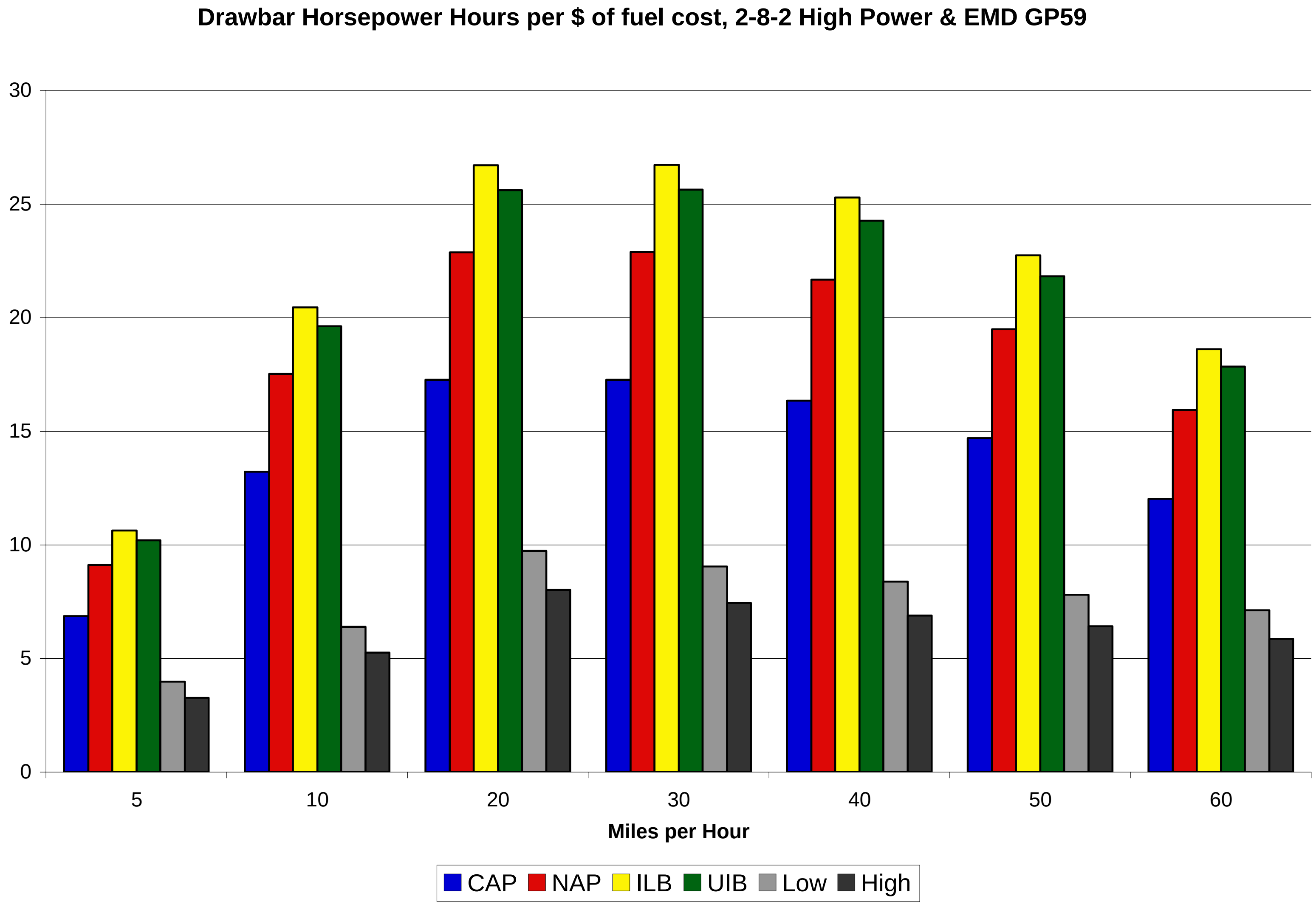
Full Throttle Fuel Cost / Hr.	
Coal Cost	
CAP	$56.67
NAP	$41.77
ILB	$35.20
UIB	$36.88
Diesel Cost	
Low	$1.80
High	$2.19
Economy	
CAP	$108.44
NAP	$81.92
ILB	$70.24
UIB	$73.22
High Power	
CAP	$160.48
NAP	$121.08
ILB	$103.73
UIB	$108.16
GP38-2	
Low	$220.52
High	$267.78
GP59	
Low	$270.97
High	$329.04


2-8-2 Drawbar Pull Curve
100,000
75,000
50,000
25,000
0
0
10
20
30
40
50
60
MPH
Economy
High Power
EMD GP38-2
EMD GP59


2-8-2 Drawbar Horsepower Curve
3,000
2,500
2,000
1,500
1,000
500
0
0
10
20
30
40
50
60
MPH
Economy
High Power
EMD GP38-2
EMD GP59

Drawbar Horsepower Hours per $ of fuel cost, 2-8-2 Economy & EMD GP38-2




Drawbar Horsepower Hours per $ of fuel cost, 2-8-2 High Power & EMD GP59
30
25
20
15
10
5
0
5
10
20
30
40
50
60
Miles per Hour
CAP
NAP
ILB
UIB
Low
High

The Modern 0-10-0 versus the low horsepower, four-axle, DC traction diesel switcher:

This 0-10-0 is a scaled up version of the N&W Class S1a 0-8-0 switcher. The N&W bought 30 similar S1 0-8-0's and built 45 S1a's between 1950 and 1953. S1a 244 built in December of 1953 was the last steam locomotive constructed by N&W and the last built for service in America. The small drivers and high tractive effort of this class gave it better acceleration than diesel switchers, and they were very sure-footed, with heavy loads as well. The tender was proportioned to need coaling once and watering twice per day.[75] The 0-8-0 has a wide shallow firebox similar to the N&W Y classes. Also for the same reason listed with the 2-8-8-4, this arrangement is not useable with GPCS. A wide deep firebox could be used, making the locomotive a 0-8-2, but having one unpowered axle on a switcher is not efficient. The narrow deep type firebox located between the drivers is more beneficial on this type of locomotive. If this type of firebox is used, one more axle should be added, making the locomotive a 0-10-0, so the tube and flue length in the boiler won't be too short. The modern 0-10-0 is roughly designed to replace up to approximately two switchers in conventional flat switching. Two 0-10-0's MU'ed in a consist would replace a mother-slug set in hump duty at a classification yard.

Note: All numbers are calculated by the author with the explanations in the "Calculations" section of this paper.

Drawbar Pull & Drawbar Horsepower:

At 10 mph the DBPull of the 0-10-0 is essentially the same as 1.95 EMD MP15's and above about 3 mph is about the same as 1.65 NRE GenSets. The DBHP curves, as can be seen on the following pages, is nearly identical. The 0-10-0 in hump duty would match 60% of a mother-slug set at 5 mph. Over this speed, the 0-10-0 has nearly twice the DBHP.

Fuel Cost:

As can be seen in the chart on the following page, the fuel costs of the diesels is significantly higher than the 0-10-0. DBHP hours per dollar graphs are attached.

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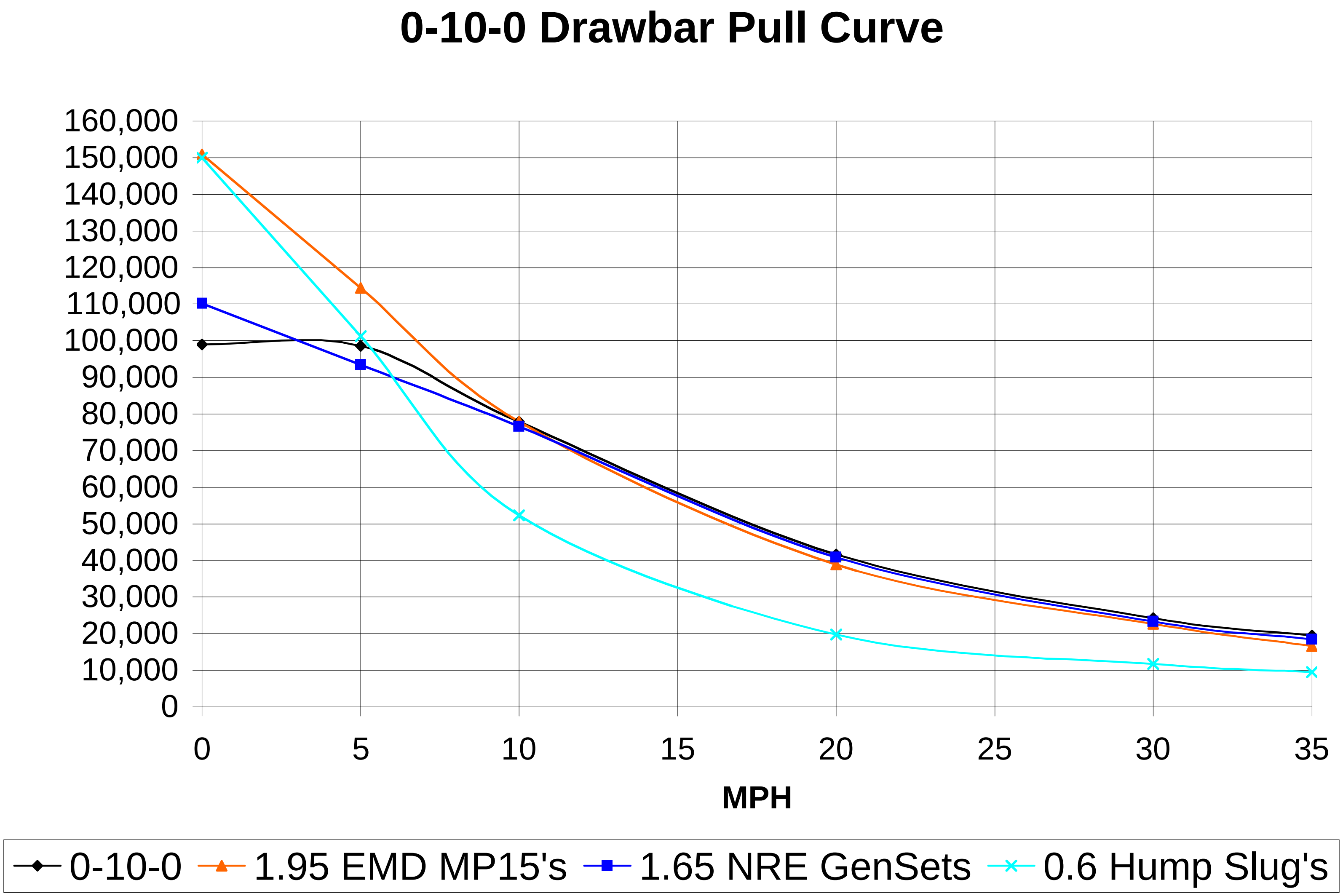
[75] Colonel Lewis Ingles Jeffries, *N&W Giant of Steam* (Hong Kong: Norfolk & Western Historical Society, 2005) 260

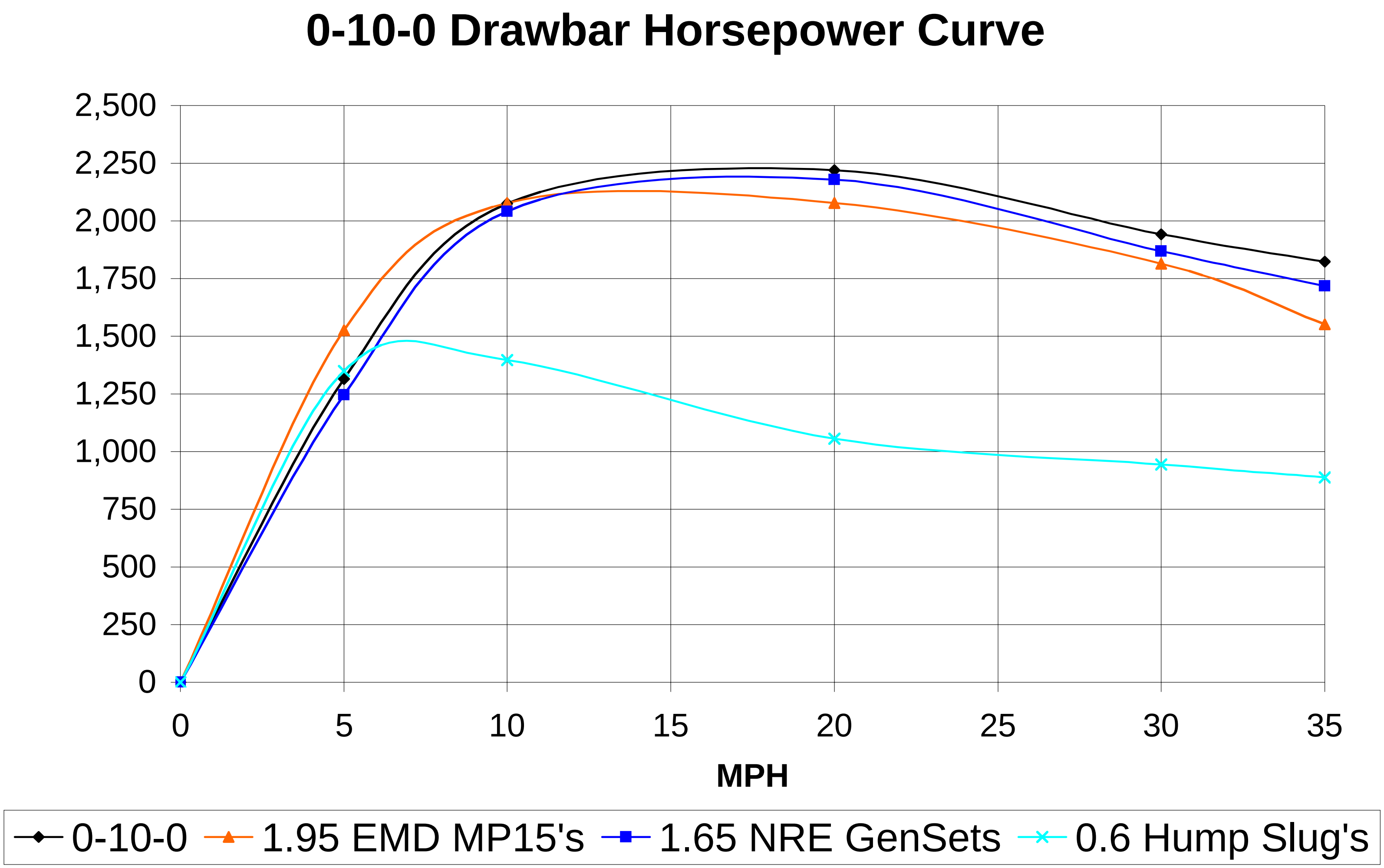
Full Throttle / Notch 8, Comparison - Modern 0-10-0 & Switchers

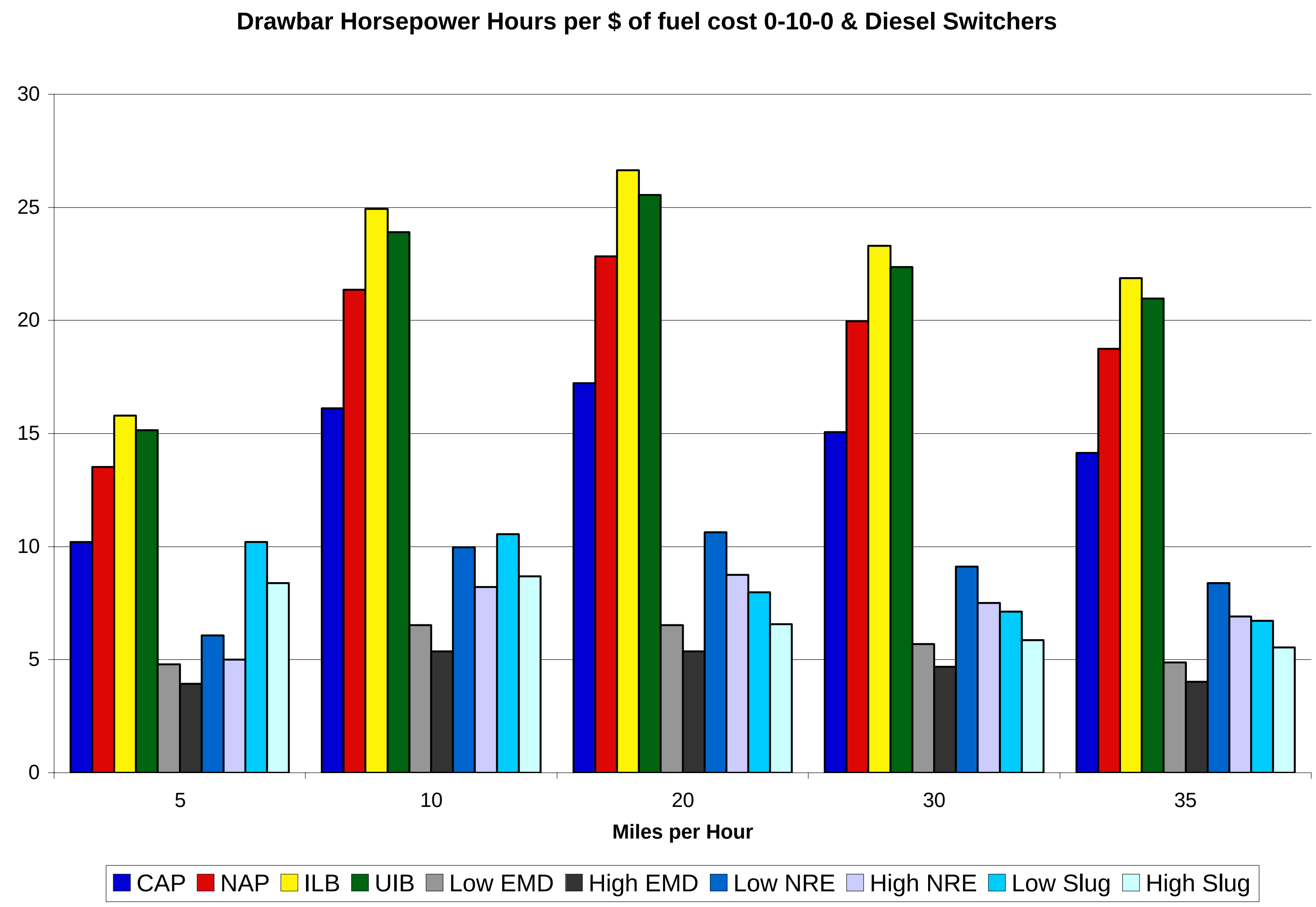
	MPH	0	5	10	20	30	35
High Power Setting							
Drawbar pull, level track		**98,998**	**98,636**	**77,866**	**41,624**	**24,276**	**19,525**
Drawbar Horse Power, level track		**0**	**1315**	**2076**	**2220**	**1942**	**1,822**
DBHP Hours per $ of Fuel Cost, CAP		0	10	16	17	15	14
DBHP Hours per $ of Fuel Cost, NAP		0	14	21	23	20	19
DBHP Hours per $ of Fuel Cost, ILB		0	16	25	27	23	22
DBHP Hours per $ of Fuel Cost, UIB		0	15	24	26	22	21
	MPH	0	5	10	20	30	35
1.95 EMD MP15 (1500 HP)	DBPull	**150930**	**114404**	**77878**	**38939**	**22672**	**16615**
	DBHP	**0**	**1525**	**2077**	**2077**	**1814**	**1551**
DBHP Hours per $ of Fuel Cost, Low		0	5	7	7	6	5
DBHP Hours per $ of Fuel Cost, High		0	4	5	5	5	4
	MPH	0	5	10	20	30	35
1.65 NRE GenSets (1400 HP)	DBPull	**110220**	**93390**	**76560**	**40838**	**23352**	**18410**
	DBHP	**0**	**1245**	**2042**	**2178**	**1868**	**1718**
DBHP Hours per $ of Fuel Cost, Low		0	6	10	11	9	8
DBHP Hours per $ of Fuel Cost, High		0	5	8	9	8	7
	MPH	0	5	10	20	30	35
0.6 Hump Slug (2000 HP)	DBPull	**150000**	**101190**	**52380**	**19800**	**11792**	**9523**
	DBHP	**0**	**1349**	**1397**	**1056**	**943**	**889**
DBHP Hours per $ of Fuel Cost, Low		0	10	11	8	7	7
DBHP Hours per $ of Fuel Cost, High		0	8	9	7	6	6

Water Cost	
Cost per 1000 gal. water	$ 0.09
Treatment cost per 1000 gals.	$ 2.35
Total cost per 1000 gals.	$ 2.44
Total cost per 1 gal.	$ 0.002

Full Throttle Fuel Cost / Hr.	
Coal Cost	
CAP	$56.67
NAP	$41.77
ILB	$35.20
UIB	$36.88
Diesel Cost	
Low	$1.80
High	$2.19
0-10-0	
CAP	$128.88
NAP	$97.24
ILB	$83.31
UIB	$86.86
1.95 MP15's	
Low	$318.29
High	$386.51
1.65 GenSet's	
East	$204.70
West	$248.57
0.6 Hump Slug	
Low	$132.31
High	$160.67


0-10-0 Drawbar Pull Curve
160,000
150,000
140,000
130,000
120,000
110,000
100,000
90,000
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
0
5
10
15
20
25
30
35
MPH
0-10-0
1.95 EMD MP15's
1.65 NRE GenSets
0.6 Hump Slug's


0-10-0 Drawbar Horsepower Curve
2,500
2,250
2,000
1,750
1,500
1,250
1,000
750
500
250
0
0
5
10
15
20
25
30
35
MPH
0-10-0
1.95 EMD MP15's
1.65 NRE GenSets
0.6 Hump Slug's


Drawbar Horsepower Hours per $ of fuel cost 0-10-0 & Diesel Switchers
30
25
20
15
10
5
0
5
10
20
30
35
Miles per Hour
CAP
NAP
ILB
UIB
Low EMD
High EMD
Low NRE
High NRE
Low Slug
High Slug

The Modern 4-8-4P versus the GE P42, Amtrak's passenger diesel:

The 4-8-4P is based on the N&W Class J. The 4-8-4 was the standard locomotive for fast traffic in America, with most North American Railroads operating them.[76] The Class J could run at speeds up to 100 mph and handle heavy 16 car passenger trains up steep grades on the N&W. The Class J's were also used in freight service and rated at up to 13,000 tons, between Williamson, WV and Portsmouth, OH.[77] The 4-8-4P has larger cylinders and 80" drivers like the Santa Fe 2900 Class 4-8-4's.[78] This was done to give a 110 mph top speed that matches the GE P42. The 4-8-4P in economy mode is comparable to the GE P42, while in high power mode, the 4-8-4 is equal to 1.75 GE P42's. This feature would allow Amtrak to reduce the number of locomotives it has on its roster and uses in service on a regular basis. Amtrak could use one 4-8-4 to replace two P42's on certain trains and two 4-8-4's to replace three P42's on other trains or use the higher power output to increase average speeds and reduce schedules on trains handled by a single P42. One significant issue would be that steam locomotives cannot produce Head End Power (HEP) for passenger cars. There are two ways could be used to resolve this issue. Short term, a HEP car could be used (a car with a diesel generator) to power the cars. The long-term solution is to use boiler steam, axle generators on the passenger cars and air pressure from the brake system to operate the car's subsystems. This system was used for decades before HEP was introduced in the 1970's. The cars would use steam for heating, hot water and air conditioning (steam ejector type, which works on the principle of evaporation, uses some electricity for the blower fans[79]). The water pressure, automatic doors and toilets could be operated using the compressed air from the brake system. The lights and other electrical devices would be powered by axle generators when the train is moving and batteries when the train is stopped at stations. Propane would be used for stoves and ovens in the dining car. The calculations consider boiler steam being used for the cars and the cars having the increased resistance of axle generators.

Note: All numbers are calculated by the author with the explanations in the "Calculations" section of this paper.

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[76] Andre Chapelon, *La Locomotive A Vapeur*, trans. George W. Carpenter, C.Eng., M.I. Mech.E. (Great Britain: Camden Miniature Steam Service, 2000), 331

[77] Colonel Lewis Ingles Jeffries, *N&W Giant of Steam* (Hong Kong: Norfolk & Western Historical Society, 2005) 239 & 247

[78] San Bernardino Railroad Historical Society, http://www.sbrhs.org/Pages/484com.html

[79] Steam ejector air conditioning was used by many railroads including the Santa Fe, which runs through some of the hottest parts of the country.

Drawbar Pull & Drawbar Horsepower:

The 4-8-4P in economy has about 18% more DBPull at starting than the GE P42. The 4-8-4P produces more DBHP than a P42 until just over 80 mph. Amtrak trains running on standard Class I freight railroad tracks are limited to 79 mph top speed. The 4-8-4P in high power mode produces less DBPull than 1.75 P42's under about 32 mph. Passenger trains exhibit more train resistance at high speeds rather than low speeds so this deficit in DBPull is of no significant consequence. On the other hand, from about 32 to 95 mph the 4-8-4P would produce more DBHP than 1.75 P42's.

Fuel Cost:

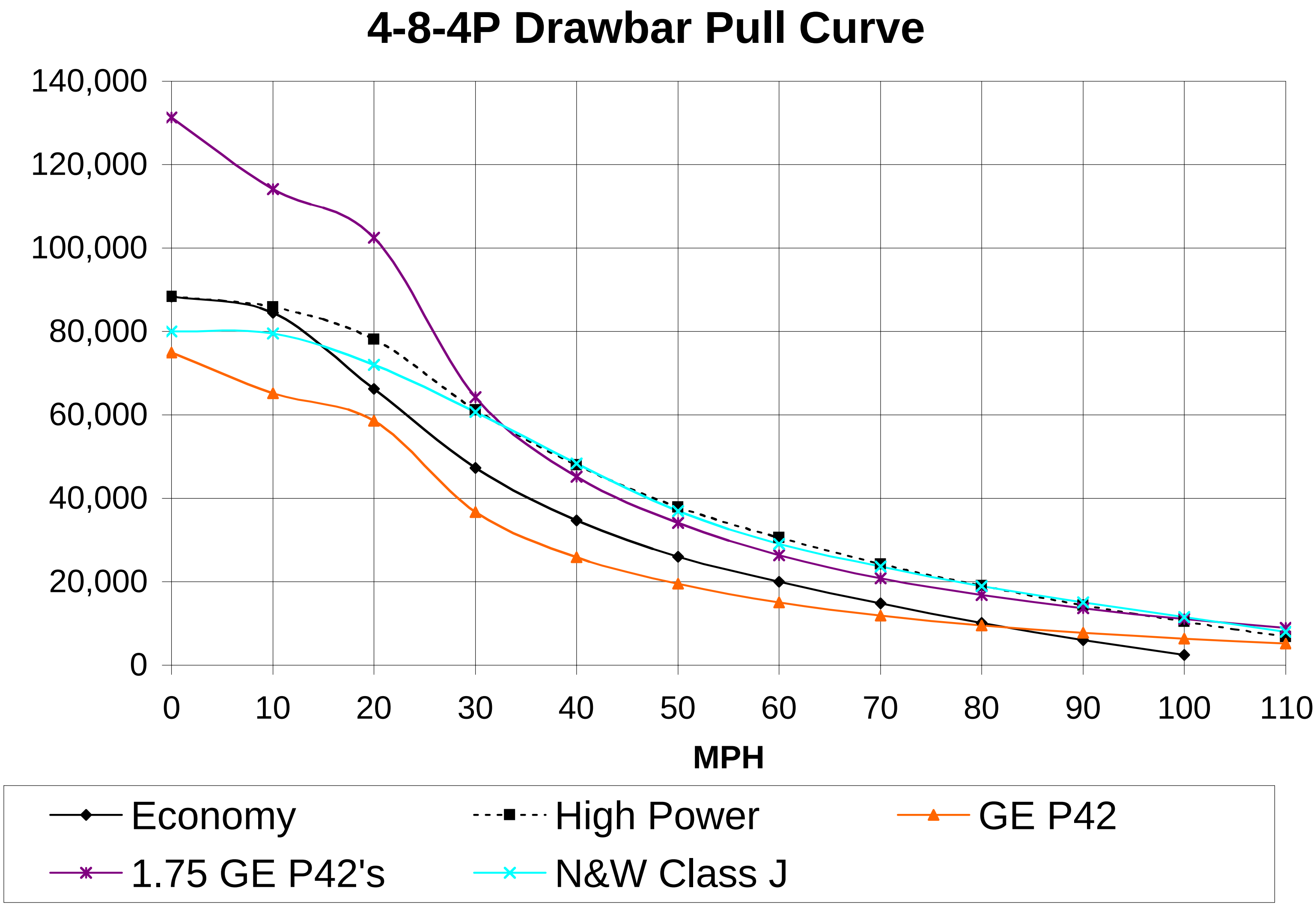
As can be seen on the chart on the following page, the 4-8-4P has a full throttle fuel cost of only $145 to $221 depending on coal type used, compared with $480 for the P42. The 4-8-4 in high power also has fuel costs significantly lower than its diesel counterpart. The DBHP hours produced per dollar of fuel cost is also graphed on the following pages.

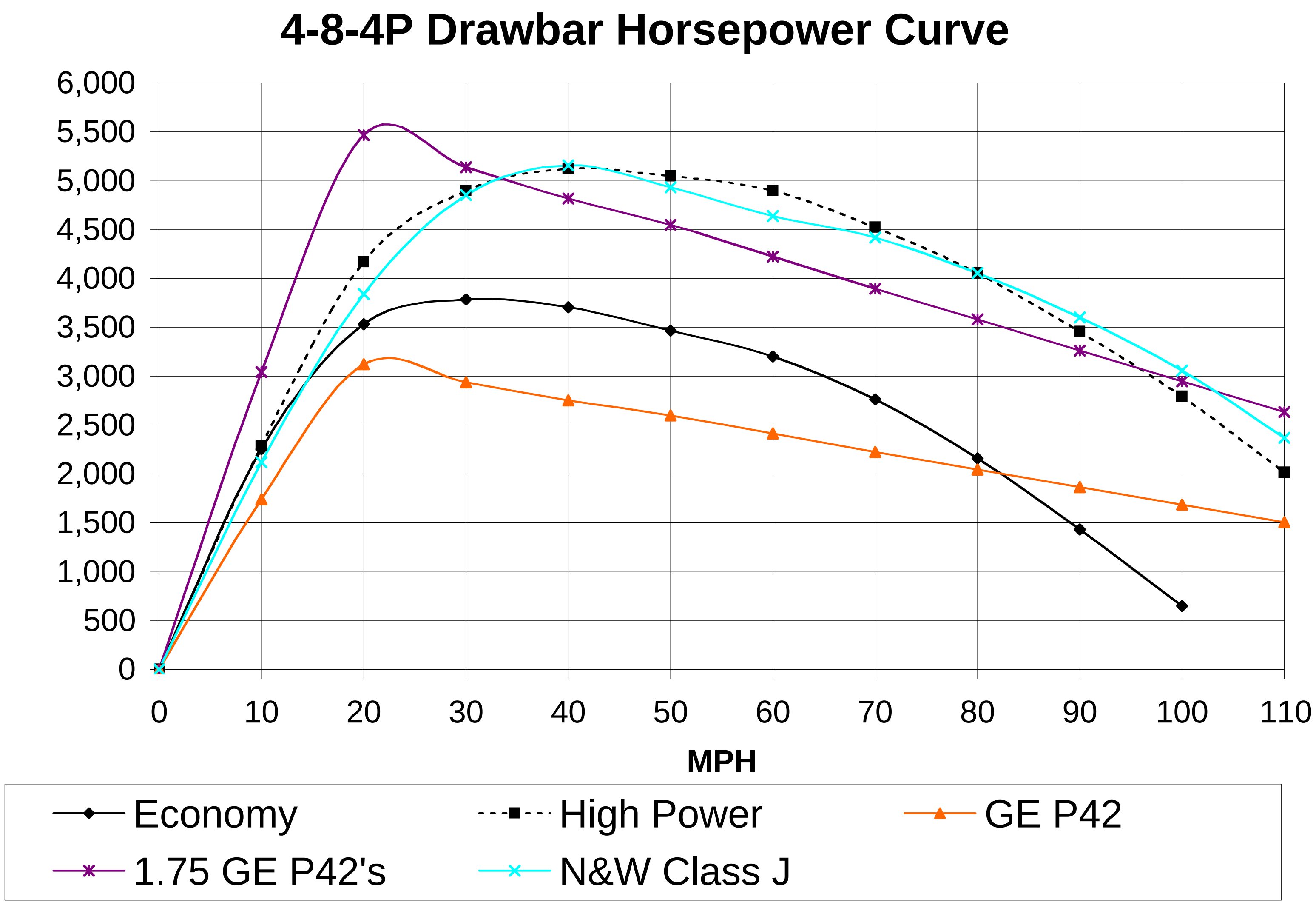
Full Throttle / Notch 8, Comparison - Modern 4-8-4P & GE P42

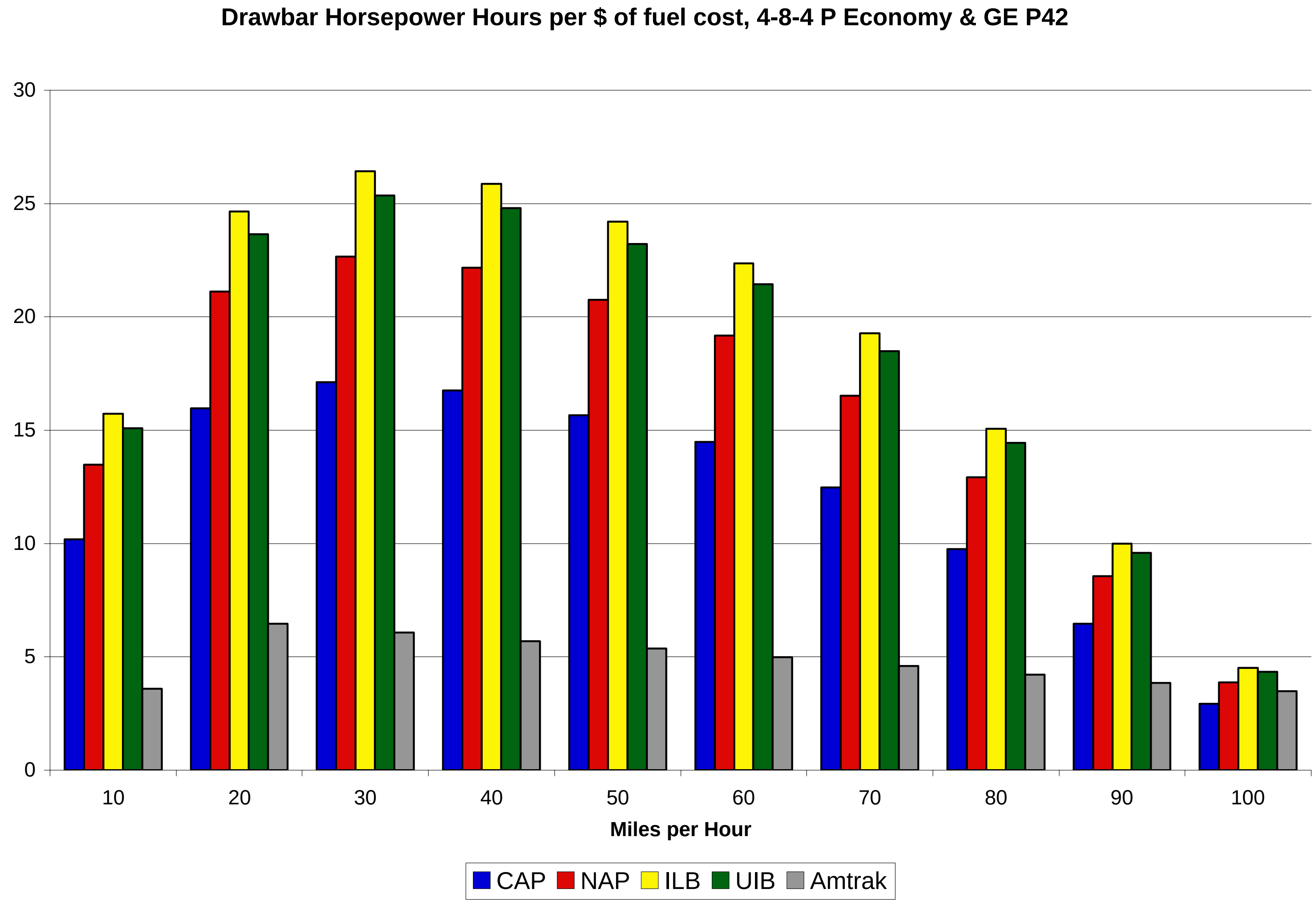
	MPH	0	10	20	30	40	50	60	70	80	90	100	110
Economy Setting													
Drawbar pull, level track		**88,401**	**84,465**	**66,212**	**47,330**	**34,740**	**26,005**	**20,026**	**14,792**	**10,118**	**5,963**	**2,427**	
Drawbar Horse Power, level track		**0**	**2252**	**3531**	**3786**	**3706**	**3467**	**3204**	**2761**	**2158**	**1431**	**647**	
DBHP Hours per $ of Fuel Cost, CAP		0	10	16	17	17	16	14	12	10	6	3	
DBHP Hours per $ of Fuel Cost, NAP		0	13	21	23	22	21	19	17	13	9	4	
DBHP Hours per $ of Fuel Cost, ILB		0	16	25	26	26	24	22	19	15	10	5	
DBHP Hours per $ of Fuel Cost, UIB		0	15	24	25	25	23	21	18	14	10	4	
GE P42 (4250 HP)	DBPull	**75000**	**65230**	**58575**	**36703**	**25824**	**19490**	**15091**	**11919**	**9586**	**7772**	**6320**	**5132**
	DBHP	**0**	**1739**	**3124**	**2936**	**2755**	**2599**	**2415**	**2225**	**2045**	**1865**	**1685**	**1506**
DBHP Hours per $ of Fuel Cost, Amtrak		0	4	6	6	6	5	5	5	4	4	3	3
High Power Setting													
Drawbar pull, level track		**88,401**	**85,833**	**78,145**	**61,219**	**48,017**	**37,840**	**30,609**	**24,227**	**19,001**	**14,406**	**10,478**	**6,865**
Drawbar Horse Power, level track		**0**	**2,289**	**4,168**	**4,897**	**5,122**	**5,045**	**4,897**	**4,522**	**4,054**	**3,457**	**2,794**	**2,014**
DBHP Hours per $ of Fuel Cost, CAP		0	7	13	15	16	16	15	14	13	11	9	6
DBHP Hours per $ of Fuel Cost, NAP		0	10	17	20	21	21	20	19	17	14	12	8
DBHP Hours per $ of Fuel Cost, ILB		0	11	20	24	25	25	24	22	20	17	14	10
DBHP Hours per $ of Fuel Cost, UIB		0	11	19	23	24	24	23	21	19	16	13	9
1.75 GE P42's (4250 HP)	DBPull	**131250**	**114153**	**102506**	**64229**	**45191**	**34108**	**26410**	**20858**	**16775**	**13600**	**11060**	**8982**
	DBHP	**0**	**3044**	**5467**	**5138**	**4820**	**4548**	**4226**	**3893**	**3579**	**3264**	**2949**	**2635**
DBHP Hours per $ of Fuel Cost, Amtrak		0	4	6	6	6	5	5	5	4	4	3	3
	MPH	0	10	20	30	40	50	60	70	80	90	100	110
N&W Class J	DBPull	80000	79500	72000	60667	48333	37000	29000	23667	19000	15000	11500	8000
	DBHP	0	2120	3840	4853	5156	4933	4640	4418	4053	3600	3058	2369

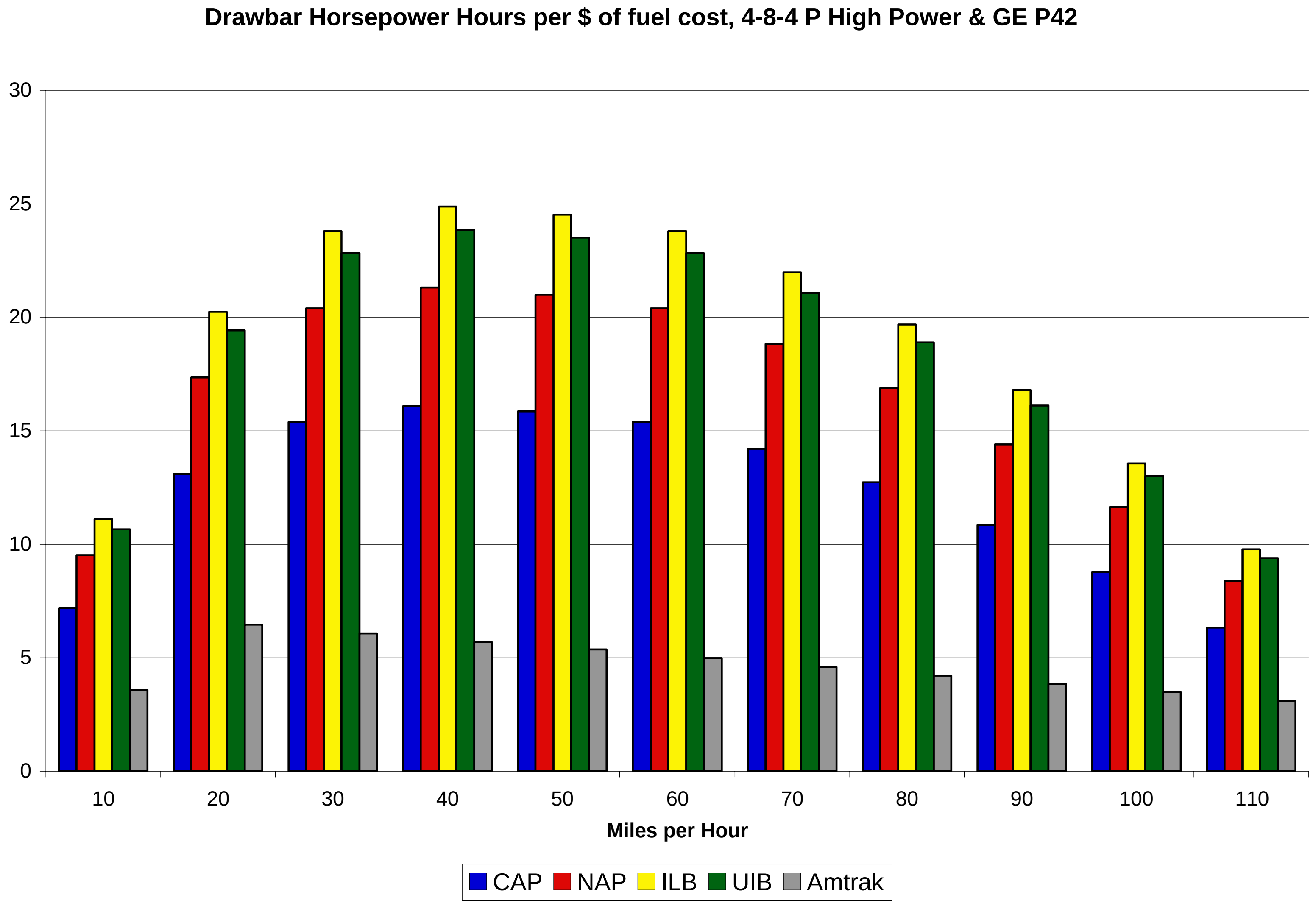
Full Throttle Fuel Cost / Hr.	
Coal Cost	
CAP	$56.67
NAP	$41.77
ILB	$35.20
UIB	$36.88
Diesel Cost	
Amt.	$2.30
Economy	
CAP	$221.25
NAP	$167.13
ILB	$143.29
UIB	$149.37
High Power	
CAP	$318.41
NAP	$240.24
ILB	$205.81
UIB	$214.59
P42	
Amt.	$483.92
1.75 P42's	
Amt.	$846.86

Water Cost	
Cost per 1000 gal. water	$ 0.09
Treatment cost per 1000 gals.	$ 2.35
Total cost per 1000 gals.	$ 2.44
Total cost per 1 gal.	$0.002


4-8-4P Drawbar Pull Curve
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
0
10
20
30
40
50
60
70
80
90
100
110
MPH
Economy
High Power
GE P42
1.75 GE P42's
N&W Class J


4-8-4P Drawbar Horsepower Curve
6,000
5,500
5,000
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
0
10
20
30
40
50
60
70
80
90
100
110
MPH
Economy
High Power
GE P42
1.75 GE P42's
N&W Class J


Drawbar Horsepower Hours per $ of fuel cost, 4-8-4 P Economy & GE P42
30
25
20
15
10
5
0
10
20
30
40
50
60
70
80
90
100
Miles per Hour
CAP
NAP
ILB
UIB
Amtrak


Drawbar Horsepower Hours per $ of fuel cost, 4-8-4 P High Power & GE P42
30
25
20
15
10
5
0
10
20
30
40
50
60
70
80
90
100
110
Miles per Hour
CAP
NAP
ILB
UIB
Amtrak

The Modern 4-8-4C versus the MPI MP36 & MP40, Commuter diesels:

The 4-8-4C is basically the same locomotive as the 4-8-4P. The economy firing rate is lower to correspond with the lower power output of the MP36 as compared to the GE P42. The high power output of the 4-8-4C is slightly higher than the economy rate on the 4-8-4P to correspond to the MP40, which has more horsepower available for traction as compared to a P42. The main difference between the two 4-8-4's is in tender configuration. The 4-8-4C is designed to need one water refill per coal refill instead of two water refills per coal refill. Consequently, refueling/rewatering can be concentrated at a single point on a commuter railroad, thereby reducing infrastructure costs and simplifying operations. Making the design for the commuter and passenger locomotives basically the same greatly reduces design and production costs, especially on a per unit basis, since the number of units produced would be higher. Also, the locomotives could be used interchangeably in service with only modest changes in operating practices, relating to refueling/rewatering.

Note: All numbers are calculated by the author with the explanations in the "Calculations" section of this paper.

Drawbar Pull & Drawbar Horsepower:

The 4-8-4C operating in either mode produces roughly 18% more DBPull at starting than the MPI MP36 or MP40, just as in the case of the P42. Below about 72 mph the 4-8-4C in economy mode produces more DBHP than the MP36, which is the speed range of most commuter trains. The 4-8-4C in high power mode produces more DBHP until about 80 mph; speed limits on most tracks used by commuter railroads don't exceed this speed.

Fuel Cost:

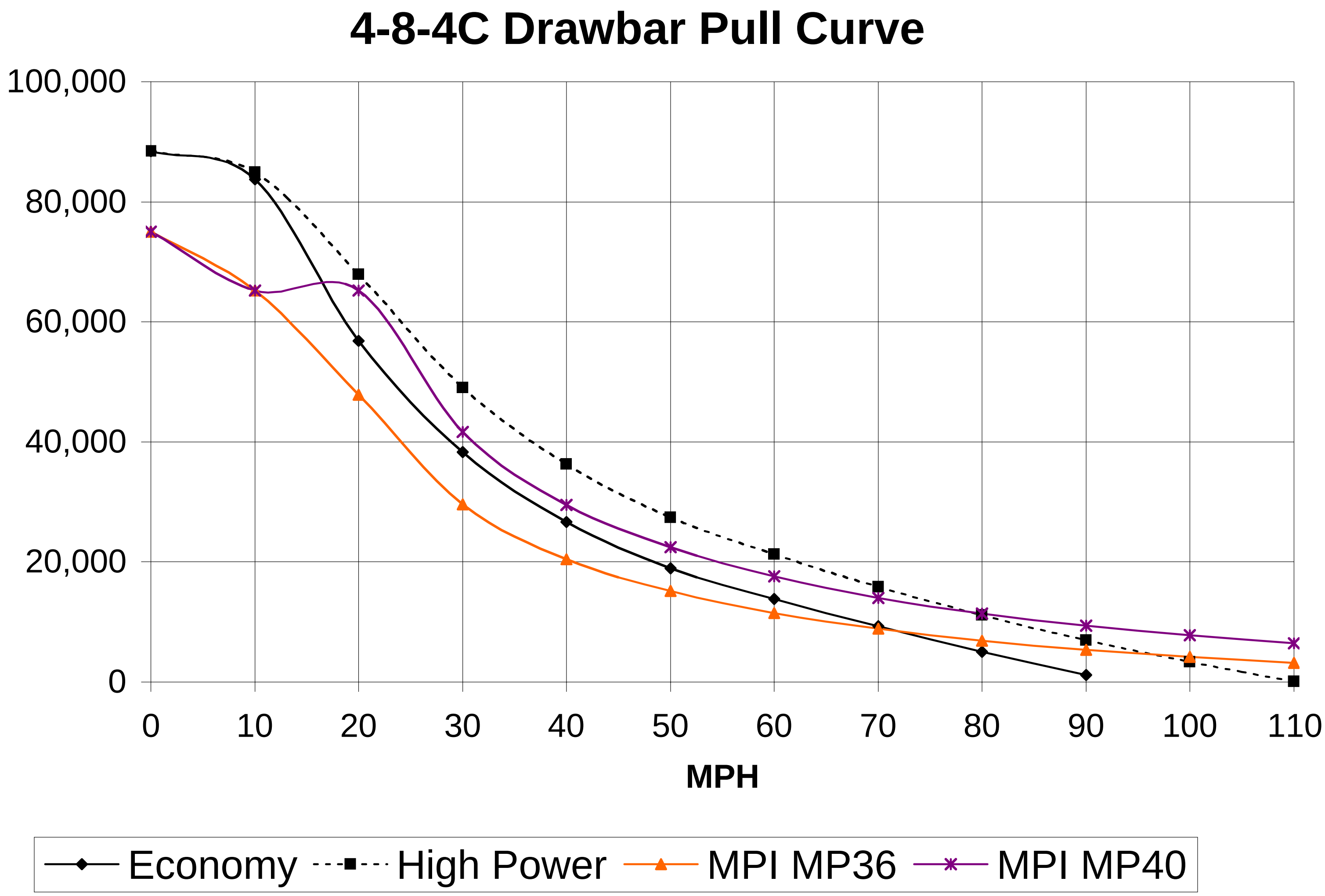
The 4-8-4C in economy mode costs between \$115 and \$180 per hour at full throttle compared to \$380 for the MP36. In high power mode similar cost savings are available in comparison to the MP40. The detailed information is displayed on a chart and two graphs on the following pages.

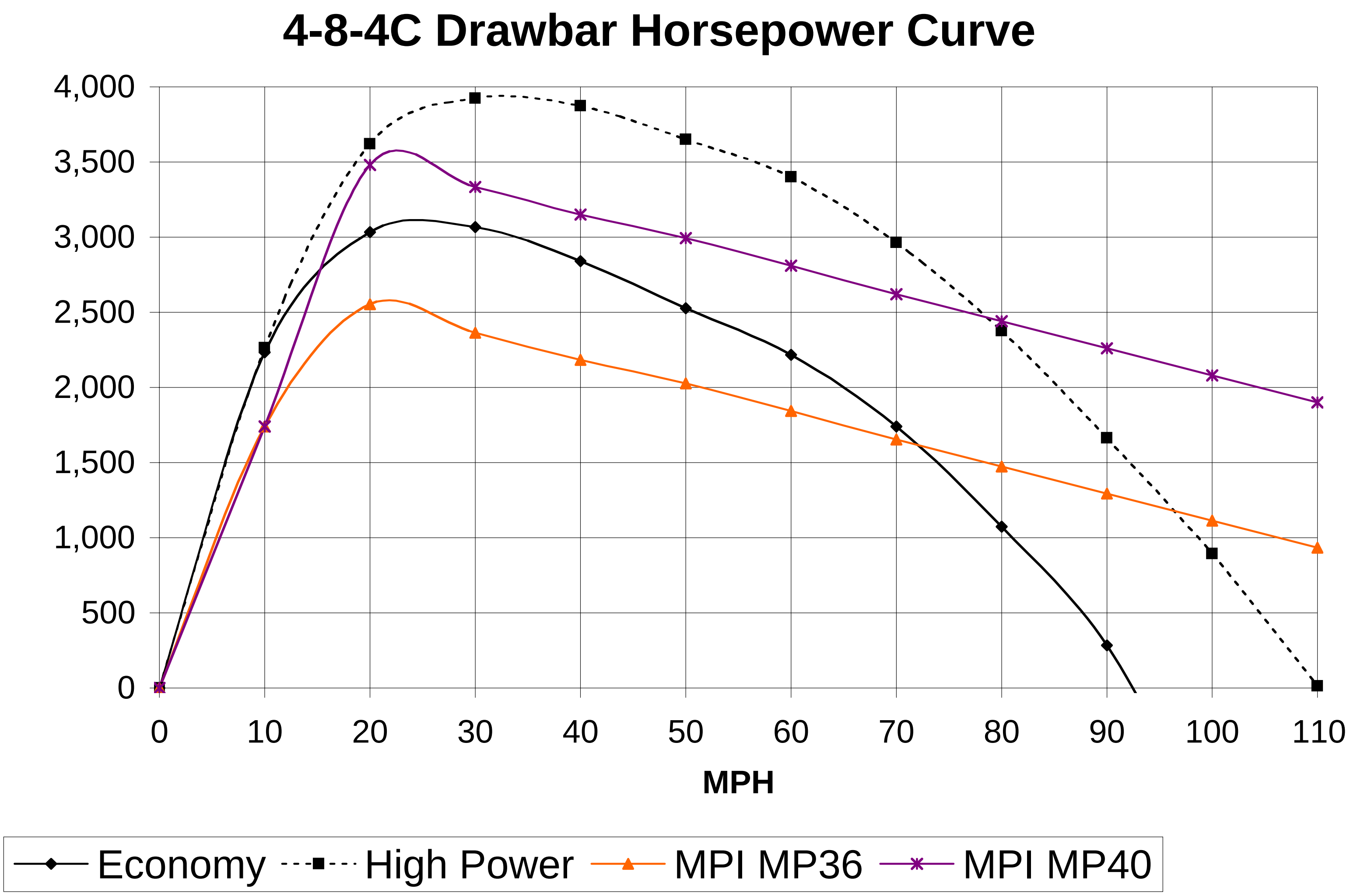
Full Throttle / Notch 8, Comparison - Modern 4-8-4C, MPI MP36 & MPI MP40

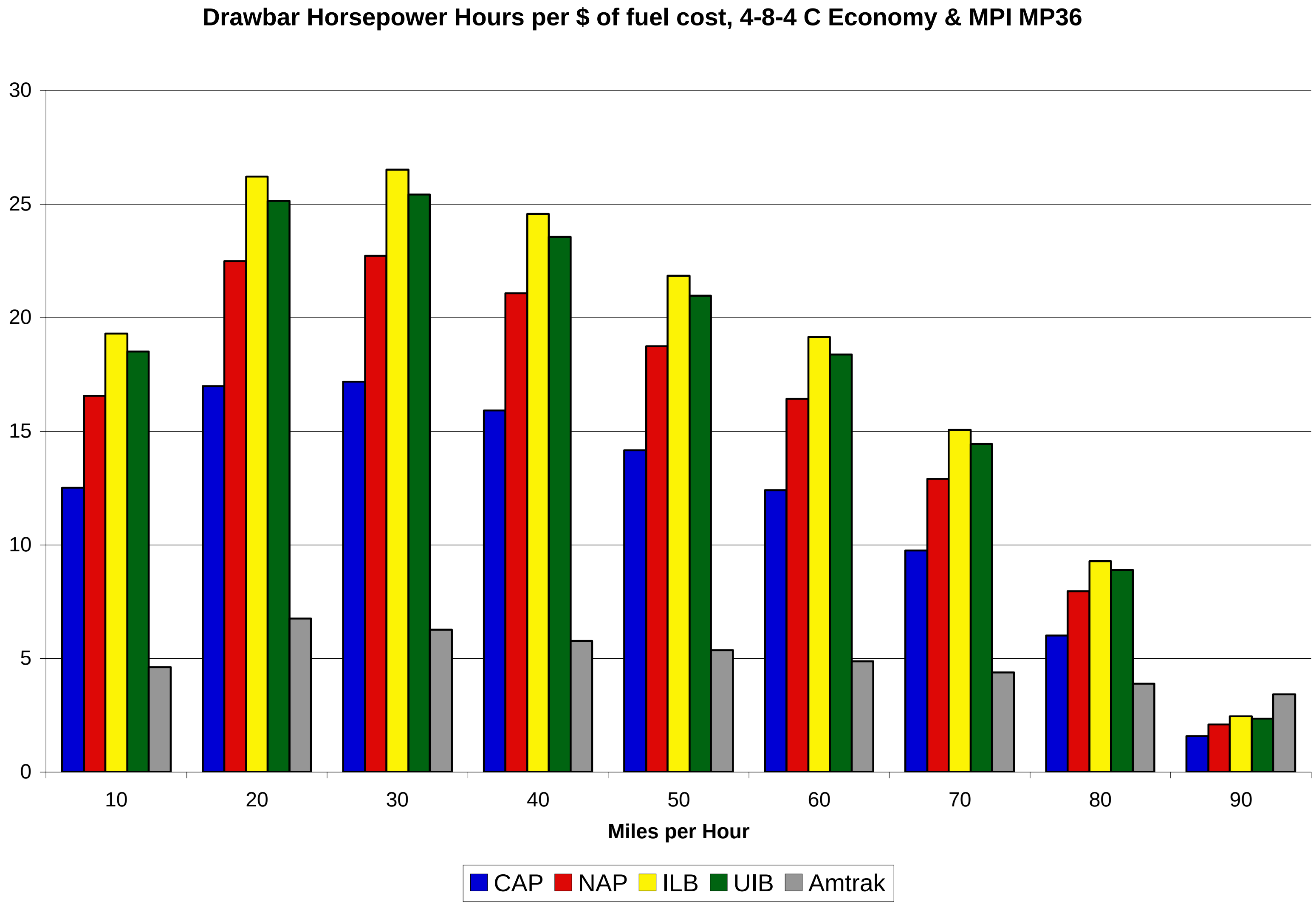
	MPH	0	10	20	30	40	50	60	70	80	90	100	110
Economy Setting													
Drawbar pull, level track		**88,401**	**83,725**	**56,853**	**38,325**	**26,640**	**18,962**	**13,845**	**9,330**	**5,035**	**1,182**		
Drawbar Horse Power, level track		**0**	**2233**	**3032**	**3066**	**2842**	**2528**	**2215**	**1742**	**1074**	**284**		
DBHP Hours per $ of Fuel Cost, CAP		0	13	17	17	16	14	12	10	6	2	0	0
DBHP Hours per $ of Fuel Cost, NAP		0	17	22	23	21	19	16	13	8	2	0	0
DBHP Hours per $ of Fuel Cost, ILB		0	19	26	27	25	22	19	15	9	2	0	0
DBHP Hours per $ of Fuel Cost, UIB		0	19	25	25	24	21	18	14	9	2	0	0
MPI MP36	DBPull	**75000**	**65230**	**47850**	**29553**	**20461**	**15200**	**11516**	**8854**	**6905**	**5388**	**4175**	**3182**
	DBHP	**0**	**1739**	**2552**	**2364**	**2183**	**2027**	**1843**	**1653**	**1473**	**1293**	**1113**	**934**
DBHP Hours per $ of Fuel Cost, Amtrak		0	5	7	6	6	5	5	4	4	3	3	2
High Power Setting													
Drawbar pull, level track		**88,401**	**84,900**	**67,864**	**49,032**	**36,310**	**27,387**	**21,252**	**15,883**	**11,142**	**6,933**	**3,351**	**44**
Drawbar Horse Power, level track		**0**	**2,264**	**3,619**	**3,923**	**3,873**	**3,652**	**3,400**	**2,965**	**2,377**	**1,664**	**894**	**13**
DBHP Hours per $ of Fuel Cost, CAP		0	10	16	17	17	16	15	13	10	7	4	0
DBHP Hours per $ of Fuel Cost, NAP		0	13	21	22	22	21	19	17	13	9	5	0
DBHP Hours per $ of Fuel Cost, ILB		0	15	24	26	26	24	22	20	16	11	6	0
DBHP Hours per $ of Fuel Cost, UIB		0	14	23	25	25	23	22	19	15	11	6	0
MPI MP40	DBPull	**75000**	**65230**	**65230**	**41650**	**29534**	**22459**	**17565**	**14039**	**11441**	**9421**	**7804**	**6482**
	DBHP	**0**	**1739**	**3479**	**3332**	**3150**	**2995**	**2810**	**2621**	**2441**	**2261**	**2081**	**1901**
DBHP Hours per $ of Fuel Cost, Amtrak		0	4	8	8	7	7	6	6	6	5	5	4

Full Throttle Fuel Cost / Hr.	
Coal Cost	
CAP	$56.67
NAP	$41.77
ILB	$35.20
UIB	$36.88
Diesel Cost	
Amt.	$2.30
Economy	
CAP	$178.47
NAP	$134.87
ILB	$115.67
UIB	$120.57
High Power	
CAP	$233.44
NAP	$176.31
ILB	$151.15
UIB	$157.57
MP36	
Amt.	$377.20
MP40	
Amt.	$441.37

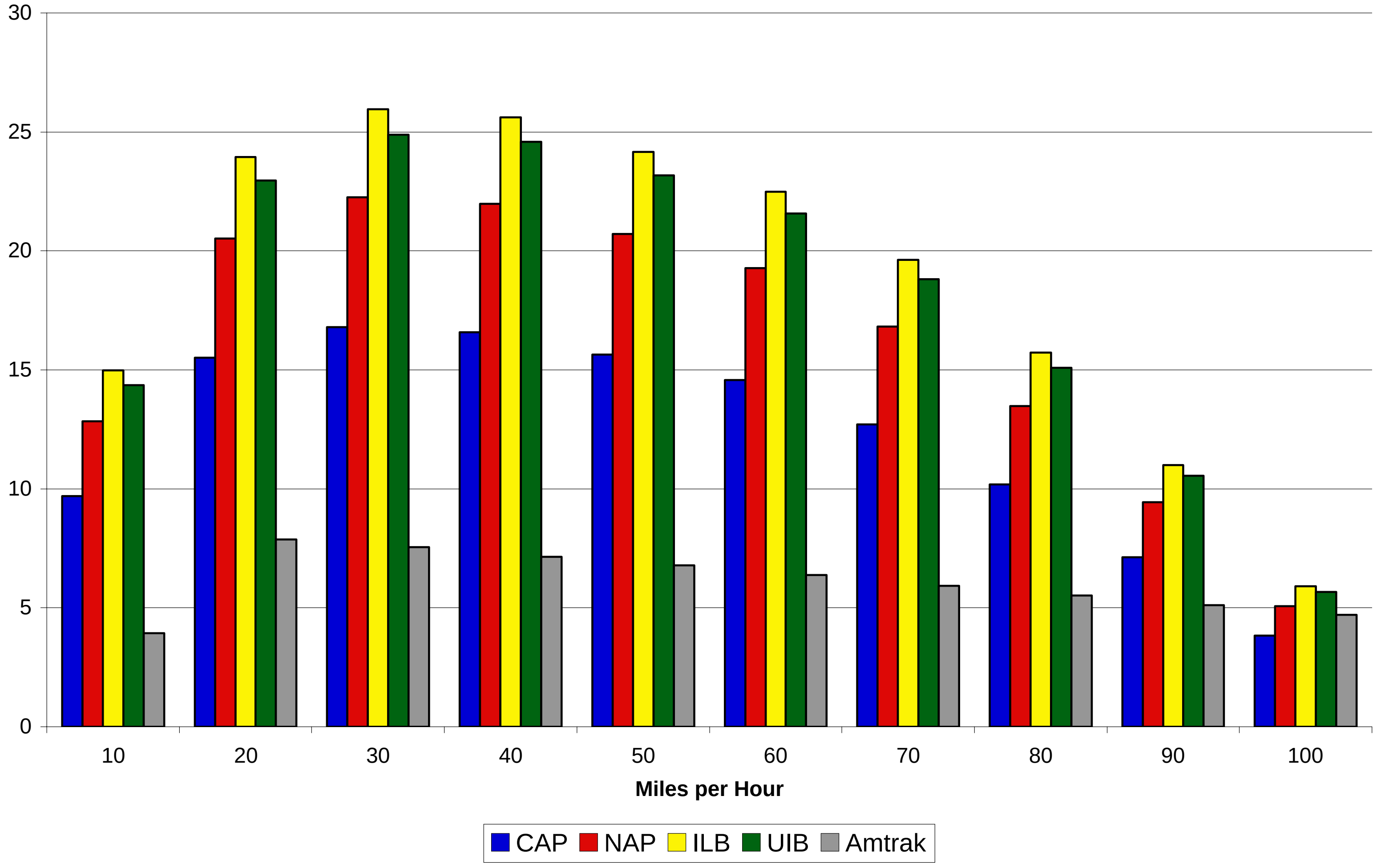
Water Cost	
Cost per 1000 gal. water	$ 0.09
Treatment cost per 1000 gals.	$ 2.35
Total cost per 1000 gals.	$ 2.44
Total cost per 1 gal.	$0.002


4-8-4C Drawbar Pull Curve
100,000
80,000
60,000
40,000
20,000
0
0
10
20
30
40
50
60
70
80
90
100
110
MPH
Economy
High Power
MPI MP36
MPI MP40


4-8-4C Drawbar Horsepower Curve
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
0
10
20
30
40
50
60
70
80
90
100
110
MPH
Economy
High Power
MPI MP36
MPI MP40


Drawbar Horsepower Hours per $ of fuel cost, 4-8-4 C Economy & MPI MP36
30
25
20
15
10
5
0
10
20
30
40
50
60
70
80
90
Miles per Hour
CAP
NAP
ILB
UIB
Amtrak

Drawbar Horsepower Hours per $ of fuel cost, 4-8-4 C High Power & MPI MP40



The Modern 4-4-4-4 versus the Bombardier Turbine Electric Locomotive:

The 4-4-4-4 is patterned after the Pennsylvania T1 locomotive. Two prototype locomotives were delivered in 1942, with 50 production models delivered in 1946 for a total of 52 locomotives.[80] The T1 "was designed to match the performance of the GG1 Electric Locomotive, and to replace double-headed K4's (4-6-2's) on PRR's Blue Ribbon Fleet, a group of heavy, limited stop trains."[81] The T1 was designed from the outset to run very fast. It was designed to have the capacity to haul 880-ton passenger trains at a sustained speed of 100 mph, with one stop for fuel between Harrisburg, PA and Chicago.[82] These locomotives were reputed to have exceeded 125 mph when running late, and 140 mph was reported when in use on short eight car trains. The modern 4-4-4-4 is targeted at the Federal Railroad Administration/Bombardier Turbine Electric Locomotive (TEL). This locomotive is designed for 150 mph in service similar to Amtrak's Acela. In fact the TEL uses a Acela power car as its starting point. Bombardier markets the TEL under the Jetrain label.[83] To achieve 150 mph, larger drivers than the T1 used, would be required to keep rpm and piston speed within normal limits. The Milwaukee Road F7 Class of 4-6-4's had 84" drivers and were used on the Hiawatha high speed trains between Milwaukee and Chicago. These locomotives were run at 125 mph, which is at least the same speed attained by the T1 with 80" drivers. Using 84" drivers on the T1 would proportionally increase the top speed.[84] By using shorter stroke pistons than the PRR T1, the piston speed would be 2400 feet per minute at 150 mph where the N&W Class J at its authorized speed of 100 mph had a piston speed of over 2500 feet per minute. The PRR S1 was an earlier 6-4-4-6 that used 84" drivers so the application of 84" drivers to a divided-drive X-4-4-X has been successful.[85]

Note: All numbers are calculated by the author with explanations in the "Calculations" section of this paper.

Drawbar Pull & Drawbar Horsepower:

When starting the 4-4-4-4 produces 23% more DBPull than the TEL. Up to 130 mph the 4-4-4-4 produces more DBPull than the TEL. At 130 mph the two locomotives have virtually identical DBHP values. Between 30 and 130 mph the 4-4-4-4 produces

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[80] Andre Chapelon, *La Locomotive A Vapeur*, trans. George W. Carpenter, C.Eng., M.I. Mech.E. (Great Britain: Camden Miniature Steam Service, 2000), 352

[81] David R. Stephenson, "T vs. J The 1948 test of Pennsy's 4-4-4-4 with N&W's powerful 4-8-4: The truth at last.," *The Arrow Norfolk and Western Historical Society Magazine,* November / December 2006, 6

[82] Railway Mechanical Engineer, January 1943, pg 1

[83] Michael Coltman, Federal Railroad Administration, email messages, various dates and Daniel Hubert, Bombardier, email messages and phone conversation, 3/28/07

[84] Andre Chapelon, *La Locomotive A Vapeur*, trans. George W. Carpenter, C.Eng., M.I. Mech.E. (Great Britain: Camden Miniature Steam Service, 2000), 273 & 274

[85] Andre Chapelon, *La Locomotive A Vapeur*, trans. George W. Carpenter, C.Eng., M.I. Mech.E. (Great Britain: Camden Miniature Steam Service, 2000), 346

much more DBHP than the TEL. At 60 mph this difference is at its maximum with the 4-4-4-4 producing nearly 50% more DBHP than the TEL. The 4-4-4-4's greater drawbar pull up to 130 mph will give it much better acceleration characteristics than the TEL.

Fuel Cost:

At full throttle the 4-4-4-4 can use between $285 and $440 of fuel and water per hour depending on coal type. On the other hand the fuel cost of the TEL is $580 per hour using Amtrak's fuel cost. The fuel price is considerably less for the 4-4-4-4.

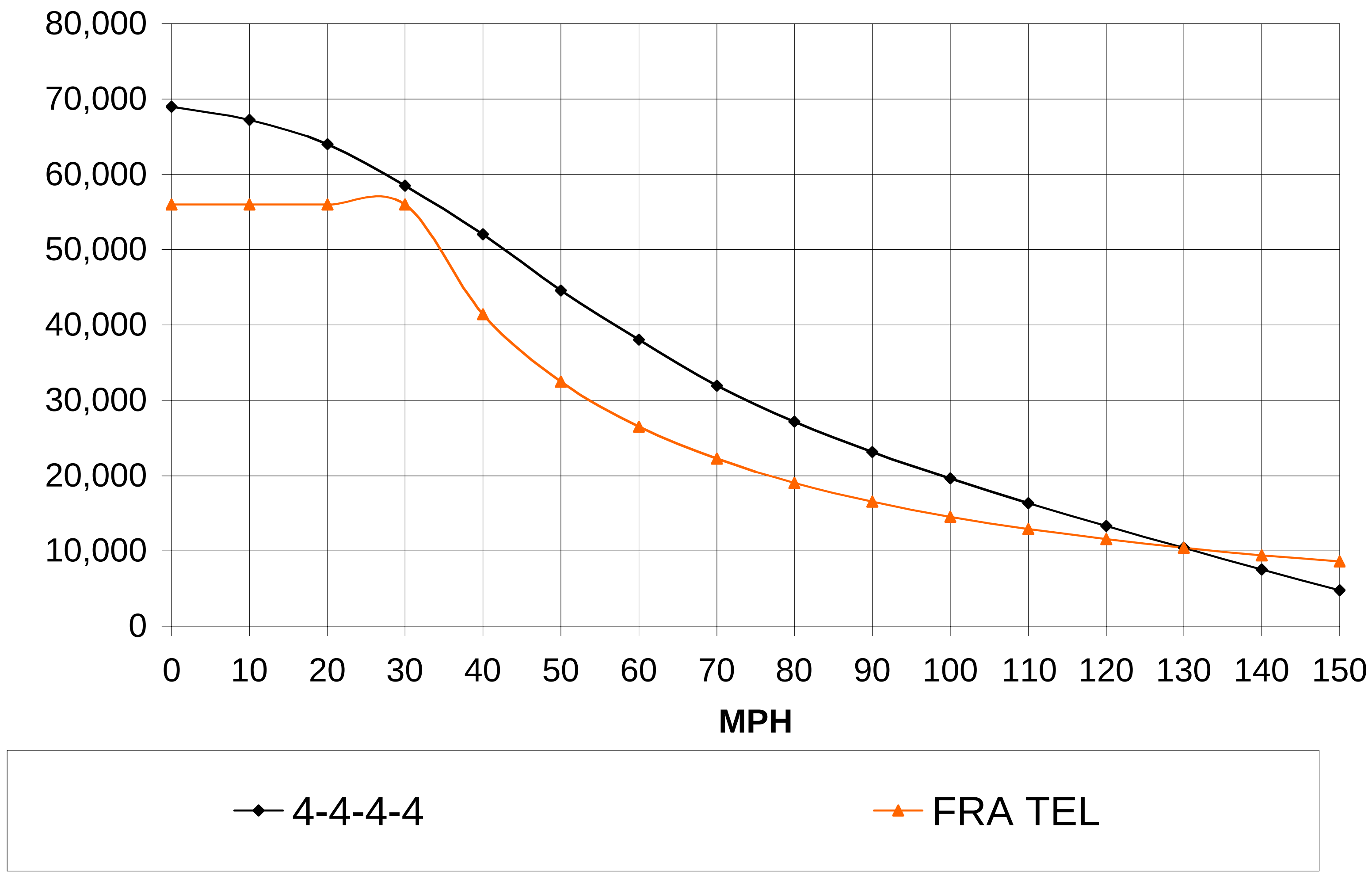
Full Throttle / Notch 8, Comparison - Modern 4-4-4-4 & FRA Turbine Electric Locomotive

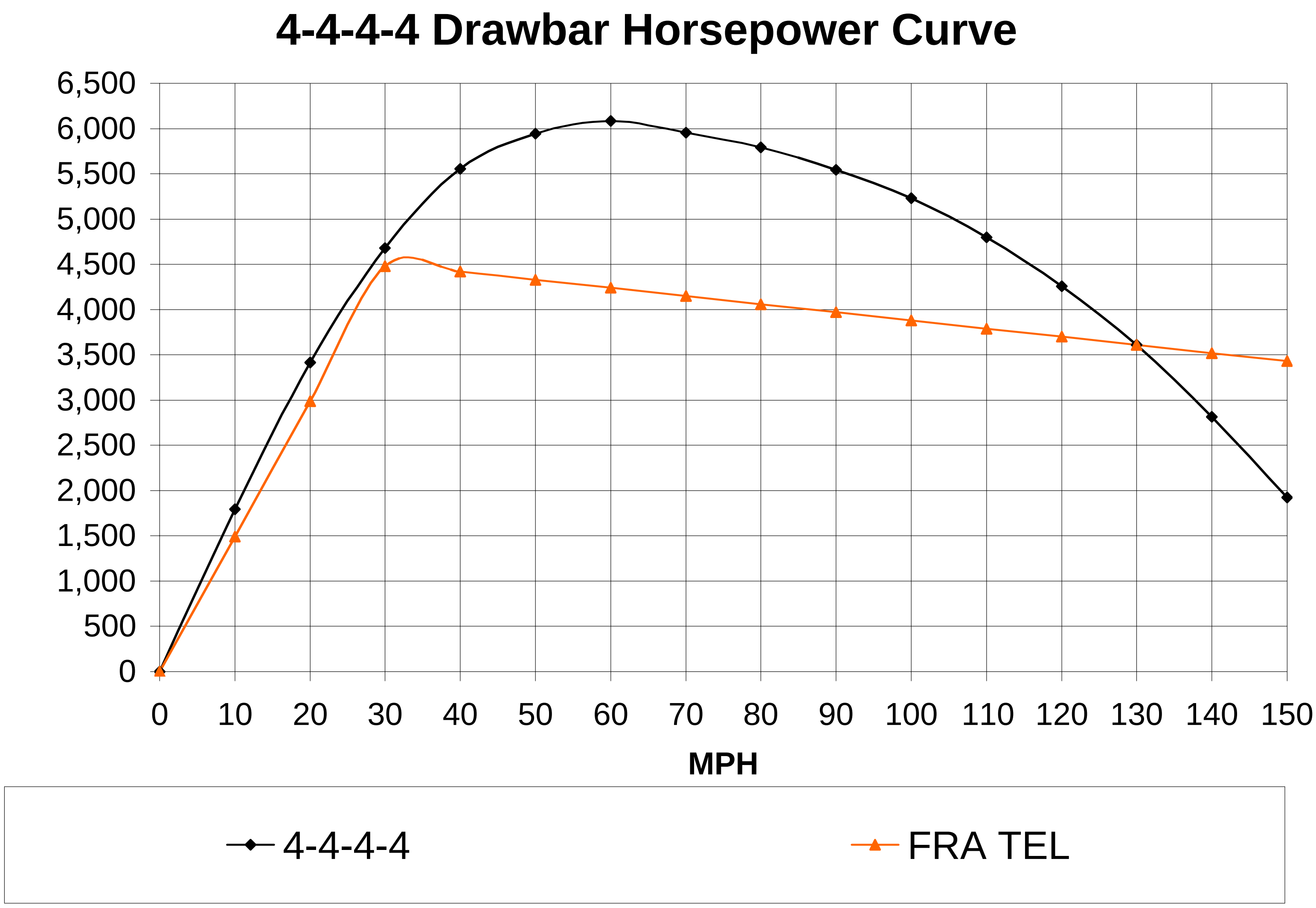
	MPH	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150
High Power																	
Drawbar pull, level track		**68,983**	**67,221**	**64,030**	**58,501**	**52,056**	**44,563**	**38,018**	**31,911**	**27,148**	**23,100**	**19,607**	**16,354**	**13,302**	**10,418**	**7,537**	**4,804**
Drawbar Horse Power, level track		**0**	**1793**	**3415**	**4680**	**5553**	**5942**	**6083**	**5957**	**5792**	**5544**	**5229**	**4797**	**4257**	**3612**	**2814**	**1922**
DBHP Hours per $/Fuel Cost, CAP		0	4	8	11	13	14	14	14	13	13	12	11	10	8	6	4
DBHP Hours per $/Fuel Cost, NAP		0	5	10	14	17	18	18	18	18	17	16	15	13	11	9	6
DBHP Hours per $/Fuel Cost, ILB		0	6	12	17	20	21	22	21	20	20	18	17	15	13	10	7
DBHP Hours per $/Fuel Cost, UIB		0	6	12	16	19	20	21	20	20	19	18	16	14	12	10	7
FRA TEL 5,000 SHP	DBPull	**56000**	**56000**	**56000**	**56000**	**41435**	**32473**	**26498**	**22231**	**19030**	**16540**	**14549**	**12919**	**11562**	**10413**	**9428**	**8574**
	DBHP	**0**	**1493**	**2987**	**4480**	**4420**	**4330**	**4240**	**4150**	**4060**	**3970**	**3880**	**3790**	**3700**	**3610**	**3520**	**3430**
DBHP Hours per $/Fuel Cost, Amtrak		0	3	5	8	8	7	7	7	7	7	7	7	6	6	6	6

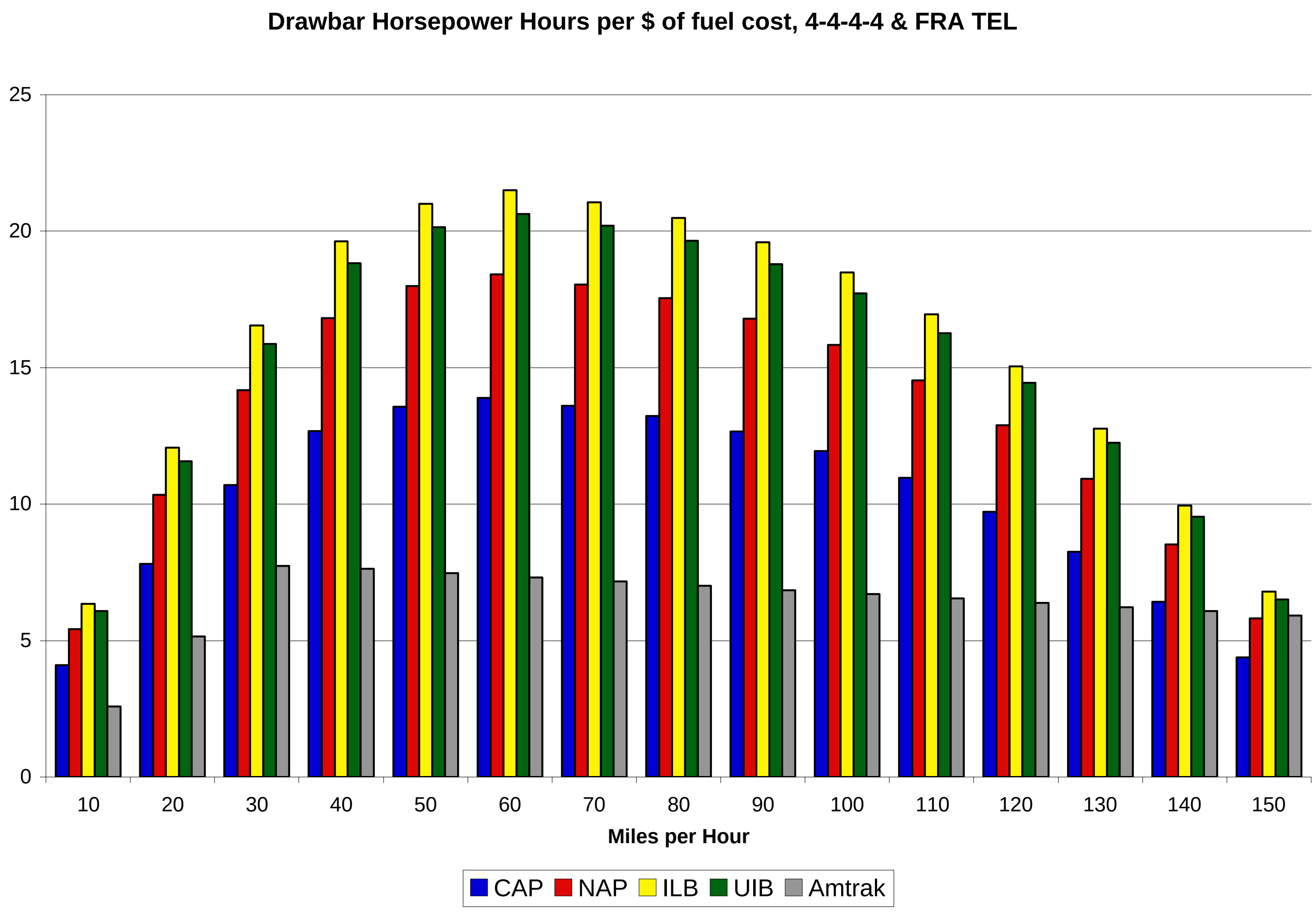
Full Throttle Fuel Cost/Hr.	
Coal Cost	
CAP	$56.67
NAP	$41.77
ILB	$35.20
UIB	$36.88
Diesel Cost	
Amt.	$2.30
4-4-4-4	
CAP	$437.73
NAP	$330.15
ILB	$282.77
UIB	$294.86
FRA TEL	
Amt.	$579.37

Water Cost	
Cost per 1000 gal. water	$ 0.09
Treatment cost per 1000 gals.	$ 2.35
Total cost per 1000 gals.	$ 2.44
Total cost per 1 gal.	$ 0.002

4-4-4-4 Drawbar Pull Curve




4-4-4-4 Drawbar Horsepower Curve
6,500
6,000
5,500
5,000
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
MPH
4-4-4-4
FRA TEL


Drawbar Horsepower Hours per $ of fuel cost, 4-4-4-4 & FRA TEL
25
20
15
10
5
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
Miles per Hour
CAP
NAP
ILB
UIB
Amtrak

Tonnage Ratings:

Tonnage ratings comparisons were made for all the freight locomotives compared previously. The comparisons were made theoretically using four districts of the Norfolk Southern Railway. The tonnage ratings for the diesels came from a Norfolk Southern Employee Timetable and the top speed was determined using the Modified Davis train resistance equation. The average speed was determined from historical documentation, adjusted by using different acceleration rates between various locomotives and train types. The ton-miles/hour is the tonnage times the average speed. This is the most representative test to use when comparing the abilities of different locomotives. It shows how much work the locomotives can produce in total, not just a comparison of power outputs at different speeds.

2-8-8-4:

The 2-8-8-4 in economy mode can haul more tonnage and produce more ton-miles per hour in bulk type freight service than an SD70ACe. In intermodal service the 2-8-8-4 in economy mode doesn't perform as well as an SD70ACe. The 2-8-8-4 in high power mode can handle more tonnage and produce more ton-miles/hour. than 1.4 SD70ACe's on the two more level districts. In intermodal service the two locomotive are virtually identical in performance with a slight edge to the diesel. The 2-8-8-4 can be the predominant power for unit trains such as coal and other heavy freight tasks.

2-6-6-4:

The 2-6-6-4 in economy mode can also handle more tonnage and produce more t-m/hr. than its diesel counterpart, the SD70M-2. In high power mode the 2-6-6-4 can haul more tonnage than 1.5 SD70M-2 except for on the two hillier districts. In intermodal service the 2-6-6-4 in economy mode can haul 6% more tonnage and produce more ton-miles/hour than the SD70M-2. In high power mode the 2-6-6-4 can handle 4% more tonnage than 1.5 SD70M-2's. Because of its flexibility, the 2-6-6-4 would be the general purpose road freight locomotive.

2-10-2:

The 2-10-2 in economy mode is capable of hauling more bulk freight tonnage than the SD40-2 and will produce more ton-miles/hour as well. In local type switching services the 2-10-2 would be able to handle anything that an SD40-2 could and more.

When working in high power mode, the 2-10-2 is comparable to an SD60, which is currently more of a road freight locomotive than the SD40-2. In this context the 2-10-2 could carry more tonnage in bulk service than the SD60 on the flatter two districts and slightly less on the two hillier ones. In intermodal service the 2-10-2 would haul slightly more tonnage than the SD60.

2-8-2:

The 2-8-2 in economy mode is capable of hauling more bulk freight tonnage than the GP38-2 and producing more ton-miles/hour as well. In local type switching services the 2-8-2 could handle more cars than the GP38-2.

When working in high power mode the 2-8-2 is comparable to a GP59. This would allow the locomotive to be more useful than a GP38-2 when pressed into road freight service. In this context the 2-8-2 could haul more tonnage in bulk service than the GP59 on any grade. In intermodal service the 2-8-2 would haul slightly more tonnage than the GP59.

0-10-0:

In the flat switching environment the 0-10-0 is compared with the EMD MP15 and the NRE GenSet. The 0-10-0 could handle 162 cars or 23,166 tons at a theoretical balance speed of 10.2 mph. At the same balance speed an NRE GenSet could handle 83 cars or 11,869 tons, allowing the 0-10-0 to replace up to two GenSets in this type of service. The EMD MP15 can handle 97 cars at the 10.2 mph balance speed in flat switching service. This equates to 60% of an 0-10-0, allowing the 0-10-0 to replace to replace two EMD MP15's in many cases.

In the context of hump operations two 0-10-0's are compared to a Mother-Slug set. The Mother-Slug set could handle 170 cars or 24,310 tons at a balance speed of 5.1 mph on a hump consisting of 1% grade and 20 feet maximum elevation. The two 0-10-0's could take a larger cut of 232 cars and 33,176 tons under the same conditions.

Freight Road Locomotive Statistics

Type of Service		1.4 SD70ACe	2-8-8-4		SD70ACe	1.5 SD70M-2	2-6-6-4		SD70M-2
			High Power	Economy			High Power	Economy	
Grade Distict		Low Grade (Williamson WV to Portsmouth OH, Northbound, Norfolk Southern)							
Bulk	Tonnage	27,258	31,010	29,070	19,470	24,750	24,508	23,791	16,500
	Top Speed	50.9	50.6	46.9	50.9	52.4	54.4	50.3	52.4
	Avg. Speed	39.8	39.3	34.0	39.8	41.0	42.2	36.5	41.0
	Ton-miles/hour	1,084,009	1,217,176	987,847	774,292	1,013,874	1,034,267	867,558	675,916
Double Stack	Tonnage	3,150	3,100	1,840	2,250	3,159	3,294	2,229	2,106
	Top Speed	74.6	73.4	70.4	74.6	77.3	77.5	75.1	77.3
	Avg. Speed	52.6	51.5	48.6	52.6	54.5	54.4	51.9	54.5
	Ton-miles/hour	165,839	159,781	89,475	118,456	172,282	179,165	115,643	114,854
Trailer or Single Stack	Tonnage	3,234	3,170	1,880	2,310	3,233	3,371	2,282	2,155
	Top Speed	75.4	74.1	70.9	75.4	78.6	78.6	76.0	78.6
	Avg. Speed	53.6	52.2	49.4	53.6	55.8	55.4	52.9	55.8
	Ton-miles/hour	173,308	165,572	92,808	123,792	180,489	186,793	120,794	120,326
Grade Distict		Medium-Low Grade (Portsmouth OH to Columbus OH, Northbound, Norfolk Southern)							
Bulk	Tonnage	18,172	20,530	18,690	12,980	16,500	16,578	15,900	11,000
	Top Speed	33.9	32.6	29.0	33.9	36.1	36.7	31.9	36.1
	Avg. Speed	31.0	28.9	24.5	31.0	33.0	32.5	27.0	33.0
	Ton-miles/hour	563,229	593,237	458,080	402,307	545,141	539,138	429,098	363,427
Double Stack	Tonnage	3,150	3,100	1,840	2,250	3,159	3,294	2,229	2,106
	Top Speed	65.7	64.5	62.6	65.7	66.5	66.4	64.8	66.5
	Avg. Speed	58.0	56.5	55.1	58.0	58.6	58.1	57.0	58.6
	Ton-miles/hour	182,606	174,999	101,340	130,433	185,221	191,255	127,091	123,481
Trailer or Single Stack	Tonnage	3,234	3,170	1,880	2,310	3,233	3,371	2,282	2,155
	Top Speed	66.2	64.9	62.9	66.2	67.1	66.9	65.2	67.1
	Avg. Speed	58.5	56.9	55.4	58.5	59.3	58.7	57.4	59.3
	Ton-miles/hour	189,174	180,404	104,094	135,124	191,796	197,742	131,075	127,864

Freight Road Locomotive Statistics

Type of Service		1.4 SD70ACe	2-8-8-4		SD70ACe	1.5 SD70M-2	2-6-6-4		SD70M-2
			High Power	Economy			High Power	Economy	
Grade Distict		Medium Grade (Williamson WV to Farm WV, Eastbound, Norfolk Southern)							
Bulk	Tonnage	11,812	9,700	8,540	8,437	10,725	8,014	7,454	7,150
	Top Speed	26.8	31.3	28.3	26.8	28.7	35.6	30.6	28.7
	Avg. Speed	20.6	26.6	22.5	20.6	22.0	30.2	24.4	22.0
	Ton-miles/hour	243,096	257,714	192,076	173,640	236,286	242,043	181,702	157,524
Double Stack	Tonnage	3,150	3,100	1,840	2,250	3,159	3,294	2,229	2,106
	Top Speed	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0
	Avg. Speed	45.6	43.9	45.6	45.6	45.5	44.0	45.6	45.5
	Ton-miles/hour	143,551	136,235	83,863	102,537	143,858	144,878	101,631	95,906
Trailer or Single Stack	Tonnage	3,234	3,170	1,880	2,310	3,233	3,371	2,282	2,155
	Top Speed	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0
	Avg. Speed	45.1	43.6	45.3	45.1	45.2	43.6	45.3	45.2
	Ton-miles/hour	145,985	138,092	85,153	104,275	146,056	146,924	103,337	97,371
Grade Distict		Heavy Grade (Farm WV to Bluefield VA, Eastbound, Norfolk Southern)							
Bulk	Tonnage	5,617	4,710	4,390	4,012	5,100	3,658	3,541	3,400
	Top Speed	21.1	23.7	19.8	21.1	23.6	28.1	23.6	23.6
	Avg. Speed	15.2	16.8	13.4	15.2	16.9	19.9	16.0	16.9
	Ton-miles/hour	85,231	79,034	58,723	60,879	86,393	72,746	56,507	57,596
Double Stack	Tonnage	3,150	3,100	1,840	2,250	3,159	3,294	2,229	2,106
	Top Speed	32.2	31.6	35.6	32.2	32.3	29.3	32.0	32.3
	Avg. Speed	28.7	24.3	30.6	28.7	28.8	22.6	27.6	28.8
	Ton-miles/hour	90,280	75,446	56,396	64,485	90,853	74,301	61,451	60,568
Trailer or Single Stack	Tonnage	3,234	3,170	1,880	2,310	3,233	3,371	2,282	2,155
	Top Speed	31.5	31.1	35.2	31.5	31.7	28.9	31.5	31.7
	Avg. Speed	27.9	23.3	30.1	27.9	28.1	21.6	26.9	28.1
	Ton-miles/hour	90,126	73,810	56,550	64,376	90,693	72,935	61,329	60,462

Freight Road Locomotive Statistics										
Type of Service		SD60	2-10-2		SD40-2	GP59	2-8-2		GP38-2	Sevice
			High Power	Economy			High Power	Economy		
Grade Distict		Low Grade (Williamson WV to Portsmouth OH, Northbound, Norfolk Southern)								
Bulk	Tonnage	14,850	19,180	17,750	12,000	10,000	14,990	13,300	7,500	Bulk
	Top Speed	51.8	50.3	45.9	51.0	53.3	49.8	43.7	50.0	
	Avg. Speed	40.5	39.0	33.3	39.9	41.7	38.6	31.7	39.1	
	Ton-miles/hour	601,749	748260	590310	478,277	416,726	579061	421099	293,485	
Double Stack	Tonnage	1,810	1,840	7,150	7,150	1,320	1,345	7,150	7,150	Local
	Top Speed	74.1	71.1	54.9	57.1	73.1	71.0	48.9	49.2	
	Avg. Speed	52.3	49.9	50	50	51.6	49.8	50	50	
	Ton-miles/hour	94,670	91798	Cars	Cars	68,131	66981	Cars	Cars	
Trailer or Single Stack	Tonnage	1,850	1,880	X	X	1,350	1,375	X	X	X
	Top Speed	75.0	71.7	X	X	73.9	71.5	X	X	
	Avg. Speed	53.3	50.5	X	X	52.5	50.4	X	X	
	Ton-miles/hour	98536	94921	X	X	70,880	69269	X	X	
Grade Distict		Medium-Low Grade (Portsmouth OH to Columbus OH, Northbound, Norfolk Southern)								
Bulk	Tonnage	9,900	12,990	11,620	8,000	6,700	10,050	8,480	5,000	Bulk
	Top Speed	35.5	33.0	28.5	34.7	38.0	32.3	27.0	34.7	
	Avg. Speed	32.5	29.3	24.1	31.7	34.8	28.7	22.8	31.7	
	Ton-miles/hour	321,615	380111	279938	253,419	233,009	288130	193606	158,604	
Double Stack	Tonnage	1,810	1,840	7,150	7,150	1,320	1,345	7,150	5,005	Local
	Top Speed	65.4	63.4	36.7	36.4	65.0	63.2	29.0	34.3	
	Avg. Speed	57.6	55.4	50	50	57.3	55.3	50	35	
	Ton-miles/hour	104340	101,968	Cars	Cars	75638	74,331	Cars	Cars	
Trailer or Single Stack	Tonnage	1,850	1,880	X	X	1,350	1,375	X	X	X
	Top Speed	65.9	63.7	X	X	65.4	63.5	X	X	
	Avg. Speed	58.2	55.8	X	X	57.8	55.7	X	X	
	Ton-miles/hour	107724	104,950	X	X	78076	76,520	X	X	

Freight Road Locomotive Statistics

Type of Service		SD60	2-10-2		SD40-2	GP59	2-8-2		GP38-2	Sevice
			High Power	Economy			High Power	Economy		
Grade Distict		Medium Grade (Williamson WV to Farm WV, Eastbound, Norfolk Southern)								
Bulk	Tonnage	6,435	6,230	5,360	5,200	4,300	4,780	3,810	3,250	Bulk
	Top Speed	28.2	31.6	27.7	27.7	31.1	30.9	26.4	28.2	
	Avg. Speed	21.7	26.8	22.0	21.3	23.9	26.2	21.0	21.6	
	Ton-miles/hour	139,703	167022	118014	110,578	102,927	125429	79936	70,340	
Double Stack	Tonnage	1,810	1,840	5,291	5,148	1,320	1,345	3,718	3,289	Local
	Top Speed	55.0	55.0	27.8	27.7	55.0	55.0	26.6	27.9	
	Avg. Speed	45.5	44.0	37	36	45.6	44.0	26	23	
	Ton-miles/hour	82,357	80917	Cars	Cars	60,140	59116	Cars	Cars	
Trailer or Single Stack	Tonnage	1,850	1,880	X	X	1,350	1,375	X	X	X
	Top Speed	55.0	55.0	X	X	55.0	55.0	X	X	
	Avg. Speed	45.2	43.6	X	X	45.2	43.6	X	X	
	Ton-miles/hour	83,564	81974	X	X	61,041	59,908	X	X	
Grade Distict		Heavy Grade (Farm WV to Bluefield VA, Eastbound, Norfolk Southern)								
Bulk	Tonnage	3,060	2,930	2,700	2,450	2,050	2,270	2,000	1,550	Bulk
	Top Speed	23.1	25.1	20.2	22.5	26.4	24.3	18.9	23.3	
	Avg. Speed	16.6	17.8	13.6	16.2	18.9	17.2	12.8	16.7	
	Ton-miles/hour	50,710	52134	36,833	39610	38,847	39057	25575	25,917	
Double Stack	Tonnage	1,810	1,840	2,574	2,431	1,320	1,345	1,859	1,573	Local
	Top Speed	32.7	34.2	21.2	22.6	33.5	34.2	19.7	22.9	
	Avg. Speed	29.1	26.3	18	17	29.8	26.4	13	11	
	Ton-miles/hour	52,616	48372	Cars	Cars	39,368	35450	Cars	Cars	
Trailer or Single Stack	Tonnage	1,850	1,880	X	X	1,350	1,375	X	X	X
	Top Speed	32.1	33.7	X	X	33.0	33.8	X	X	
	Avg. Speed	28.4	25.3	X	X	29.2	25.3	X	X	
	Ton-miles/hour	52,560	47511	X	X	39,412	34844	X	X	

Switcher Locomotive Statistics

Type of Service		EMD MP15	NRE GenSet	0-10-0	Hump Mother-Slug	2 ea. 0-10-0
Flat Switch	Cars	97	83	162		
	Speed	10.1	10.1	10.1		
	Tonnage	13,871	11,869	23,166		
	% of 0-10-0	60%	51%			
Hump	Cars				170	232
	Speed				5.1	5.1
	Tonnage				24,310	33,176
	% of 2 ea. 0-10-0				73%	

Idle Fuel Costs:

As you can see on the next page the modern steam locomotive is substantially cheaper to leave at idle. The modern steam locomotive with high performance boiler insulation would only use fuel to replace the small amount of heat that is dissipated into the surrounding air and operate a few auxiliaries such as an air compressor from time to time. The diesel locomotive on the other hand must continue to run burning about 3-5 gallons of fuel per hour. Even if an auxiliary power unit (APU) is installed, allowing the diesel prime mover to be shut down, it is still more expensive to operate the diesel.

Diesels without APU's cost from $5.40 to $11.40 per hour to idle. APU equipped units cost between $1.22 and $1.48 per hour to idle. However, the steam locomotive on average would only cost between $0.27 and $0.89 per hour to idle.

Idle Costs

Per Hour

	Coal Type	**2-8-8-4**	**2-6-6-4**	**2-10-2**	**2-8-2**	**0-10-0**	**4-8-4C or P**	
Cost (Coal) Overnight	CAP	$ 0.24	$ 0.23	$ 0.15	$ 0.12	$ 0.09	$ 0.23	
	NAP	$ 0.17	$ 0.17	$ 0.11	$ 0.08	$ 0.07	$ 0.16	
	ILB	$ 0.16	$ 0.15	$ 0.10	$ 0.08	$ 0.06	$ 0.15	
	UIB	$ 0.17	$ 0.16	$ 0.11	$ 0.08	$ 0.06	$ 0.16	
Cost (Coal & Water) Hot	CAP	$ 1.54	$ 1.48	$ 1.00	$ 0.77	$ 0.64	$ 1.46	
	NAP	$ 1.11	$ 1.08	$ 0.73	$ 0.57	$ 0.48	$ 1.06	
	ILB	$ 1.04	$ 1.00	$ 0.69	$ 0.54	$ 0.45	$ 0.99	
	UIB	$ 1.09	$ 1.06	$ 0.72	$ 0.56	$ 0.47	$ 1.04	
Idleing Type	Overnight	50%	50%	50%	50%	50%	50%	Based on idling rate
	Hot	50%	50%	50%	50%	50%	50%	
Cost (Average)	**CAP**	**$ 0.89**	**$ 0.86**	**$ 0.58**	**$ 0.44**	**$ 0.37**	**$ 0.84**	
	NAP	**$ 0.64**	**$ 0.62**	**$ 0.42**	**$ 0.33**	**$ 0.27**	**$ 0.61**	
	ILB	**$ 0.60**	**$ 0.58**	**$ 0.39**	**$ 0.31**	**$ 0.25**	**$ 0.57**	
	UIB	**$ 0.63**	**$ 0.61**	**$ 0.41**	**$ 0.32**	**$ 0.27**	**$ 0.60**	

Railroad	$ per G.	SD70ACe	SD70M-2	SD60	SD40-2	GP59	GP38-2	MP15	MP36	MP40	P42	APU
BNSF	**$ 1.85**	**$ 5.55**	**$ 5.55**	**$ 5.55**	**$ 9.62**	**$ 5.55**	**$ 9.25**	**$ 3.70**	**$ 5.55**	**$ 5.55**	**$ 5.55**	**$ 1.25**
KCS	**$ 2.04**	**$ 6.11**	**$ 6.11**	**$ 6.11**	**$10.58**	**$ 6.11**	**$ 10.18**	**$ 4.07**	**$ 6.11**	**$ 6.11**	**$ 6.11**	**$ 1.38**
CP (US)	**$ 2.19**	**$ 6.56**	**$ 6.56**	**$ 6.56**	**$ 11.38**	**$ 6.56**	**$ 10.94**	**$ 4.38**	**$ 6.56**	**$ 6.56**	**$ 6.56**	**$ 1.48**
UP	**$ 2.05**	**$ 6.15**	**$ 6.15**	**$ 6.15**	**$10.66**	**$ 6.15**	**$ 10.25**	**$ 4.10**	**$ 6.15**	**$ 6.15**	**$ 6.15**	**$ 1.39**
CSX	**$ 1.86**	**$ 5.58**	**$ 5.58**	**$ 5.58**	**$ 9.68**	**$ 5.58**	**$ 9.30**	**$ 3.72**	**$ 5.58**	**$ 5.58**	**$ 5.58**	**$ 1.26**
NS	**$ 1.88**	**$ 5.65**	**$ 5.65**	**$ 5.65**	**$ 9.79**	**$ 5.65**	**$ 9.41**	**$ 3.76**	**$ 5.65**	**$ 5.65**	**$ 5.65**	**$ 1.28**
CN (US)	**$ 1.80**	**$ 5.40**	**$ 5.40**	**$ 5.40**	**$ 9.37**	**$ 5.40**	**$ 9.01**	**$ 3.60**	**$ 5.40**	**$ 5.40**	**$ 5.40**	**$ 1.22**

http://www.ecotranstechnologies.com for APU

Running Time Comparison:

One disadvantage of the modern steam locomotive is that it needs fuel and water more often than a comparable diesel. The steam locomotive uses larger quantities of fuel and water than the diesel, even though the steam locomotive's fuel/water cost is less than the diesel's fuel cost. This factor makes the in-service running time of the steam locomotive less than that of a diesel. For every fill up on the diesel locomotive the steam locomotives proposed in this paper will need approximately two coalings and four watering. This works out to about a 500-mile range for coal and a 250-mile range for water. The locomotives used for comparison in this paper are about half as efficient as what Porta said the Third Generation steam locomotive could be. This would allow the steam locomotive to equal the diesel locomotive in time between coalings and half the time for waterings. This operating difference is just something that would have to be addressed on steam locomotives. Fortunately, as will be explained in the next section on infrastructure, coaling and watering a steam locomotive is a quick and easy proposition. Exact comparison data between the steam and diesel types is listed on the chart on the following page.

Running Time Comparison

Diesel	**SD70ACe**	**SD70M-2**	**SD40-2**	**GP38-2**		**MP36**	**P42**
Running Time Min.	**26.7**	**26.7**	**27.4**	**23.8**		**20.3**	**13.9**
Running Time Max.	**32.2**	**32.2**	**33.0**	**28.7**		**30.5**	**20.9**

Steam - Economy	**2-8-8-4**	**2-6-6-4**	**2-10-2**	**2-8-2**		**4-8-4 "C"**	**4-8-4 "P"**
Running Time, Min. (hours) economy coal	**17.1**	**17.8**	**16.0**	**20.2**		**15.2**	**21.9**
Running Time, Min. (hours) economy water	8.2	8.6	7.7	9.7			10.5
Running Time, Max. (hours) economy coal	**20.6**	**21.4**	**19.2**	**24.3**		**22.6**	**32.9**
Running Time, Max. (hours) economy water	10.0	10.4	9.3	11.8			16.0

Steam - High Power	**2-8-8-4**	**2-6-6-4**	**2-10-2**	**2-8-2**	**0-10-0**	**4-8-4 "C"**	**4-8-4 "P"**
Running Time, Min. (hours) high power coal	**12.8**	**13.3**	**11.7**	**13.6**	**32.8**	**11.8**	**15.2**
Running Time, Min. (hours) high power water	6.4	6.7	5.8	6.8			7.6
Running Time, Max. (hours) high power coal	**15.5**	**16.2**	**14.2**	**16.5**	**56.3**	**18.0**	**23.0**
Running Time, Max. (hours) high power water	7.8	8.1	7.1	8.3			11.5

Diesel			**SD60**	**GP59**	**MP15**	**MP40**	
Running Time Min.			**26.9**	**27.6**	**57.8**	**17.4**	
Running Time Max.			**32.4**	**33.3**	**86.7**	**26.1**	

Infrastructure and Servicing Needs for the Modern Steam Locomotive:

The modern steam locomotive needs three basic types of facilities for servicing needs: (1) the coaling station, which replenishes coal, water and sand; (2) the watering station, which replenishes water only; and (3) the servicing facility, which has fire cleaning and lubricating capabilities.

The Coaling and Watering Station:

Two sizes of stations are envisioned by the author and are scaled from installations on the N&W in the 1950's. The N&W facilities could fill a steam locomotive with coal, water and sand with the locomotive in the same spot in only eight or nine minutes.[86] These facilities were placed over the main line so locomotives could stop for coal, water and sand if needed and continue on their way without uncoupling from their train, delaying the train or impeding other traffic. Of the three manufacturers of coaling towers, Fairbanks, Morse & Co., Ogle Engineering Company and Roberts & Schaefer Company, only Roberts & Schaefer is still in business designing and producing coal handling equipment for the mining and power generation industries.[87]

The large coaling facility would have four service tracks running through it plus a supply track for inbound coal. The facility would have three 2,000 ton coaling towers in a row so consists of up to three locomotives of any class, facing in either direction, could have their coal space and water spaces in the tender and auxiliary tender filled without having to move the train from the initial spotting. Larger consists would have to pull forward to coal and water the trailing units. The author chose three locomotives for the large facility standard since three locomotives could handle most trains that the Class I railroads operate. With 6,000 tons of total coal capacity, the facility could accept unit trains of coal for refilling, which would be a plus in today's railroading environment. On the water side of the equation, it would have three elevated one-million gallon water tanks. This will allow the water pumps to run at night only, when electric power is cheaper and gravity to feed the standpipes for filling the tenders and auxiliary tenders. The coaling and watering process could be automated where the locomotive pulls to the correct spot, the water hatches open, and the process of coaling and watering begins.

The small coaling facility would be one-third the size of the large one, and configured to handle two locomotive consists on two tracks. The coaling tower would hold 2,000 tons, and a single 1 million gallon water tank would be provided.

The Watering Station:

There would also be a large and small watering station. Just like the large coaling station, the large watering station would have three one-million gallon water tanks and be capable of watering three locomotive consists on four tracks. The small watering station

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[86] Norfolk and Western Historical Society Archives, *File 00106.7 Bluefield WV Coaling Station*

[87] Thomas W. Dixon, Jr., *Steam Locomotive Coaling Stations and Diesel Locomotive Fueling Facilities* (Lynchburg, VA: TLC Publishing, 2002) 21

would have a single one-million gallon water tank handling two locomotive consists on two tracks.

The Servicing Facility:

The servicing facility would also come in two sizes and be comprised of two items: a hydraulic ash handling plant for fire cleaning and a lubricating and inspection building for routine servicing. This lubricating and inspection function could most likely be carried out in the existing facilities of the railroad, but the author wanted to be more conservative and include the cost of providing these facilities from the ground up in the breakeven analysis.

The large servicing facility would consist of the large ash plant incorporating a six-track design, allowing six locomotives to have their fires cleaned simultaneously. The hydraulic ash plant was only installed at two locations in the world, both on the N&W, because it was developed as the steam era was ending after World War II. Ash is washed out of the locomotive into pits where high-pressure water jets and pumps collect the ash and carry it to a dewatering bin. The dried ash is then discharged into hopper cars for disposal. All of this movement and loading of ash was done automatically. The manufacturer of this device, United Conveyor Corporation, is still produces ash handling equipment for the power generation industry.[88] Also, the large lubricating and inspection building would be part of the large inspection facility. This building would have two tracks with inspection pits and would be used for the routine lubrication and inspection of locomotives.

The small servicing facility would be a half size version. It would have a three-track ash plant and a single track lubricating and inspection building.

Modern Steam Servicing Needs:

Late steam era locomotives such as the N&W Class J could run 1,300 miles before the lubricators needed to be refilled and 500 miles before the oil reservoirs on the rods and valve gear needed to be refilled.[89] These items and fire cleaning were the routine servicing factors, which limited locomotive range. A modern steam locomotive with sealed roller bearings on the motion, just as sealed roller bearings are now used on axles, would eliminate the 500 mile lubricating interval for the motion, as in the case of Roger Waller's 52 8055 discussed earlier.[90] Also, larger lubricators could be used allowing the locomotive to go farther than the 1,300-mile limit, as in the case of the Class J. When working for the China National Railways, David Wardale planned on fitting

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[88] Thomas W. Dixon, Jr., *Steam Locomotive Coaling Stations and Diesel Locomotive Fueling Facilities* (Lynchburg, VA: TLC Publishing, 2002) 72

[89] Colonel Lewis Ingles Jeffries, *N&W Giant of Steam* (Hong Kong: Norfolk & Western Historical Society, 2005) 239

[90] Andre Chapelon, *La Locomotive A Vapeur*, trans. George W. Carpenter, C.Eng., M.I. Mech.E. (Great Britain: Camden Miniature Steam Service, 2000), 621

lubricators on steam locomotives that would give a range of between 5,700 and 9,300 miles.[91]

The other limiting factor for length of run was the interval of fire cleaning. With GPCS Porta's locomotives were able to go 40-50 hours between fire cleanings.[92] With computer controlled combustion, it is assumed that the fire-cleaning interval could go longer than what Porta's Rio Turbio locomotives were capable of. A 54-hour interval would be a reasonable conservative number to start with. This number of hours would allow for four shifts with six hours additional allowance time, 12 hours being the maximum number of hours of service for a shift. Also a constant rocking grate, the V Clinkering grate has since been developed which is a self cleaning design.[93]

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[91] David Wardale, *The Red Devil and Other Tales from the Age of Steam* (Scotland: Highland Printers, 2002), 451

[92] L.D. Porta, *Advanced Steam Locomotive Development Three Technical Papers* (Britain: Camden Miniature Steam Services, 2006) 19

[93] Martyn Bane, personal communication to author, January, 3, 2008.

The Use of Modern Steam on Amtrak and Commuter Railroads:

Amtrak:

Amtrak could use Modern Steam for its trains other than in the electrified North East and Keystone Corridors linking Washington, New York City, Boston and Harrisburg as well as its diesel-third rail electric routes out of New York City on the Empire Corridor. In 2006 on the routes slated for conversion, Amtrak spent $175.2 million on diesel fuel.[94] This could be replaced by $56.8 million dollars for coal and water facilities if a modern steam locomotive were used.[95] This is a $118.3 million annual cost savings. Amtrak would need to purchase 214 4-8-4P's to replace 265 GE P42 & P32 and EMD F59 diesel passenger locomotives, provided Amtrak used a 25-year replacement cycle on the diesel fleet compared to a fifteen-year conversion timeline for steam locomotives. The purchase of modern steam locomotives would equate to a $32 million per year increase in acquisition costs for locomotive fleet renewal. Amtrak would need seven servicing facilities at major terminals along with the use of coal and water facilities owned by freight railroads, where Amtrak operates. Also the economics of servicing facilities would not make much sense unless Amtrak could partner with commuter operators to construct joint facilities. If Amtrak could pay half the cost of the seven servicing facilities they would need, then Amtrak would break even on fuel savings. This would pay for additional locomotive and servicing facilities costs in the tenth year of conversion.[96] By the fifteenth year of conversion the cumulative cost savings would be $350 million.[97]

For the same reasons stated in the executive summary, the payoff time could be substantially reduced if the locomotive costs are closer to equaling the cost of passenger diesels. Also as fuel efficiency would increase with development during implementation, the cost savings would be higher than calculated in this paper. But the case for Amtrak to convert to Modern Steam is not a clear one. Realistically Amtrak should only start a conversion if the freight railroads convert to modern steam. Due to Amtrak's route structure and minimal frequency, it would not make sense for Amtrak to install the coal and water infrastructure solely for its own use. Critical mass probably could not be achieved even on corridors such as those in California if Amtrak had to bear the full burden of purchasing locomotives and infrastructure for only a part of their system. But, the politics of wanting a transportation mode that does not use foreign oil as its fuel source could change the dynamic significantly. Amtrak uses 76.2 million gallons of

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[94] Calculated on, "Amtrak Fuel Savings Use.xls" Sheet: "Amtrak Fuel Savings" Cell I10 in the file addendum.

[95] Calculated on, "Amtrak Fuel Savings Use.xls" Sheet: "Amtrak Fuel Savings" Cell I11 in the file addendum.

[96] Calculated on, "Amtrak Breakeven.xls" Sheet: "Breakeven" Cell E22 in the file addendum.

[97] Calculated on, "Amtrak Breakeven.xls" Sheet: "Breakeven" Cell D29 in the file addendum.

diesel fuel on the types of services mentioned above and this could be a point of interest to politicians who want to consider an alternative fuel source.[98]

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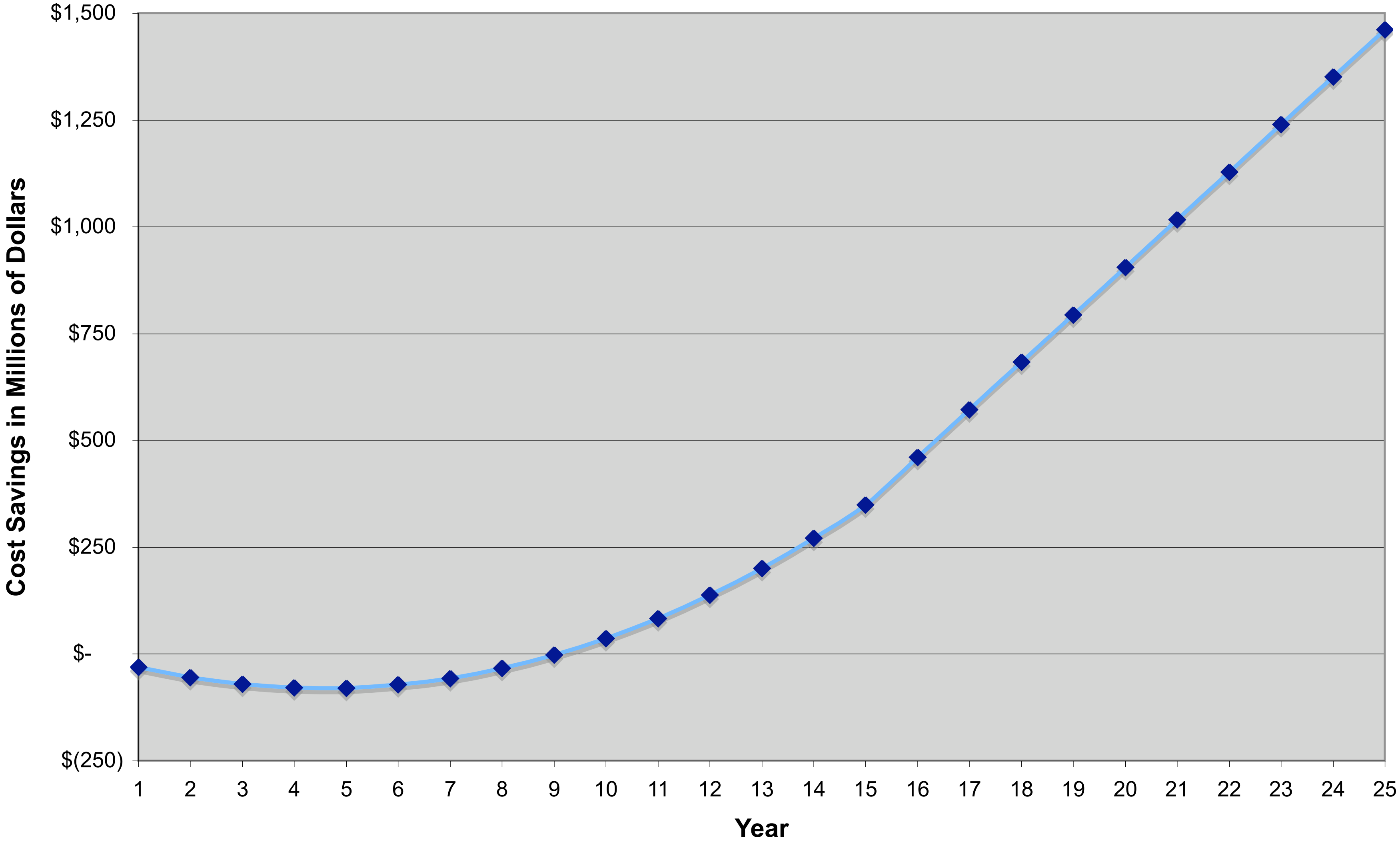
[98] Calculated on, “Amtrak Fuel Savings Use.xls” Sheet: “Amtrak Fuel Consumption” Cell B52 in the file addendum.

Cumulative Cost Savings Steam



Commuter Rail:

The modern steam locomotive could also have significant cost savings over diesel-electric in commuter rail service. The following calculations are based on the 2006 average diesel fuel cost of Amtrak because the cost and usage information from the commuter railroads was not available. Chicago's Metra, using all Illinois Basin Coal could experience fuel cost savings of 60% over MPI commuter diesels. VRE and Marc operating out of Washington, DC could have fuel cost savings of 56% using a 50-50 blend of Northern and Central Appalachian Coals. Tri-Rail in southern Florida could see cost savings of 53% using Central Appalachian Coal. Boston's MBTA could have fuel cost savings of 59% using Northern Appalachian Coal. Finally the west coast commuter agencies - Sounder, CalTrain and Metrolink - could also experience 59% cost savings using Uinta Basin Coal. The MPI MP36 and MP40, the only two available commuter diesels currently in production, cost $2.65 and $4.1 million each respectively.[99] The 4-8-4C, which can produce the performance levels of either of the two MPI locomotives, is priced conservatively at a 50% premium over the MP36, or $4 million.[100] Also an all-inclusive servicing facility with coal and water capability might cost from $4.4 to $6.1 million depending on its size and throughput.[101]

For the same political reasons as stated in the section on Amtrak, an initiative might be started with commuter rail. In the context of commuter rail, a conversion to modern steam could be contemplated and performed regardless of the interest of Class I freight railroads or Amtrak. Commuter rail systems are very self-contained. The locomotives and cars stay associated with a single terminal and they don't roam over a wide area. Consequently, a single servicing facility could coal, water and maintain all of the locomotives in a fleet. Since a commuter rail operation would not need to rely on the freight railroad for coal and water facilities at multiple locations, they could convert their system in isolation.

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[99] Calculated on, "Amtrak Loco Roster.xls" Sheet: "Loco Costs" Cells C6&7 in the file addendum.

[100] See note concerning locomotive costs from Roger Waller in the executive summary.

[101] Calculated on, "Infrastructure.xls" Sheet: "Passenger Facilities" Cells D9&18 in the file addendum.

Next Steps:

Where to go from here:

The author has developed a critical path describing how this idea of using a Modern Steam Locomotive to reduce the fuel costs of America's Class I railroads as well as Amtrak and Commuter Railroads could be pursued and the relative costs of doing so. What follows is a six-step plan , indicating where the Modern Steam Locomotive needs to pass each step before moving to the next. The plan would contain the following elements:

- Feasibility Study,
- Test Bed Locomotive – Phase 1,
- Test Bed Locomotive – Phase 2,
- New Build Prototype,
- Preproduction Samples and
- Series Production.

Feasibility Study:

The first step is an in-depth feasibility study, which at a minimum should be sponsored by one or more Class I Freight Railroads, but preferably sponsored by a combination of the Association of American Railroads (representing all of America's Class I Freight Railroads), the Coal Institute (or other coal organizations), the American Public Transportation Association (to represent the Commuter Railroads), Amtrak and the US Department of Energy. Also EMD and GE should be included as the potential builders of these new locomotives. Getting their support will be very important. This may seem like a long shot but the replacement of the North American locomotive fleet at an accelerated rate should be quite profitable for the two companies. The chance to render that number of diesel locomotives obsolete and sell their replacements should be very enticing unless they can't swallow their pride.

The feasibility study would need to investigate a wide number of topics more thoroughly. One of the main things would be using advanced train performance simulation software, such as Berkeley Simulation Software's Rail Traffic Controller, to make detailed estimates of the ton-miles per dollar that the diesel and modern steam locomotive would be capable of producing along with developing the input data to drive this software.[102] Also much more detailed investigation of infrastructure costs and needs, should be made. More specific fuel use data from the Class I's should be analyzed and compared to the total consumption for a year. Also more detailed information on the use characteristics and statistics of each type of locomotive in a railroads fleet should be studied, instead of using "broad-brush" data. Also the availability of water should be

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[102] http://www.berkeleysimulation.com/

studied in a more specific way to determine if condensing operation would be appropriate. These and other factors would go into an all-inclusive engineering and strategic planning feasibility study.

Test Bed Locomotive – Phase 1:

The first phase of testing will include showing that the modern steam locomotive could operate in today's operating environment. It will also serve as a starting point for accumulating test data. Overall, this phase would serve as a demonstration case. To keep costs low a museum steam locomotive could be used. This first phase would not include automatic controls of the boiler or the ability to MU. These features would be addressed on in the next step provided it makes sense to continue development. The ability to test in many scenarios would be a strong point, allowing the cost to be spread out beyond the Class I Freight Railroads. Testing in intermodal as well as bulk type unit trains, as well as conventional passenger rail, commuter rail and high speed rail would be possible if the right locomotive is selected initially.

Norfolk & Western Class J No. 611 might be a good choice. The Class J was a very versatile locomotive for the N&W. It was used very successfully in fast and slow freight as well as passenger service and was capable of speeds over 100 mph. Norfolk Southern used 611 until 1994 as part of their steam program. Mechanically the locomotive is in good shape having been stored at the Virginia Museum of Transportation.[103] The Class J also had roller bearing rods and motion, which would allow a range of 500 miles. This fact is very useful because it would eliminate the extra expense in lubricating or fitting roller bearings for the test.

The 611 would be rebuilt using the same types of modifications as David Wardale made on the *Red Devil*. It is envisioned that the 611 would be assigned to freight trains, intermodal and heavy unit trains, on the same four sections of the Norfolk Southern used as the basis of comparison in this paper, namely between Bluefield, WV and Columbus, OH. The 50 miles of nearly straight and level track from Petersburg to west of Norfolk, VA would be a good location for some of the tests similar to what Wardale did on the *Red Devil*.

In conventional passenger service 611 could run the Amtrak train from Washington, DC to Newport News, VA over CSX. For commuter demonstration, the VRE Manassas line, between its namesake city and Washington could be used over NS. Finally to test high speed service 611 could be used on Amtrak's Keystone corridor from Harrisburg to Philadelphia, PA at speeds of 110 mph. All of these runs would be the right distances based on 611's fuel and water range.

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[103] Rick Musser, shop foreman of the Strasburg Railroad, e-mail messages to author, various dates.

The costs of this step would between $1 and $3 million dollars.[104] The modification work and testing of the locomotive would take over one year.[105] After the following pages on the tests, a chart and graphs are presented showing the performance of the modified locomotive. While the modified locomotive would not be as efficient or capable as a new build locomotive, it will allow useful comparisons to be made. The modified locomotive will demonstrate that the modern steam locomotive can work in today's railroading industry. It will show minimally what a modern steam locomotive is capable of.

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[104] Various sources as shown on the following pages and Matt Janssen of the Vapor Locomotive Company, e-mail message to author, 9-25-07

[105] Rick Musser, shop foreman of the Strasburg Railroad, e-mail messages to author, various dates.

Testing Cost:

Item:	Cost:	Entity:	Notes:
Locomotive	**$ 566,715**	See Locomotive Sheet	
Instrumentation	$ 52,461	See Instrumentation sheet	
Dyno Car	$ -	NS Corp	Loan, NS 31 Research Car, Ex SOU 21/ R1 Research Car
Tool Car	$ -	NS Corp	Loan
Setup	$ 20,000	Strasburg RR	Get the tool car ready: storage and work areas, etc.
Crew Car	$ -	NS Corp	Loan
Flat Car / Crane	$ -	NS Corp	Loan, Clam shell crane for coal loading and ash pickup.
Hot Pressure Washer	$ 4,200	Northern Tool	Boiler Washout and Cleaning
Subtotal	**$ 643,376**	**Locomotive and Equipment**	
Personnel	$ 210,048	See Personnel sheet	
Coal	$ 193,679	4,099 Tons @ $47.25/t	Central Appalachian Coal, washed & sized 2.5" x 1.25"
Coal	$ 6,864	160 Tons @ $43/t	Northern Appalachian Coal, washed & sized 2.5" x 1.25"
Coal	$ 5,268	160 Tons @ $33/t	Illinois Basin Coal, washed & sized 2.5" x 1.25"
Coal	$ 5,746	160 Tons @ $36/t	Uinta Basin Coal, washed & sized 2.5" x 1.25"
Boiler Chemicals	$ 20,118	$3.43/1,000 gal.	Porta Treatment
Miscellaneous/Spares	$ 10,000	Contingency, Supplies, Spares, etc.	
Total (gross)	**$ 1,095,099**		
Freight	$ 5,000	Cost attributed to freight only	
Passenger	$ 22,000	Cost attributed to passenger only	
Total (base)	**$ 1,068,099**	**Base cost of test less items needed for freight or passenger**	
Total	$ -	Loaned or gifts-in-kind from Corporate Sponsors (Freight)	
Total	$ -	Loaned or gifts-in-kind from Corporate Sponsors (Passenger/Government)	
Total (net)	$ 1,095,099	Less Loaned Items & Gifts-in-kind	
Share Freight	$ 717,066	Cost of Freight Share of Test	
Total Less Loaned	**$ 717,066**	**Cash Cost of Freight Share of Test**	
Share Passenger	$ 378,033	Cost of Passenger Share of Test	
Total Less Loaned	**$ 378,033**	**Cash Cost of Passenger Share of Test**	

Locomotive

Item:	Cost:	Entity:	Notes:
Locomotive Procurement			
N&W 611	$ -	City of Roanoke/VMT	Loan if FRA/DOE is sponsor
Aux. Tender	$ -	City of Roanoke/VMT	Loan if FRA/DOE is sponsor
Prep to move	$ 5,200	Strasburg RR	Get Locomotive ready to ship "cold" to Strasburg
Move to Shop	$ -	NS Corp	Sponsor
Return to service			
1472 SDI	$ 70,000	Strasburg RR	Hydro test, UT survey
FRA Form 4	$ 15,000	Strasburg RR	Determine if safety valves can be set to 310 psi, working pressure to remain 300 psi
Tubes & Flues	$ 27,500	Strasburg RR	Flues (standard) & Tubes (XID http://www.tektube.com/tektube/xid.html)
Truck Work	$ 20,000	Strasburg RR	Lead truck trammed
Boiler Efficiency			
GPCS Design	$ 25,000	Nigel Day	Convert to Gas Producer Combustion System
Pin Hole Grates	$ 30,000	Nigel Day / Strasburg RR	Cast and install new pinhole grates (reduced air opening)
Secondary Air	$ 6,500	Nigel Day / Strasburg RR	roughly 16 air inlets 6" diameter with swirl plates
Anticlinker Steam	$ 3,725	Nigel Day / Strasburg RR	Pipe in Exhaust steam and Blower steam
Lempor Design	$ 15,000	Nigel Day	Design new Lempor Exhaust system and improve smokebox design
Fabricate / Install	$ 25,000	Nigel Day / Strasburg RR	4 Stack System, with Kordina and deLaval type blower nozzles
Stack Caps	$ 100	Nigel Day / Strasburg RR	Simple caps for use when engine is sitting overnight
Nose Cone	$ 19,000	Nigel Day / Strasburg RR	Nose Cone internal streamlining & modification. See note.
HP Insulation	$ 19,850	Nigel Day / Strasburg RR	Thermal Ceramics Superwool 607: boiler, smokebox, firebox, cylinder saddle, heads, etc.
2nd Air Injectors	$ 5,000	Nigel Day / Strasburg RR	Pipe in steam jets for secondary air inlets
Cylinder Efficiency			
Design Work	$ 10,000	Nigel Day	Design, Supervise, etc.
Improve Ports	$ 25,000	Nigel Day / Strasburg RR	Shape, Size (Porta type), Increase Steam Chest Volume
Multi-ring Valves	$ 12,000	Nigel Day / Strasburg RR	Conversion of piston valves to Porta type multi-ring design
Multi-ring Pistons	$ 10,000	Nigel Day / Strasburg RR	Conversion of pistons to Porta type multi-ring design, reduce clearance volume
Lubrication	$ 8,000	Nigel Day / Strasburg RR	Between the rings cylinder lubrication, Proportional feed lubricator drive (combination lever)
Cylinder Liners	$ 10,000	Nigel Day / Strasburg RR	Cooled Valve and Cylinder Liners as per SAR No. 3450
Valve Gear	$ 5,000	Nigel Day / Strasburg RR	Modify Valve Gear geometry to improve port openings in short cutoffs
Gland Packings	$ 6,000	Nigel Day / Strasburg RR	Semi-metallic multiring type, as per SAR No. 3450
Drifting Change	$ 8,000	Nigel Day / Strasburg RR	Removal of drifting, snifting, & bypass valves, requires mid gear drifting and atomizing steam adjustment
More Superheat	$ 10,000	Nigel Day / Strasburg RR	Weld on fins to superheater elements
Porta Treatment			
Foaming Meter	$ 620	Martyn Bane/Strasburg RR	FCAF type, front & rear of boiler
Antifoam Injector	$ 720	Martyn Bane/Strasburg RR	For Direct injection of Anti-Foam to Boiler
FWH	$ 500	Martyn Bane/Strasburg RR	Currently installed, blank off FWH vents to increase evaporation
Miscellaneous	$ 2,000	Martyn Bane/Strasburg RR	Drop tubes for top feed boiler fitting, see note
Adhesion:			
Driver Tires	$ 20,000	Nigel Day / Strasburg RR	Porta High Adhesion Tire Profile
Improve Sanding	$ 5,000	Strasburg RR	Sanding of Leading and Trailing Truck, as per SNCF Standard.
Rail Washers	$ 5,000	Nigel Day / Strasburg RR	Used in conjunction with Sanding, except when brake in emergency
Miscellaneous	$ 2,000	Strasburg RR	See Note
Booster:			
Franklin Booster	$ -	Baltimore RR Museum	Loan if FRA/DOE is sponsor
Rebuild/Install	$ 95,000	Nigel Day / Strasburg RR	Trailing truck booster, Superheated, Porta cylinder work, exhaust to Lempor

Locomotive

Item:	Cost:	Entity:	Notes:
Items necessary for current practice			
Cab Signals	$ -	Amtrak	Loan from Amtrak, for Harrisburg Sub. operation
Installation	$ 6,000	Strasburg RR	
Train Stop	$ -	Amtrak	Loan from Amtrak, for Harrisburg Sub. operation
Installation	$ 6,000	Strasburg RR	
Passenger Etc.	$ -	Amtrak	HEP control for trailing diesel, Amtrak trainline signal/communications
Installation	$ 5,000	Strasburg RR	
Tite-locks	$ -	Amtrak	Tite-Lock Couplers for Tender and Aux. Tender
Installation	$ 5,000	Strasburg RR	
Ditch Lights	$ 12,000	Strasburg RR	Recessed, behind glass covers by the air compressor cooling inlets on the front of the loco.
Control Stand	$ -	NS Corp	Diesel MU stand
Installation	$ 6,000	Strasburg RR	
EOT Control	$ -	NS Corp	End Of Train Control device for freight operations.
Installation	$ 5,000	Strasburg RR	
Repaint-Labor	$ -	NS Corp	Amtrak Cascades Green and Platinum Mist Grey. See note. ($15,000 value)
Repaint-Material	$ -	Amtrak	
Total	$ 566,715	Cost	

Instrumentation on Locomotive:

Test:	Item:	Cost:	Supplier:	Notes:
Steam Circuit:				
Pressure				
Boiler at cab	PX209	$ 195	Omega	Pressure transducer
Boiler at dome	PX209	$ 195	Omega	Pressure transducer
Superheater hd, sat. side	PX209	$ 195	Omega	Pressure transducer
Superheater hd, sup. side	PX209	$ 195	Omega	Pressure transducer
Exh. ejector	PX209	$ 195	Omega	Pressure transducer
Barometric	PX309	$ 175	Omega	Pressure transducer
Temperature:				
Exh. ejector	TC-K-NPT-E-72	$ 34	Omega	Pipe plug thermocouple
Superheater header	TC-K-NPT-E-72	$ 34	Omega	Pipe plug thermocouple
Indicating:				
Pressure:				
Steam chest, engineer's side	PX209	$ 195	Omega	Pressure transducer
Steam chest, fireman's side	PX209	$ 195	Omega	Pressure transducer
Exhaust chest, engineer's side	PX209	$ 195	Omega	Pressure transducer
Exhaust chest, fireman's side	PX209	$ 195	Omega	Pressure transducer
Cylinder front, engineer's side	PX209	$ 195	Omega	Pressure transducer
Cylinder back, engineer's side	PX209	$ 195	Omega	Pressure transducer
Cylinder front, fireman's side	LD300-300	$ 980	Omega	Linear displacement sensor
Cylinder back, fireman's side	LD300-300	$ 980	Omega	Linear displacement sensor
Temperature:				
Steam chest, engineer's side	TC-J-NPT-G-72	$ 34	Omega	Pipe plug thermocouple
Steam chest, fireman's side	TC-J-NPT-G-72	$ 34	Omega	Pipe plug thermocouple
Ex. chest, engineer's side	TC-J-NPT-G-72	$ 34	Omega	Pipe plug thermocouple
Ex. chest, fireman's side	TC-J-NPT-G-72	$ 34	Omega	Pipe plug thermocouple
Cylinder front, engineer's side	TC-J-NPT-G-72	$ 34	Omega	Pipe plug thermocouple
Cylinder back, engineer's side	TC-J-NPT-G-72	$ 34	Omega	Pipe plug thermocouple
Cylinder front, fireman's side	TC-J-NPT-G-72	$ 34	Omega	Pipe plug thermocouple
Cylinder back, fireman's side	TC-J-NPT-G-72	$ 34	Omega	Pipe plug thermocouple
Cylinder position, engineer's side	TC-J-NPT-G-72	$ 34	Omega	Pipe plug thermocouple
Cylinder position, fireman's side	TC-J-NPT-G-72	$ 34	Omega	Pipe plug thermocouple
Booster:				
Pressure:				
Supply pipe	PX209	$ 195	Omega	Pressure transducer
Steam chest	PX209	$ 195	Omega	Pressure transducer
Exhaust pipe	PX209	$ 195	Omega	Pressure transducer
Temperature:				
Supply pipe	TC-J-NPT-G-72	$ 34	Omega	Pipe plug thermocouple
Steam chest	TC-J-NPT-G-72	$ 34	Omega	Pipe plug thermocouple
Exhaust pipe	TC-J-NPT-G-72	$ 34	Omega	Pipe plug thermocouple
Locomotive Brakes:				
Main Reservoir	PX309	$ 175	Omega	Pressure transducer
Equalizing Reservoir	PX309	$ 175	Omega	Pressure transducer
Brake Pipe	PX309	$ 175	Omega	Pressure transducer
Brake cylinder	PX309	$ 175	Omega	Pressure transducer
Collection				
Data logging computer	OMB-LOGBOOK	$ 4,600	Omega	
Cabling, connectors, etc.	Various	$ 3,000	Omega	
Installation		$ 10,400	Strasburg RR	
Total		$ 52,461		

Instrumentation on Locomotive:

Test:	Item:	Cost:	Supplier:	Notes:
Throttle position	LD300-300	$ 980	Omega	Linear displacement sensor
Cutoff position	LD300-300	$ 980	Omega	Linear displacement sensor
Booster throttle position	LD300-300	$ 980	Omega	Linear displacement sensor
Booster engaged	Micro Switch	$ 5		
Coal Delivery:				
Coal fired	Micro Switch	$ 5		200 Lb. Scale-box N&W type.
Coal fired	Micro Switch	$ 5		Stoker engine revolution counter
Stoker engine	PX209	$ 195	Omega	Pressure transducer
Stoker blast jet	PX209	$ 195	Omega	Pressure transducer
Feedwater / Evaporation:				
Water flow, FWH	FMG-1004	$ 1,636	Omega	Electromagnetic Flowmeter with data logger
Water flow, injector	FMG-1004	$ 1,636	Omega	Electromagnetic Flowmeter with data logger
FWH hot pump stroke counter	Micro Switch	$ 5		Proximity Sensor
Boiler level		$ -		From front & rear boiler foaming meter
Tender level	LVU-41 2ea.	$ 1,374	Omega	Sensors in opposite corners
Calorimeter		$ 5,500	Cal Research	Steam at dome
Water Sampling Valve	Strasburg RR	$ 150	With condensing coil with the take off below the crown sheet level	
Boiler pH Tester	PHH-5012	$ 47	Omega	
Boiler TDS Tester	TDH-5031	$ 45	Omega	
Pressure				
Exhaust steam entering FWH	PX209	$ 195	Omega	Pressure transducer
Water entering boiler	PX209	$ 195	Omega	Pressure transducer
Water entering FWH	PX309	$ 175	Omega	
Temperature:				
Water leaving tank	TC-J-NPT-G-72	$ 34	Omega	Pipe plug thermocouple
Water entering FWH	TC-J-NPT-G-72	$ 34	Omega	Pipe plug thermocouple
Water entering boiler, from FWH	TC-J-NPT-G-72	$ 34	Omega	Pipe plug thermocouple
FWH condensate	TC-J-NPT-G-72	$ 34	Omega	Pipe plug thermocouple
Steam space FWH (exh steam)	TC-J-NPT-G-72	$ 34	Omega	Pipe plug thermocouple
Combustion Efficiency:				
Draft:				
Ashpan	PX160	$ 120	Omega	2.5-28" H2O vacuum sensor
Firebox	PX160	$ 120	Omega	2.5-28" H2O vacuum sensor
Secondary air inlets	PX160	$ 120	Omega	2.5-28" H2O vacuum sensor
Back of diaphragm, smokebox	PX160	$ 120	Omega	2.5-28" H2O vacuum sensor
Front of diaphragm, smokebox	PX160	$ 120	Omega	2.5-28" H2O vacuum sensor
Temperature:				
Combustion chamber	TC-K-NPT-E-72	$ 34	Omega	Pipe plug thermocouple
Firebox, over arch	TC-K-NPT-E-72	$ 34	Omega	Pipe plug thermocouple
Firebox, under arch	TC-K-NPT-E-72	$ 34	Omega	Pipe plug thermocouple
Back of diaphragm, smokebox	TC-K-NPT-E-72	$ 34	Omega	Pipe plug thermocouple
Front of diaphragm, smokebox	TC-K-NPT-E-72	$ 34	Omega	Pipe plug thermocouple
Atmosphere	TC-J-NPT-G-72	$ 34	Omega	Pipe plug thermocouple
Pressure:				
Blower	PX209	$ 195	Omega	Pressure transducer
Anti- clinker steam, primary	PX209	$ 195	Omega	Pressure transducer
Anti- clinker steam, blower	PX209	$ 195	Omega	Pressure transducer
Secondary air injector	PX209	$ 195	Omega	Pressure transducer
Exhaust gas analysis:				
Exhaust Gas Analyzer	TSTO-350XL-P4	$ 8,034	Electro Rent	
Smoke opacity	6500RR	$ 4,295	Robert H. Wager Co.	Smoke Opacity Meter

Personnel:

Personnel:	Hours:	Rate:	Cost:	Notes:
Host Railroad:				
Pilot Engineer	[redacted]	[redacted]	[redacted]	Provides by Host Railroad/Operator, would be running normal in-service trains, run in this project.
Conductor	[redacted]	[redacted]	[redacted]	
Project:				
Project Leader	1392	$ 32.49	$ 45,226	Manager
Engineer	1392	$ 26.69	$ 37,152	For entire test, on all operating areas, assisted by Pilot Engineer
Fireman	1392	$ 18.65	$ 25,961	For entire test, on all operating areas
Data Specialist	1200	$ 21.55	$ 25,860	Handles data collection in Dyno Car
Mechanic	1392	$ 20.45	$ 28,466	Maintenance
Laborer #1	1392	$ 18.28	$ 25,446	Coal Weighing, Servicing, etc.
Laborer #2	1200	$ 18.28	$ 21,936	Coal Weighing, Servicing, etc.
Laborer #3	1200	$ 18.28	$ 21,936	Coal Weighing, Servicing, etc.
Totals:	9360	[redacted]	$ 210,048	All wage info BLS.gov May 2005, most current

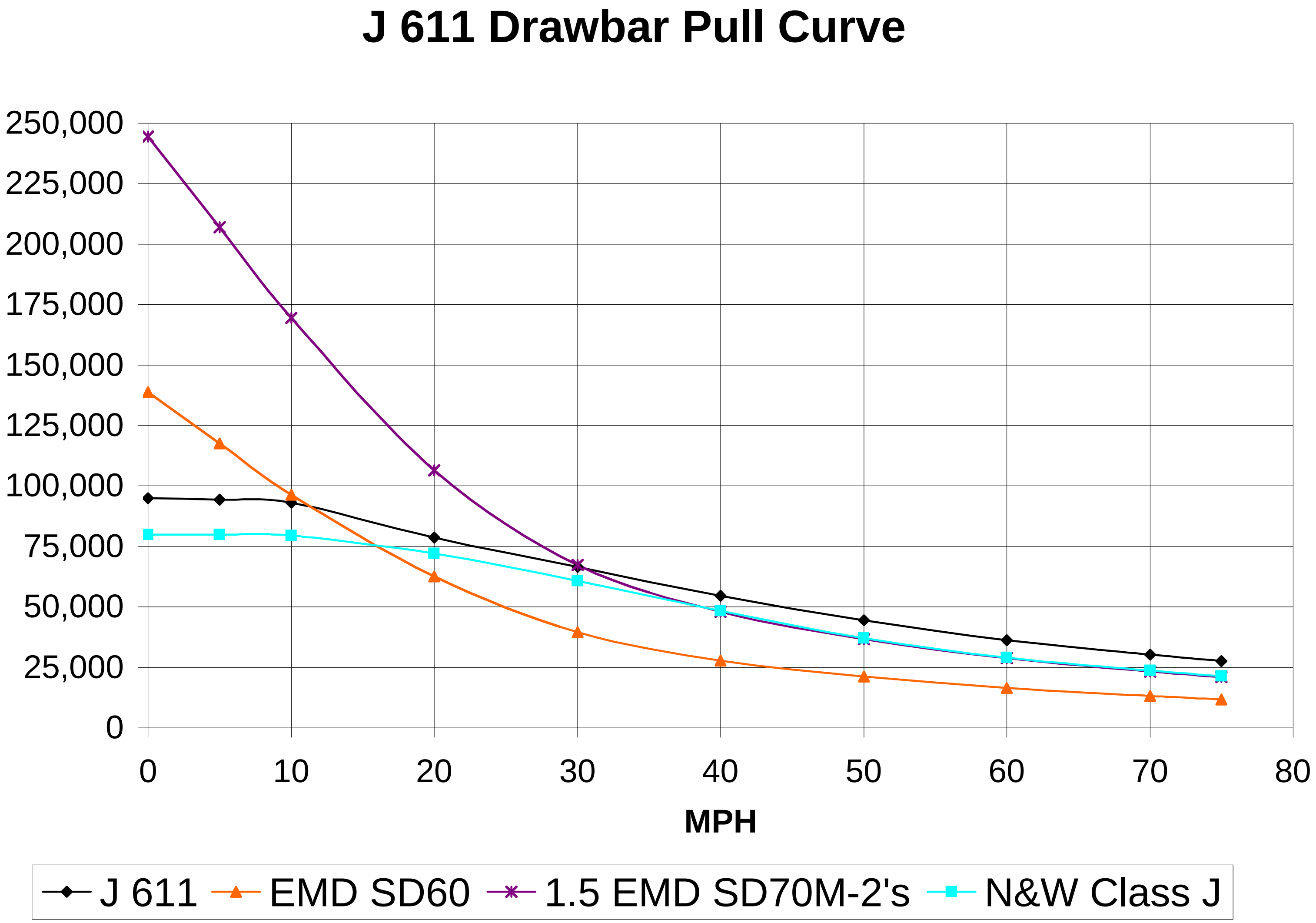
Schedule of Tests							All tests except first are dynamometer car road tests w/ indicating
Wk #	**Type**	**Place**	**Owner**	**Coal**	**Water**	**Miles**	Notes: (coal for each series of tests will be from the same lot)
Reposition for tuning up		Strasburg - Harrisburg	NS Corp.	12	10824	47	Move done on weekend before series of tests.
1-4	Tuning Up	Harrisburg - Reading	NS Corp.	169	169179	1320	Get locomotive sorted out and ready for testing.
31 day inspection		Project Team					Inspection done on weekend.
5,6	Sensor Testing	Harrisburg - Reading	NS Corp.	139	163179	660	Test all sensors on loco & dyno. Prepare for testing.
7 **8**	Stationary boiler testing	Harrisburg, PA - Enola Yard	NS Corp.	160	468438	0	Test using the 4 main types of US high BTU coal. Test multiple firing rates, determine maximum firing rate.
31 day inspection		Project Team					Inspection done on weekend between series of tests.
9 **10**	High Speed Passenger	Harrisburg - Philadelphia, PA	Amtrak	438	664912	4160	104 miles, 110mph max. 65mph avg. 2 runs per day each direction. 5:00a - 7:20p Trains 640, 641, 42, & 651. Each run is 1:40 to 1:50 in length. 4-10 intermediate stops
Reposition for next test		Harrisburg - DC	Amtrak	23	27196	239	Move done on weekend between series of tests.
11 **12**	Passenger Rail	Washington, DC - Newport News, VA	Amtrak - CSX	308	446608	3740	187 miles, 79mph max. 45mph avg. 1 runs per day each direction. 7:30a - 7:20p Trains 75 & 76. Each run is 4:00 in length. 8 intermediate stops
31 day inspection		Project Team					Inspection done on weekend between series of tests.
13 **14**	Commuter Rail	Washington, DC - Manassas, VA	VRE - NS Corp.	308	441608	1360	34 miles, 79mph max. 30mph avg. 2 runs per day each direction. 6:25a - 6:25p Trains 321, Deadhead, 325, & 338. Each run is 1:10 to 1:20 in length. 8 intermediate stops
15,16	Break	Time	Off				
Reposition for next test		DC - Petersburg	CSX	23	26696	141	Move done on weekend between series of tests.
17	Constant Evap Test	Petersburg - Norfolk VA	NS Corp.	187	460938	1500	50 miles straight level track, use diesels in dynamic braking mode
Reposition for next test		Petersburg - Williamson	NS Corp.	35	44000	372	Move done on weekend between series of tests.
18 **19**	Low Grade - Intermodal	Williamson WV - Portsmouth OH	NS Corp.	321	397947	2260	1 run each direction per day. Trailer or container on flat car. Start with tonnage rating in steam era then increase. 113 miles
92 day inspection		Project Team					Inspection done on weekend between series of tests.
20 **21**	Low Grade - Bulk	Williamson WV - Portsmouth OH	NS Corp.	321	397947	2260	1 run each direction per day. Solid coal trains. Start with tonnage rating in steam era then increase. 113 miles
Reposition for next test		Williamson-Portsmouth	NS Corp.	23	26696	113	Move done on weekend between series of tests.
22 **23**	Med. Low Grade - Intermodal	Portsmouth - Columbus OH	NS Corp.	341	430693	1980	1 run each direction per day. Trailer or container on flat car. Start with tonnage rating in steam era then increase. 99 miles
31 day inspection		Project Team					Inspection done on weekend between series of tests.
24 **25**	Med. Low Grade - Bulk	Portsmouth - Columbus OH	NS Corp.	341	430693	1980	1 run each direction per day. Solid coal trains. Start with tonnage rating in steam era then increase. 99 miles
Reposition for next test		Portsmouth-Williamson	NS Corp.	23	26696	113	Move done on weekend between series of tests.
26 **27**	Intermodal - Medium Grade / Heavy Grade	Williamson - Farm WV / Farm - Bluefield WV	NS Corp.	464	616251	1940	1 run each direction per day. Trailer or container on flat car. Start with tonnage rating in steam era then increase. 62 miles then 35 miles
31 day inspection		Project Team					Inspection done on weekend between series of tests.
28 **29**	Bulk - Medium Grade / Heavy Grade	Williamson - Farm WV / Farm - Bluefield WV	NS Corp.	464	616251	1940	1 run each direction per day. Solid coal trains. Start with tonnage rating in steam era then increase. 62 miles set off cars then 35 miles
Return to Storage		Williamson - Roanoke	NS Corp.	28	33246	201	Move done on weekend following test
			Total:	4099	5866753	26125	
Testing Percent:		Freight:	67%	Commuter:		11%	Passenger: 11% High Speed Rail: 11%

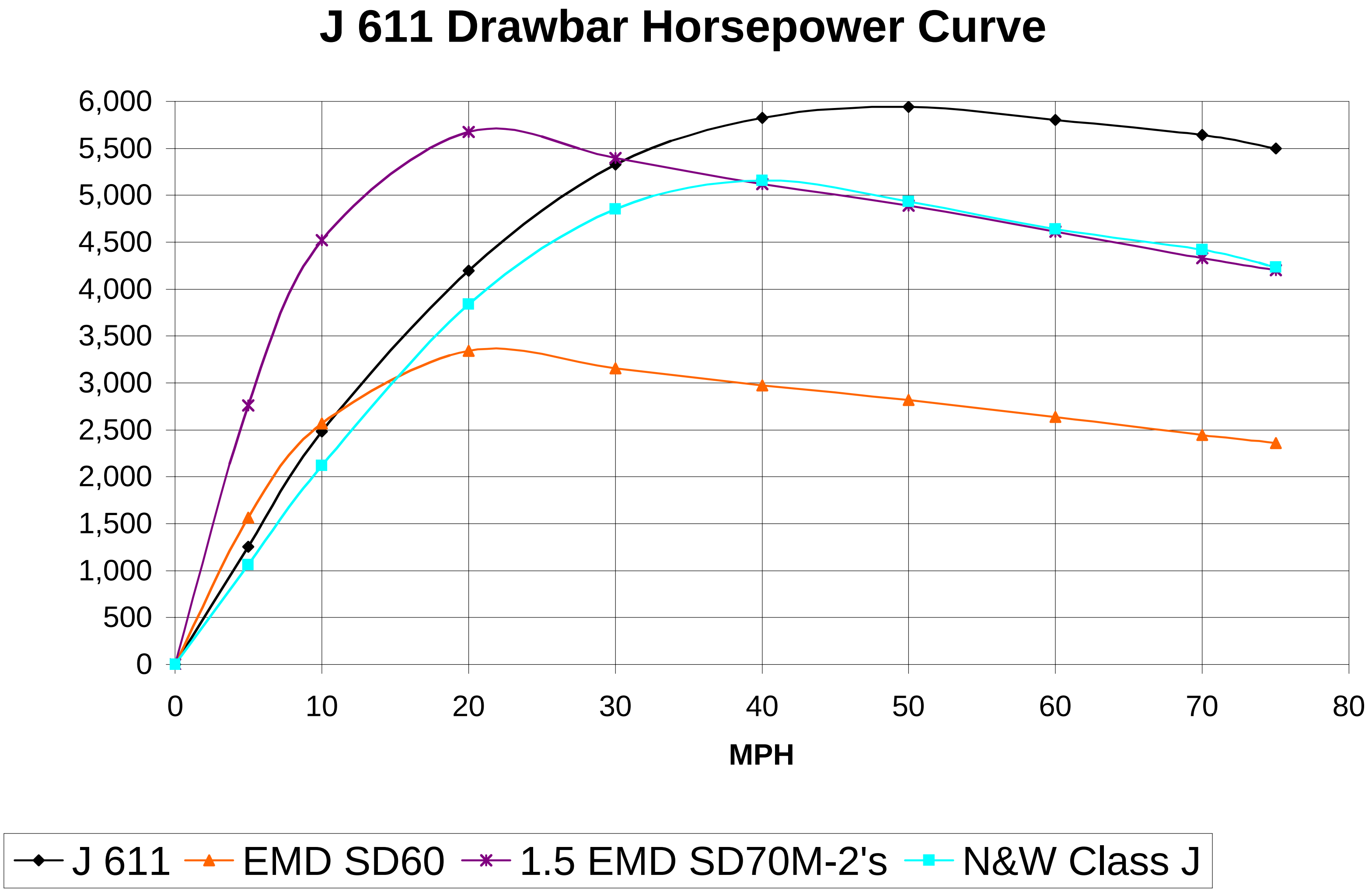
Full Throttle / Notch 8, Comparison - N&W J 611 & EMD SD60 & SD70M-2

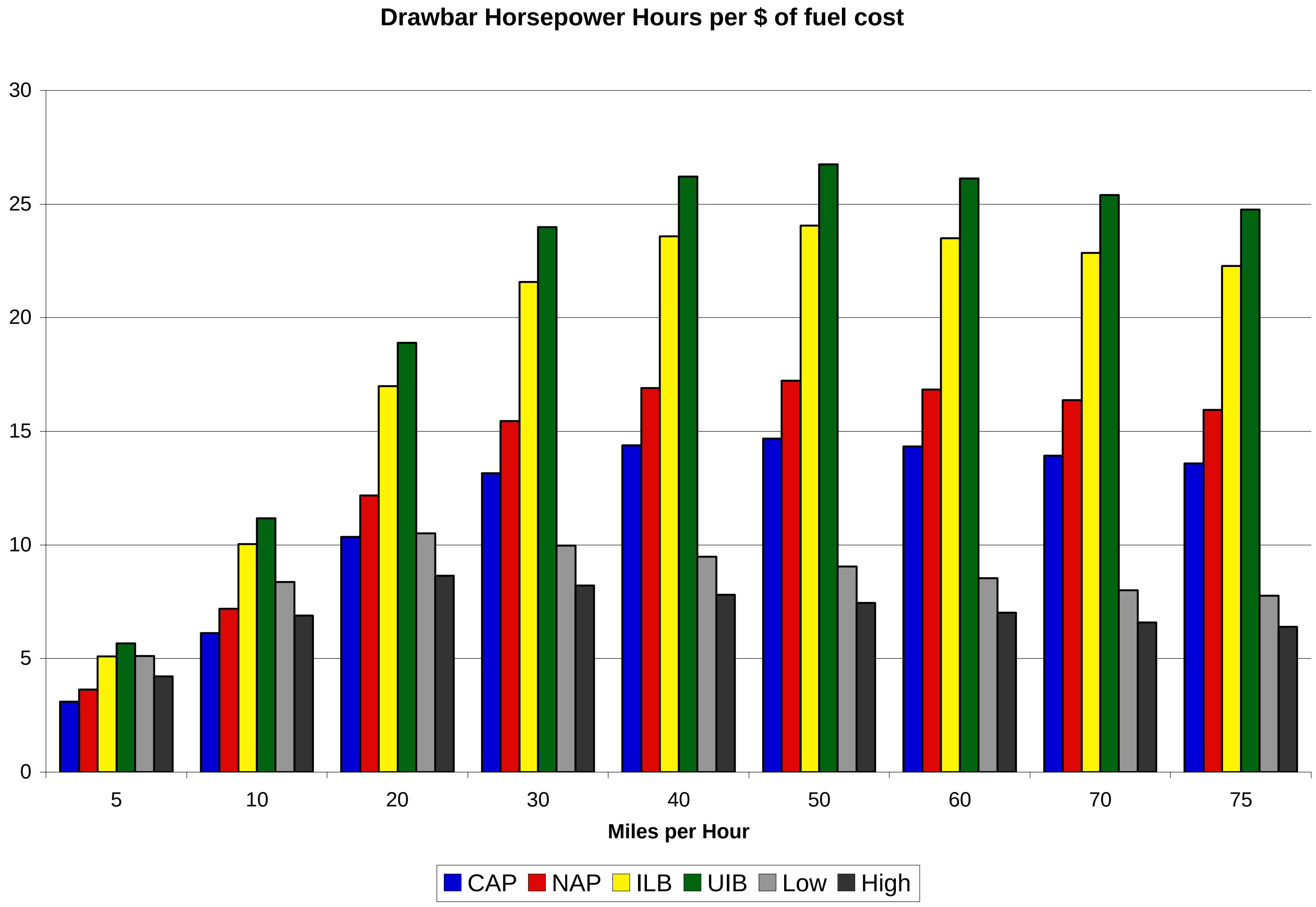
	MPH	0	5	10	20	30	40	50	60	70	75
Drawbar pull, level track		**95,000**	**94,263**	**92,998**	**78,649**	**66,568**	**54,582**	**44,544**	**36,252**	**30,223**	**27,655**
Drawbar Horse Power, level track		**0**	**1257**	**2480**	**4195**	**5325**	**5822**	**5939**	**5800**	**5642**	**5497**
DBHP Hours per $ of Fuel Cost, CAP		0	3	6	10	13	14	15	14	14	14
DBHP Hours per $ of Fuel Cost, NAP		0	4	7	12	15	17	17	17	16	16
DBHP Hours per $ of Fuel Cost, ILB		0	5	10	17	22	24	24	23	23	22
DBHP Hours per $ of Fuel Cost, UIB		0	6	11	19	24	26	27	26	25	25
EMD SD60 (3800 HP)	DBPull	**138700**	**117500**	**96300**	**62700**	**39453**	**27886**	**21140**	**16466**	**13097**	**11804**
	DBHP	**0**	**1567**	**2568**	**3344**	**3156**	**2975**	**2819**	**2635**	**2445**	**2361**
1.5 EMD SD70M-2 (4300 HP)	DBPull	**244500**	**207000**	**169500**	**106425**	**67429**	**48017**	**36661**	**28824**	**23182**	**21006**
	DBHP	**0**	**2760**	**4520**	**5676**	**5394**	**5122**	**4888**	**4612**	**4327**	**4201**
DBHP Hours per $ of Fuel Cost, East		0	5	8	11	10	9	9	9	8	8
DBHP Hours per $ of Fuel Cost, West		0	4	7	9	8	8	7	7	7	6
	MPH	0	5	10	20	30	40	50	60	70	75
N&W Class J	DBPull	80000	80000	79500	72000	60667	48333	37000	29000	23667	21334
	DBHP	0	1060	2120	3840	4853	5156	4933	4640	4418	4236

Water Cost	
Cost per 1000 gal. water	$ 0.09
Treatment cost per 1000 gals.	$ 2.35
Total cost per 1000 gals.	$ 2.44
Total cost per 1 gal.	$ 0.002

Full Throttle Fuel Cost / Hr.	
Coal Cost	
CAP	61.89
NAP	52.04
ILB	36.04
UIB	31.98
Diesel Cost	
Low	$1.80
High	$2.19
J 611	
CAP	404.81
NAP	344.62
ILB	246.86
UIB	222.05
SD60	
Low	$345.73
High	$419.83
1.5 SD70M-2	
Low	540.49
High	656.32


J 611 Drawbar Pull Curve
250,000
225,000
200,000
175,000
150,000
125,000
100,000
75,000
50,000
25,000
0
0
10
20
30
40
50
60
70
80
MPH
J 611
EMD SD60
1.5 EMD SD70M-2's
N&W Class J


J 611 Drawbar Horsepower Curve
6,000
5,500
5,000
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
0
10
20
30
40
50
60
70
80
MPH
J 611
EMD SD60
1.5 EMD SD70M-2's
N&W Class J


Drawbar Horsepower Hours per $ of fuel cost
30
25
20
15
10
5
0
5
10
20
30
40
50
60
70
75
Miles per Hour
CAP
NAP
ILB
UIB
Low
High

Test Bed Locomotive – Phase 2:

The second phase of the use of the test bed locomotive would be for emissions testing including the design and application of automated boiler controls. According to Matt Janssen, the design and construction of boiler controls for a steam locomotive would be in the \$1 to \$2 million range because of the complexity of the boiler demand on a steam locomotive as compared to a power plant. The boiler control system testing and emissions testing would range under \$1 million.[106] This testing would be of the utmost importance, making sure MU and the meeting of emissions standards is possible. If this stage is unsuccessful, the project would not be possible. This phase concludes the end of using the 611, and it would be returned to Roanoke, VA, less the automated boiler controls, which would be used on the prototype in the next phase.

New Build Prototype:

The design and construction of a one-off steam locomotive is estimated by Matt Janssen as being \$8 million.[107] After the locomotive was built, it would need to be put into longevity and fuel efficiency testing, most likely at the Transportation Technology Center, Inc. (TTCI) in Pueblo, CO. The TTCI is owned by the AAR and is used as the laboratory of the American railroads. The test program there should last a least a year. The cost of this testing is unknown.

Preproduction Samples:

If one example of each of the locomotives suggested in this paper were designed and built, it would likely cost \$64 million or \$8 million apiece, for the eight locomotive types. These should also be tested at the TTCI as well as being tested in service on a Class I railroad, between two fixed locations to minimize infrastructure needs associated with the test. The cost and duration of this testing is also unknown.

Series Production:

Only after these major hurdles are passed, including minor ones not stated, would the American railroading industry be in a position to contemplate converting to the Modern Steam Locomotive. Along the way, there are many factors, as stated earlier, that could stop this idea cold in its tracks, but the prospect of the substantial cost savings in fuel stated earlier deserve more investigation.

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[106] Matt Janssen of the Vapor Locomotive Company, e-mail message to author, 9-25-07

[107] Matt Janssen of the Vapor Locomotive Company, e-mail message to author, 12-12-07

Methodologies behind the Calculations:

The Modern Steam Locomotive:

All of the data for the Modern Steam Locomotives was calculated using four basic spreadsheets designed by the author. The first spreadsheet was an estimator of boiler performance and characteristics called the boiler designer. The second, called the cylinder calculator, detailed the power output of the locomotive. The third, called the tender and running time calculator, allowed the author to determine, as the title states, the proportions of the tender and the running time as well as being used to calculate the ton-miles per dollar, ton or gallon with data from the fourth spreadsheet. These first three spreadsheets allowed the author to determine the DBPull and DBHP curves as well as the fuel and water use of the modern steam locomotives. The DBPull curve was then fed into the Modified Davis Equation on the spreadsheet referred to as the tonnage and train speed calculator to develop tonnage ratings. The spreadsheets will be explained in greater detail below.

Boiler Designer Spreadsheet:

The basis of the boiler designer spreadsheet comparison uses the N&W Class J 4-8-4's boiler as a starting point to estimate the relationship of overall physical dimensions to square footages of heating surface. As a statistical check, the dimensions of other locomotives were entered into the spreadsheet, and the spreadsheets outputted data very close to the actual heating surfaces of those locomotives. One of the most important things about the spreadsheet is it allows the user to determine if the desired steam rate is possible to be made utilizing a boiler that will fit on a certain wheel arrangement. The spreadsheet allows the calculation of steam available to the cylinders for the cylinder calculator spreadsheet. The spreadsheet bases its calculations on data gathered during a test by the New York Central's Class S1b Niagara 4-8-4 and also from Ralph Johnson of Baldwin Locomotive Works. The top and bottom end of the average coal firing rate and evaporation rate, as a percent of maximum firing rate, is from the N&W 1952 steam versus diesel test. The spreadsheet uses test data collected on Wardale's "Red Devil" to estimate the amount of water a pound of coal can evaporate in a GPCS firebox. These are the major sources that the author used to base the spreadsheet on. An example of the first sheet of the spreadsheet is attached on the following page.

2-6-6-4 Boiler Designer Type E+A

Double Belpaire Firebox - Combustion Chamber

Max. Boiler Diameter (<105)=	88.1	inches
Grate Area(<162)=	82.31	sq. ft.

Desired Pressure, PSI =	310
Estimated degree of Superheat, °F =	357.94
Boiling Point @ PSI =	424.62
Estimated steam temperatue, °F =	783

	E/A Flue (in.)	Tube (in.)	Length & Diameter
	4.25 / 5.375	3	26.9' -29.3'
815	4 / 5.25	2.75	24.3' -26.8
783	3.75 / 5.125	2.5	22.1' -24.2'
	3.5 / 5	2.25	18.1' -22'
	3.5 / 5	2	16.1' -18'
	3.25 / 4.875	1.75	13.1' -16'
	3.25 / 4.875	1.5	0' -13'

Min. Diameter	78.1	inches	# Allowed	# Used	Tube & Flue Length =	22.0
# of S.H. Elements	Tubes	2.25	0.85	0.0	Tube area ft. =	0.0
197.27	"E" Flues	3.5		167.0	"E" Flue area ft. =	3366.0
	"A" Flues	5		15.0	"A" Flue area ft. =	302.3
Grate Width	91.77	inches	Width Used	91.78	Superheater area ft. =	2367.3
Grate Length	129.14	inches			Superheater elements in.	1.25

Available Steam, #/hr. =		**61,190**	**HP**
Desired Steam, #/hr. =		**61,190**	**78364**
Gain form Hot Well		Gain from Insulation	
107	**107**	**205**	**205**
	Enter value from white in grey cell		

Arch Tubes	4.0	ea.
Arch Tubes dia.	3.5	in.
Range of Arch Tubes	4.4	Avg.
	3.8	4.1
"T" Circulator Area	19.24	sq. in.
"T" Circulator Diameter	4.95	in.

Length of Combustion Chamber & Flues		
Total ft. =	32.08	
	CC length(in.)	Flue length(ft.)
class J 68.4%	119	22.2
class A 71.4%	109	23.0
74.4%	99	23.9
77.4%	87	24.8
Combustion Chamber =		121

GPCS Firebox Info

Primary Air (10% of Grate Area)		
Opening Area	8.2	sq. ft.
Damper between firebox/ashpan both sides, 50% opening		
Length	129.14	in.
Width	9.18	in.
Secondary Air (2.5%)	0.0375	% of Grate Area
Opening Area	3.09	sq. ft.
Damper restricted to 75% of flow		

Estimated Evaporative Heating Surface sq. ft.			
Tube + Flue	3668.3	Sup.heat	
Superheater	2367.3	2370.5	
Firebox	249.1	Based on grate area	
Combustion Chamber	172.3		
Arch Tubes	28.0		
Circulators	19.8		
Direct Heating Surface	469.3	442.0	N&W J
Indirect Heating Surface	3668.3	3673.5	3586.2
Total Heating Surface	4137.6	Max.	N&W J

Input data in grey boxes

Boiler Insulation		Max. (in.)
Inches of boiler insulation	6	6.0

If 0-8-0 trailing=0, drivers=16

Wheel Diameters	
Driver Diameter (inches)	70
Trailing Wheel Diameter (inches)	42

Cylinder Calculator Spreadsheet:

The cylinder calculator is based on the standard tractive effort equation in Ralph Johnson’s book, *The Steam Locomotive*, but continuing on from there to allow the entire DBPull curve of any locomotive to be determined, including those with modernization such as Lempor Exhaust. The spreadsheet uses the work of Richard E. Kirk, who has devised a mathematical formula to determine the power output of a steam locomotive based on the percent cutoff. Also, the equation developed by E. A. Phillipson to determine steam use by a steam locomotive was utilized in rearranged form, along with Kirk’s equation to form the basis of the estimation method. The locomotive resistance used in the estimation method to turn cylinder power into that available on the drawbar was developed by Kiesel of the Pennsylvania Railroad as modified by David R. Stephenson. The estimation method was checked against the N&W Classes A and J, and the estimation method was able to produce DBPull and DBHP curves that were essentially the same as the curves recorded for those two locomotives by the Norfolk and Western Railway. A copy of the first sheet of the spreadsheet is attached on the next page.

70" 2-6-6-4 Freight, Single Expansion, High Power

Enter data in grey boxes

Data Inputs

1	# of Cylinders	4	
2	Boiler PSI	310	PSIG
3	Driver Diameter	70	in.
4	Cyl. Bore	24.4	in.
5	Suggested Stroke (in.)		
6	ATSF 3751 Class	24.4	in.
7	RFIRT 2-10-2's	25.7	in.
8	ATSF 2900 Class	27.9	in.
9	N&W Class J	28.9	in.
10	N&W Class A	30.5	in.
11	PRR Class T1	32.1	in.
12	Cyl. Stroke	32.0	in.
13	Cutoff %	46.582	55.2% @ 0 MPH, 88% Max
14	Boiler Max. Steam lb./hr.	78364	
15	MPH	**20**	
16	Streamlined Y=1, N=0	0	
17	Lempor Y=1, N=0	1	Based on GCRY
18	Draft (In of H2O)	24	
19	Valves, Piston=0, Poppet=1	1	Based on PRR K4 5399 / T1
20	Number of driving axles	6	
21	Number of locomotive axles	9	
22	Number of engine sets	2	
23	Number of tender axles	12	
24	Weight on drivers	459780	Lb.
25	Weight of engine	591780	Lb.
26	Weight of tender(s)	780000	Lb.
27	Resistance Factor	0.60	

PRR, p.19629, Kiesel, Rearranged by Dave Stephenson

Data Outputs

A	Back Pressure	9.6	
B	Clearance Volume %	8%	
C	Exhaust opening %	90.9	
D	"K" Factor (based on rpm)	0.8360	
E	Calculated Max. Cutoff %	46.582	Make input cell 13 equal this once engine can use all boiler steam
F	Steam Consuption #/hr.	78364.0	
G	Weight of engine and tender(s)	1371780	Lb.
H	Total locomotive resistance	5632	
I	Kirk Corection Factor	0.750	
J	Effective Pressure	249.6	
K	RPM	96.039	
L	Wheel Rim Tractive Effort (lb.)	101838	*137000 @ 10 mph*
M	Drawbar Pull (lb.)	**96206**	*21007 @ 75 mph*
N	Drawbar Horsepower	**5131**	
O	**Resistance Factor**		
	1.00 is fabricated frames and friction bearings		
	0.90 is cast frames and friction bearings		
	0.80 is cast frames and roller bearing drivers		
	0.70 is cast frames and roller bearings all axles		
	0.60 is cast frames and roller bearings axles, rods, & motion		
	0.50 is very low rolling resistence: PRR T1 & NYC Niagra		
	By Dave Stephenson		
	Remember to Update Factors Page		

Tender and Running Time Calculator:

This spreadsheet is used to determine the size of the tender needed to have the running time desired for the locomotive. The weight of the tender used must be entered into the Cylinder Calculator Spreadsheet. All three spreadsheets are very closely interrelated, with each affecting the other. This spreadsheet was developed using the capacity versus weight data for Norfolk and Western steam locomotive tenders. It also uses basic arithmetic to make calculations using current coal prices as to costs. From the fourth main spreadsheet, ton-miles per hour are inputted to calculate ton-miles per dollar, and also per ton of coal and gallon of water. A copy of a sheet from the Tender and running time Calculator is attached on the next page.

Freight Tender Arrangement

No. water fills per coal fill =	**2**	
	Ratio	Actual (tons)
Coal	20365	67.9
Water	56701	189.0
Total	77065	256.9

67.90	Coal Tons	
Tender	Auxiliary	2nd Auxiliary
67.90	x	x
13776	32979	0
Capacity (less water reserve)		
122.4	134.6	0.0

Tons Coal	Total:
Gal. Water	46755

	Coal	Water	
	13.34	6.67	Min.
Hours of Running Time =	16.18	8.09	Max.
Total should be at least 12 hours			

Must make water stop with less than: 1403 gals.

256.9	total tons	0.015	% reserve water capacity

Tender Choices

Tender possible ton capacity:			
Axle Loading #	Axles 4 or 6	Aluminum % 0.295 Steel % 0.33	
65,000	6		
Tender	Weight 195	Capacity 137.5	Empty 57.5
6 axle	75,000	65,000	55,000
4 axle	71,500		

Auxiliary Tender:		
Axle Loading #		Axles 4 or 6
65,000		6
Weight 195	Capacity 137.5	Empty 57.5

2nd Auxiliary Tender:		
Axle Loading #		Axles 4 or 6
0		0
Weight 0	Capacity 0.0	Empty 0.0

Enter data in grey shaded boxes

Bottom Ash Storing Needs		
Hours:	Coal / Hour	5.09
54	16.50	tons
0.5	tons- for the system	
549.8	cubic feet ash @ (60#/ft.^3)	
11.40	Tons ash b4 last coal fill	

Tonnage and Train Speed Calculator:

This spreadsheet is the Modified Davis Equation. David R. Stephenson gave the author the equation, and Ralph Johnson of the Baldwin Locomotive Works references it. The data to drive the equation is from the DBPull curves of the locomotives tested, both modern steam and diesel as well as the grade and curvature characteristics of the areas of the Norfolk and Western, now Norfolk Southern. The spreadsheet uses a calculation developed by Mr. Stephenson and the author to calculate the exact top, or balance speed of the locomotive and train combination entered into the spreadsheet. Again, data from the 1952 N&W steam versus diesel test was used as the basis for determining average speeds to find the average ton-miles per hour. The 1952 data was adjusted to current conditions since the train weights, lengths and acceleration rates had changed. The tonnage ratings for the diesel locomotives came from Norfolk Southern Employee Timetables, while the Modern Steam Locomotive tonnage ratings were based on the methodology used by the N&W to create tonnage ratings for its steam locomotives. The ton-mile per dollar calculation is the way that the comparisons in this paper were developed. The comparison of steam versus diesel will be explained later. First, the way the diesel numbers were arrived at will be explained. An example of this spreadsheet is attached on the next page.

Total weight of locomotive & tender =	685.89	tons
70" 2-6-6-4 HP Bulk	0.058	% Grade
Tractive effort of engine =	137,000	Lb.
Maximum drawbar horsepower=	5,437	@30mph

Speed	0	5	10	20	30	40	50	60	70	75
Trailing tons	16,578	16,578	16,578	16,578	16,578	16,578	16,578	16,578	16,578	16,578
No of cars	116	116	116	116	116	116	116	116	116	116
No. of axles/car	4	4	4	4	4	4	4	4	4	4
Car frontal area (SF)	142.1	142.1	142.1	142.1	142.1	142.1	142.1	142.1	142.1	142.1
Weight/axle (tons)	35.75	35.75	35.75	35.75	35.75	35.75	35.75	35.75	35.75	35.75
Ruling Grade	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Curves (degrees)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Drawbar pull, level track	132,637	132,375	132,076	96,206	67,958	50,940	39,922	31,259	23,965	21,007
Drawbar Horse Power, level track		1765	3522	5131	5437	5434	5323	5002	4474	4201
MODIFIED DAVIS EQUATION	Reflects roller bearings, welded rail, typical of the 1970's to present									
Resistance, level (lbs/ton)	1.16	1.22	1.31	1.56	1.91	2.35	2.90	3.55	4.29	4.70
Resistance, curves (lbs/ton)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Resistance, grade (lbs/ton)	1.16	1.16	1.16	1.16	1.16	1.16	1.16	1.16	1.16	1.16
Total resistance (lbs/ton)	2.32	2.38	2.47	2.72	3.07	3.51	4.06	4.71	5.45	5.86
Total train resistance	38,452	39,486	40,933	45,062	50,837	58,260	67,330	78,048	90,412	97,212
Grade resistance, locomotive	796	796	796	796	796	796	796	796	796	796
DB Pull reserve	93,389	92,093	90,348	50,349	16,325	-8,116	-28,204	-47,584	-67,242	-77,001

Portsmouth-Columbus	
16,578	tons
36.7	top speed
32.5	avg. speed
0.8866	%
539138	ton miles/hr.
Medium - Low Grade	
0 deg	.058 avg

Interpolation based on DB Pull reserve	
56,591	drawbar pull/train resistance
5,535	drawbar HP
36.7	mph
0.6679	

FreightCar America AutoFlood II ™ Coal Cars (Loaded-286,000)			
Width	10.7	feet	
Height	13.3	feet	
Weight	143	tons	

Diesel Locomotive Calculations:

As stated above, the tonnage and train speed calculator was used to determine the ton-miles per hour for diesels as well as steam. The DBPull curves for the diesel locomotives are composites based on EMD company data. The actual DBPull and DBHP curves are closely guarded by GE and EMD and are not released in their entirety to the public, only the starting and continuous tractive effort ratings. The DBPull and DBHP curves were checked against the curves used in the Berkeley Software Simulation model, but since the model uses wheel rim values, the comparison was not very helpful. The model, along with EPA sources, accounts for the diesel fuel consumption data used in this paper. The peak thermal efficiencies of the diesel locomotives were calculated using peak DBHP and fuel consumption.

Comparison Calculations:

Many spreadsheets were used in the calculations of the comparisons between the Modern Steam Locomotive and the Diesel Electric Locomotive. Below are descriptions of the calculations the author made for this paper.

The comparison of the cost of coal and railroad diesel fuel was made on a BTU basis for comparison purposes. This used coal costs from the Department of Energy, Energy Information Administration, as all other coal costs used in this paper. The diesel fuel cost came from the Surface Transportation Board. This was the fuel cost of each Class I Railroad.

The thermal efficiency comparison was made between the current Diesel Locomotives and the Modern Steam Locomotives proposed in this paper. It uses very standard calculations, pairing the calculated thermal efficiencies with fuel costs to come up with the most basic method of calculating the fuel cost savings for the modern steam locomotive.

A comparison was also made on fuel consumption at idle. While the fuel use of diesel locomotives at idle is well documented, the idle fuel use of a Modern Steam Locomotive does not have the same amount of data associated with it. The fuel use for the steam locomotive is an average based on the experiences of a former locomotive fireman coupled with the fact that Roger Waller's new build rack locomotives can maintain steam pressure in their boilers over night with their oil burners off, due to high performance boiler insulation.[108]

The comparison on running time consisted of the average fuel use per hour compared with the fuel capacity, to determine the average number of hours of range. The fuel tank capacities for the diesel locomotives came from EMD and *Trains Magazine* with some of the capacities coming from *Wikipedia* also. The steam locomotive capacities were based on the calculations of the author.

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[108] Andre Chapelon, *La Locomotive A Vapeur*, trans. George W. Carpenter, C.Eng., M.I. Mech.E. (Great Britain: Camden Miniature Steam Service, 2000), 621

The locomotive fleet data came from two sources. The total number of locomotives owned or leased is published on a railroad-by-railroad basis for each year by the Surface Transportation Board. The author used locomotive rosters detailing the locomotives owned by each railroad from a rail fan website: http://www.thedieselshop.us/ This site had the best available data and was adjusted based on the government data on the total number of locomotives. Because insufficient data was available, some assumptions had to be made by the author as to what locomotives were used for certain purposes based on the type of locomotive instead of actual use statistics.

The steam locomotive infrastructure costs utilize the cost incurred by the Norfolk and Western Railway to procure these facilities in the late 1940’s or early 50’s. The costs are from Authorizations for Expenditures, Presidential Authorization and other N&W company documents preserved at the Norfolk and Western Historical Society Archives in Roanoke, VA. The costs were updated using the Producer Price Index related to machinery maintained by the Bureau of Labor Statistics. The assumptions concerning the placement and layout of the facilities are more based on the author’s knowledge of the railroading industry since there are no real sources that relate to the design and placement of facilities in the current time.

The heart of the comparisons in this paper is the fuel cost per ton-mile comparison. This comparison calculated ton-mile per dollar figures utilizing each railroad’s fuel price, locomotive types and the four grade sections and three train types, to determine the average number of ton-miles per dollar that can be created on a railroad-by-railroad basis for diesel locomotives. This is then compared to similar data for steam locomotives, taking in to account what is the most likely coal used based on operating territory and locomotive use based on assumed roster.

The only useful breakdown in the fuel use data given by the Surface Transportation Board was dividing the fuel use between switching and freight. In the freight category, educated assumptions had to be made using STB train operating data to determine the split between Bulk, Intermodal and Local freight types.

The Amtrak data relating to fuel use and costs and passenger car dimensional data used for performance characteristics modeling was provided by Amtrak. The author is very thankful for this data. It allowed a breakeven point to be established since there is no public source for this data.

All water costs came from the USDA Farm and Ranch Irrigation Survey. The boiler treatment costs were provided by Martyn Bane of PortaTreatment.com.

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Time Line of Steam Development[109]

The following provides a brief overview of steam locomotive development through the present day (most dates approximate).

1800's:

- February1804- Richard Trevithick produces Penydarren, the first steam locomotive to run on rails

1830's

- First practical steam locomotives developed

1850's

- Steam locomotive designs begin to be standardized

1890's

- First engines equipped with trailing trucks to allow wider, deeper fireboxes introduced

1900's

- Beyer-Garratt type introduced (boiler located between the two engine sets with the coal bunker over the rear engine and the water tank over the front engine)
- Mallets enter production (compound, steam used in rear engine then again in front engine, boiler over both engines)

1910's

- Practical locomotive superheater introduced
- Practical oil-fired engines developed

1920's

- Practical feedwater heaters and stokers introduced
- Lima Superpower demonstrator "A-1" built
- Cast steel locomotive engine beds introduced
- Simple articulated locomotives introduced

1930's

- Timken “Four Aces” built, first roller bearing equipped steam locomotive, built (revolutionizing running gear maintenance)
- Andre Chapelon, the grandfather of Modern Steam, achieves record steam efficiency in France

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[109] From “The Timeline of Steam Development,” with author’s additions as footnoted, http://www.trainweb.org/tusp/back.html

- Practical diesel-electric locomotives introduced
- Duplex-drive steamers introduced in U.S. (Pennsylvania Railroad S1 and Q1)

1940's
- WWII freezes steam development in most countries
- Franklin introduces poppet valves in the U.S.
- Will Woodard, Lima engineer behind "Superpower", dies
- Detailed steam/diesel comparison test on New York Central shows minimal cost difference in modern steam and new diesels
- Chapelon constructs 242A.1, 5,500 IHP from a locomotive originally producing 2,800 IHP[110] and 160A.1
- Lima 4-8-6 demonstrator proposed but not built
- Construction of next generation of French steam started, then killed in favor of electrification
- Last commercially manufactured U.S. steam locomotives built
- L. D. Porta, the father of Modern Steam, begins experiments with gas-producer firebox, rebuilds first steam locomotive the Argentina at the age of 27[111]
- Radical steamer "Leader" tested in England
- Wide-spread dieselization begins in U.S. and elsewhere

1950's
- Last privately manufactured U.S. steam locomotives built
- Steam/diesel comparison tests on N & W are a draw
- Advanced Steam Turbine Electric (Jawn Henry) tried on N & W
- Specialty steam parts manufacturers cease production
- Most U.S. mainline steam ends

1960's
- Last mainline steam in U.S. ends
- Mainline steam ends in England, many other countries
- Porta develops gas-producer combustion system (GPCS)& other refinements

1970's
- Steam cutbacks around the world
- Chapelon dies
- Mainline steam ends in France (1974)
- "Oil crisis" causes resumed interest in coal usage

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[110] Andre Chapelon, *La Locomotive A Vapeur*, trans. George W. Carpenter, C.Eng., M.I. Mech.E. (Great Britain: Camden Miniature Steam Service, 2000), 340

[111] Argentina, http://www.martynbane.co.uk/modernsteam/ldp/argentina/arg.htm
and L.D. Porta Obituary, http://www.martynbane.co.uk/modernsteam/ldp/porta-biog.pdf

- David Wardale oversees steam improvements in South Africa building the Class 26 called the Red Devil, reduced coal consumption by between 30% and 60% and water consumption by between 20% and 45% which corresponds to an increase in thermal efficiency of between 43% and 150%[112] over the 25NC from which it was built

1980's
- China continues steam locomotive production
- Numerous locomotives restored to excursion service in the U.S.
- Steam resurrected in Zimbabwe
- ACE 3000 Project Announced
- Other "new steam" projects announced
- First ACE attempt dies
- ACE resurrected
- Second ACE attempt dies
- ACE fails to interest China in production
- Steam resurrected in Sudan (1986)
- Regular mainline steam ends in South Africa

1990's
- Chinese announce plans to end steam
- Mainline steam ends in India
- Many restored U.S. excursion steamers moth-balled
- New steam locomotives built in Switzerland
- Porta works to develop steam in Cuba
- New steam locomotives proposed for Australia
- "A-1" 4-6-2 under construction in England; other full-scale reproduction steam locomotives proposed

2000's
- 5AT Project begun in the UK (David Wardale)
- L. D. Porta dies
- First Lempor installation in U.S. (Mt. Washington Cog Railway, Nigel Day)
- More Lempor installations in U.S. (Grand Canyon Railway and UP 3985, Nigel Day)
- Efforts to re-introduce steam on the RFIRT (Shaun McMahon)

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[112] David Wardale, *The Red Devil and Other Tales from the Age of Steam* (Scotland: Highland Printers, 2002), 217

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