Transitioning to a Zero or Near-Zero Emission Line-Haul Freight Rail System in California: Operational and Economic Considerations

Final Report

Prepared for:

State of California Air Resources Board

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Spring 2016

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Summary

The objective of this research, commissioned by the ARB, is to identify and examine the operational changes and economic challenges and opportunities associated with a transition from conventional diesel-electric to zero or near-zero emission line-haul freight rail operations in California.

To accomplish this objective, the research presented in this report assesses and compares the operations and economic impacts of different zero or near-zero emission locomotive technology on line-haul mainline freight railroads. For the purposes of this study, mainline line-haul freight operations are defined as trains operating on Class 1 railroad mainlines directly between origin and destination terminals.

There are two different deployment scenarios analyzed in this report:

- A South Coast Air Basin (SCAB) deployment scenario, with a smaller captive fleet of advanced technology freight locomotives.
- A North American deployment scenario, with a national fleet of advanced technology locomotives.

In the near- to mid-term, the research showed that the North American deployment of Tier 4 diesel-electric locomotives with after-treatment and onboard battery storage technology offers the best economics of any alternatives studied in this report. While this technology is not yet commercialized, prototypes of the various systems exist and have been demonstrated in service.

In the longer-term, the Solid Oxide Fuel Cell (SOFC) gas turbine locomotive with liquefied natural gas (LNG) fuel appears to offer potential for North American deployment within the larger locomotive fleet. However, further research is needed to determine if it is feasible to construct a 4,400 horsepower freight interstate line haul locomotive powered by SOFC-gas turbine technology.

The research also showed that North American deployment of these two locomotive technologies offer improved economics relative to operation with exchange points in the South Coast Air Basin or the state of California. Although North American deployment requires the purchase of more alternative technology locomotives, they realize fuel savings over longer train runs and are not hindered by the capital cost, train delay, and lost revenue associated with locomotive exchange points.

Locomotive Technology

SCAB Deployment Scenario: For the SCAB deployment scenario, this research considered six different locomotive technologies:

- Tier 4 diesel-electric with after-treatment
- Liquefied natural gas with fuel tenders (Diesel-LNG)
- Diesel-electric with battery tenders and onboard battery storage
- Solid-oxide fuel cell (SOFC)
- Electric traction from catenary electric power supply
- Linear synchronous motors (LSM)

This scenario is discussed in Chapters 1-12.

North American Deployment Scenario: For the North American national fleet deployment scenario, two technologies were considered:

- Tier 4 diesel-electric with both after-treatment and onboard batteries, and the
- Solid Oxide Fuel Cell with Gas Turbine (SOFC-GT), which was assessed in both the SCAB captive fleet and North American deployment scenarios.

This scenario is discussed in Chapter 13.

For each locomotive technology, through literature review and consultation with industry experts, the study team examined the potential energy and emissions reductions; economic and operational considerations; and current state of development. Safety of the new locomotive technology is also critical for adoption by the railroads.

It was found that there is no “off the shelf” zero or near-zero emission locomotive technology for North American line-haul freight service. All of the studied locomotive technologies require additional research, development or commercialization before they can be implemented in line-haul service:

- Line-haul Tier 4 diesel-electric locomotives entered production in 2015 but locomotives with additional after-treatment to further reduce emissions are still in experimental stages of development. It is not known how far below Tier 4 levels emissions can be reduced through a combination of further diesel combustion process refinements and additional after-treatment.
- Diesel-LNG locomotives are still in demonstration and test service and the ability of diesel-LNG to achieve additional emissions reductions below Tier 4 levels is not known. Although prototypes exist, standards for LNG tenders are still under development.
- Battery tenders for line-haul freight service are a concept with no working prototypes.
- There are no working SOFC line-haul locomotive prototypes. Other types of fuel cell locomotives have only been demonstrated in switching service.
- Further development is required to design, test and commercialize a modern line-haul electric freight locomotive tailored for operation in the United States.
- Although applied to transit, LSM has not been demonstrated for freight service and it is not known if the technology has the capability to handle the length and weight of typical freight train consists.

It was determined that the most likely implementation scenario for any of the above locomotive technologies within the South Coast is operation of a captive fleet of new technology locomotives within the basin and conventional diesel-electric locomotives outside the basin. Trains entering and exiting the basin must exchange new technology and conventional diesel-electric locomotives at a locomotive exchange point facility near the boundary of the air basin.

Line-Haul Freight Interoperability

The North American Class 1 railroads have continually worked to remove barriers that prevent the seamless movement of freight. Operation with exchange points and a captive fleet in the South Coast reintroduces those barriers. Based on experience with captive fleets and lack of interoperability in Europe, operation with exchange points in the South Coast is likely to result in: increased operating costs, delays and network disruption due to locomotive exchange; decreased locomotive utilization, increased locomotive fleet size and the capital cost of establishing extra regional alternative-technology locomotive maintenance, servicing and fueling facilities. According to the European experience, the net result of these outcomes will likely be a decrease in freight rail market share.

Line-Haul Freight Operations

UP and BNSF operate approximately 130 line-haul freight trains in the South Coast basin each day. At any moment, over 2,000 locomotives from a much larger pool of nearly 10,000 locomotives are allocated to operating trains that originate, terminate or transit the South Coast basin. Based on detailed analysis of STB waybill data, trains originating or terminating in the South Coast basin transport approximately 99 million tons of freight each year. Train data derived from the waybill sample and route data from railroad engineering track charts were used with a train performance calculator to determine the energy consumption of each train operating in the South Coast. Each year line-haul freight train operation in the South Coast consumes approximately 435,000 MWh of energy at the locomotive wheel.

Emissions Benefits

Since this analysis considers local emissions, the three technologies that utilize electricity as an energy source are considered to be zero-emissions, resulting in 100-percent reduction of all criteria pollutants. Over 743 million pounds of CO_2 emissions are potentially eliminated each year within the South Coast basin by any of these three technologies.

Implementation of Tier 4 diesel-electric locomotives with after-treatment does not change CO_2 or CO levels. Although 80 to 90 percent reductions below Tier 2 levels can be achieved, decreases in the emissions of the other criteria pollutants relative to Tier 4 levels will depend on the effectiveness of the exact after-treatment technologies employed.

The diesel-LNG locomotives decrease CO_2 emissions due to the lower carbon content of LNG but increase CO due to decreased fuel efficiency. Approximately 53 million pounds of CO_2 emissions are potentially eliminated each year within the South Coast basin by diesel-LNG technology.

The efficiency of the SOFC-gas turbine with LNG allows this technology to provide the greatest emission benefits of the liquid fuels. The SOFC-gas turbine has the potential to eliminate 423 million pounds of CO_2 emissions each year, representing a 57-percent reduction (Figure S-1 and Figure S-2).

Based on ARB estimates, the Tier 4 diesel with after-treatment would provide an estimated reduction in NOx and PM emissions, beyond the Tier 4 baseline, of up to 75 percent (i.e., Tier 4 NOx = 1.3 to 0.3 g/bhp-hr) for South Coast and North American deployment.

For the North American deployment scenario (Table S.1), a Tier 4 diesel with after-treatment and on-board batteries is assumed to currently be able to reduce fuel consumption by 15 percent. In the future, ARB staff believes by as early as 2025, advances in onboard battery technology could reduce diesel fuel consumption by up to 25 percent. This latter level of fuel reduction could further reduce NOx and PM emissions, beyond the Tier 4 baseline, by up to a total of 85 percent (i.e., Tier 4 NOx = 1.3 to 0.2 g/bhp-hr).

Table S.1: Potential Percent Emissions Reduction Control Levels from Tier 4 Baseline for North American Deployment

Technology	NOx Reductions	PM Reductions
SOFC-GT w/ LNG	50	50
Tier 4 Diesel w/ After-T	75	75
Tier 4 Diesel w/ After-T & Battery	85	85

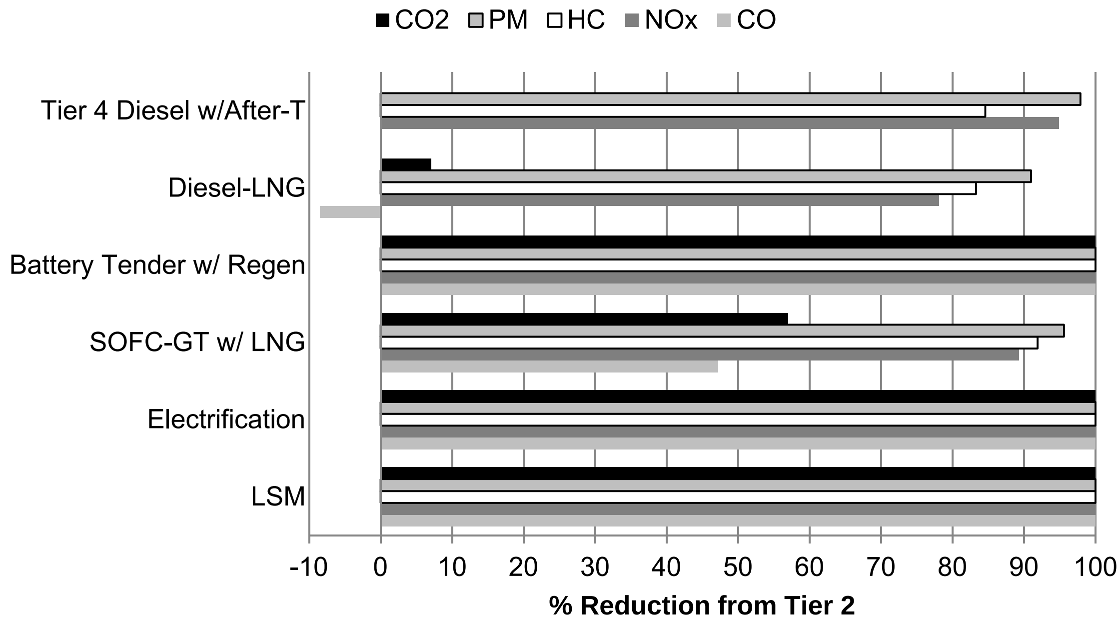

Figure S-1, Potential reduction in South Coast line-haul locomotive emissions from Tier 2 baseline

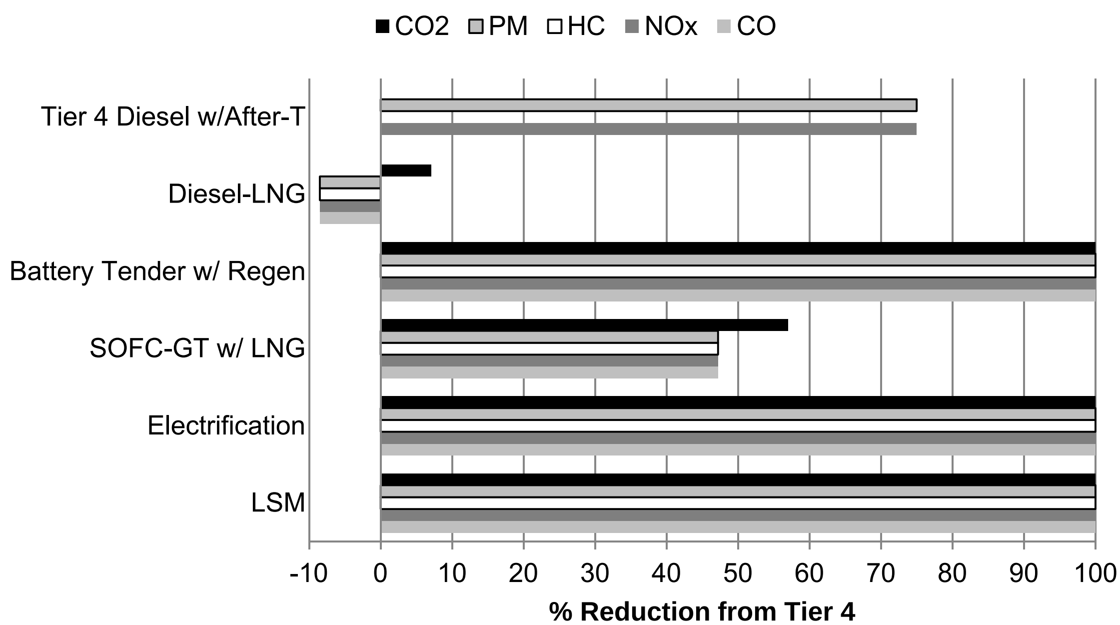

Figure S-2, Potential reduction in South Coast line-haul locomotive emissions from Tier 4 baseline

Locomotive Costs

Operation of a captive locomotive fleet within the South Coast requires 570 new technology locomotives. Depending on the technology, these locomotives are supported by 364 LNG tenders or 1,613 battery tenders. Unit costs of the various locomotive technologies are summarized below (Table S.2).

Table S.2: Assumed Capital Cost of Locomotives and Tenders ($ million/unit) for South Coast Scenarios (and North American Deployment Scenario)

Technology	Locomotive	Tender	Notes
Conventional Tier 4 Diesel	3.0	--	Current Tier 4 baseline cost
Tier 4 Diesel w/After-T	3.5	--	
Diesel-LNG	2.7	1.0	0.64 tenders per locomotive
Battery Tender w/ Regen	3.0*	11.0	2.83 tenders per locomotive
SOFC-GT w/ LNG	5.0	1.0	0.64 tenders per locomotive
Electrification	5.0	--	
LSM	unknown	--	unknown
Tier 4 Diesel w/After-T & Battery	4.0	--	For North American deployment (Section 13)

*Can also retrofit existing locomotives (if available) at a capital cost of $0.2 million per unit.

Purchase cost of new locomotives and tenders, and cost of modifications to conventional locomotives, for the captive new technology locomotive fleet within the South Coast ranges from $1.7 to $19.0 billion depending on the locomotive technology.

The installed cost of the overhead catenary traction power distribution system for electrification is $31.5 billion and LSM infrastructure is $12.6 billion. The study assumes that the capital cost of infrastructure to liquefy LNG is included in the delivered cost of LNG from third-party suppliers.

The construction cost of new locomotive shop facilities for new technology locomotives within the South Coast ranges from $109 to $285 million depending on the locomotive technology.

Annual incremental locomotive maintenance expense relative to the Tier 4 baseline ranges from a decrease of $14 million per year for electrification to an increase of $62 million per year for SOFC locomotives. However, electrification requires an additional $18.9 million per year for catenary maintenance.

Not enough is known about potential freight applications of LSM to develop complete cost data.

Exchange Point Operations and Capital Costs

Based on full-scale field trials, depending on the locomotive configuration, locomotive exchanges are likely to take between 60 and 222 minutes at the locomotive exchange points. The number of tracks at each exchange point is determined from the anticipated dwell time and peak train flow rate. The peak train flow rate is the average train flow rate multiplied by a factor of 2.5.

Construction of six appropriately-sized exchange facilities for the South Coast basin incurs \$824 million in capital construction cost, including all sitework, track, support facilities and right-of-way. Depending on the locomotive technology, an additional \$39 to \$353 million in capital cost is required to establish locomotive and tender servicing and fueling facilities, Crews to operate the exchange points correspond to an annual expense of \$61 million.

Exchange Point Delay and Mode Shift

Trains operating through locomotive exchange points are anticipated to experience between 1.59 and 4.29 hours of delay depending on the train type. The annual direct cost of train delay encountered at the South Coast basin locomotive exchange points is \$112 million per year. This cost accrues from inefficiencies in crew, railcar and locomotive utilization created by delays at the exchange point.

A mode shift model was used to evaluate the potential for time-sensitive freight in the South Coast to shift to trucks when subject to delay at the exchange points. According to the model, each year, approximately 12.5 million tons of freight would move on trucks that formerly moved on rail. Due to this freight mode shift to truck associated with the delay at the locomotive exchange points, it is estimated that the railroads have the potential lose approximately \$1.1 billion in revenue from intermodal and manifest traffic each year.

The shift of freight from rail to truck reduces the emissions benefits of the alternative locomotive technologies relative to Tier 2 (Figure S-3) and Tier 4 baseline levels (Figure S-4). Technologies that showed emissions reductions before mode shift may show increases in emissions (negative reductions) when the induced truck emissions are included in the calculations.

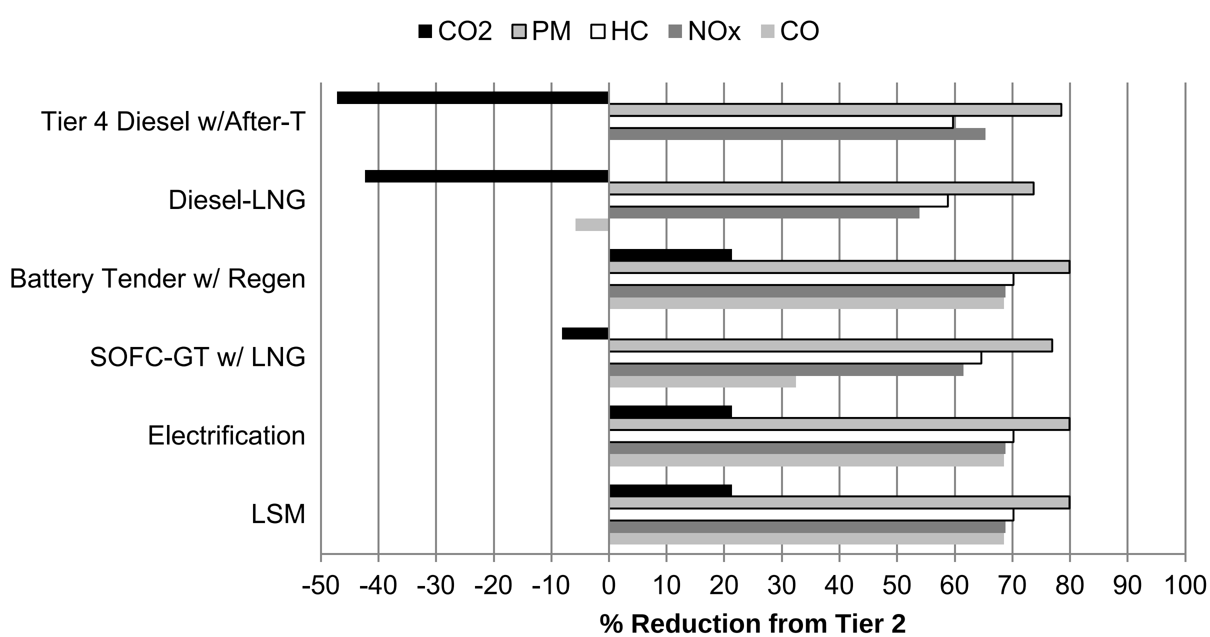

Figure S-3, Potential reduction in South Coast line-haul locomotive emissions from Tier 2 baseline after mode shift to truck

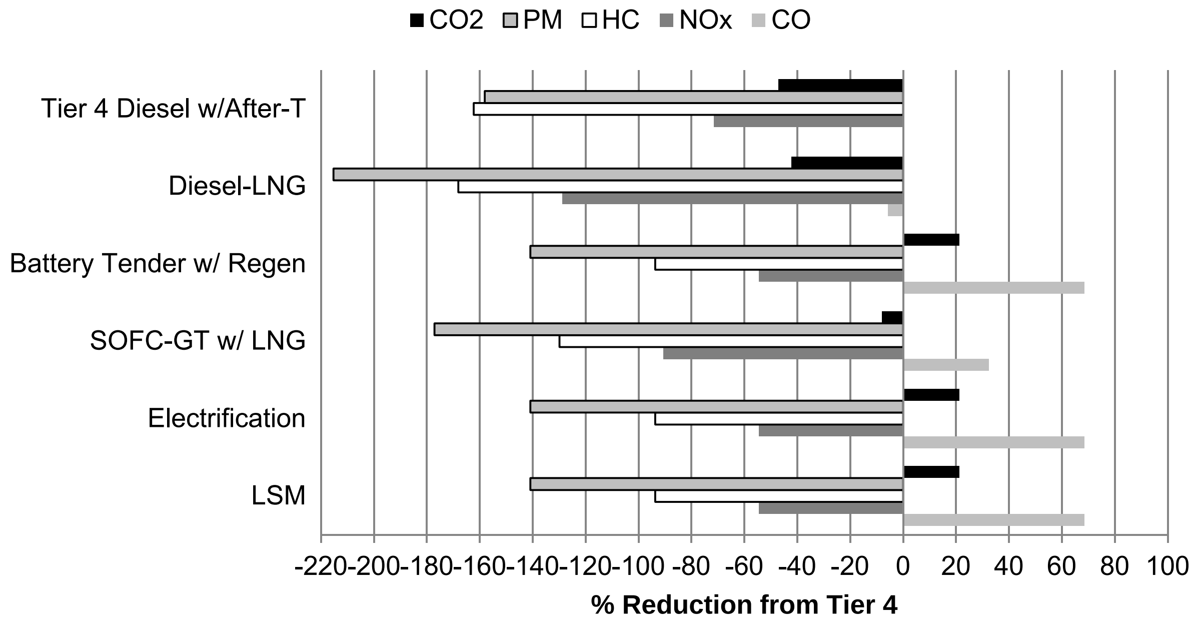

Figure S-4, Potential reduction in South Coast line-haul locomotive emissions from Tier 4 baseline after mode shift to truck

Fuel and Energy Supply Cost Reductions

The alternative locomotive fuel consumption from the train performance simulation was used to calculate the expected energy supply cost of line-haul mainline freight locomotive operations between terminals within the South Coast air basin and the locomotive exchange points (Figure S-5). The Tier 2 and Tier 4 diesel fuel costs serve as baselines for cost reductions. The diesel-LNG locomotive increases fuel cost due to decreased fuel efficiency and the small difference in the price of diesel and LNG. The efficiency of the SOFC-gas turbine with LNG provides the lowest energy supply cost of the liquid fuels, saving $117 million per year. The cost of this operation is nearly comparable to electrification and the LSM.

Unlike electrification and LSM, the limited range of the battery tender locomotive requires it to operate in diesel mode between the air basin boundary and the locomotive exchange point. The diesel fuel consumed during this portion of the trip increases annual energy costs relative to the other electric locomotive technologies. While electrification and LSM reduce energy costs by 52 percent or $116 million per year, the battery tender only exhibits an 18-percent reduction or $41 million per year.

Total Costs

To provide an overall measure of the economic impact of each alternative locomotive technology scenario, a present value cost calculation is performed over the 15-year initial mainline service life of a line-haul freight locomotive (Figure S-6). Electrification has the highest present value cost at $44.3 billion. Due to the cost of battery tenders, the battery tender locomotives have the second-highest present value cost at $30.0 billion. There is insufficient information available on the LSM technology to provide complete cost data.

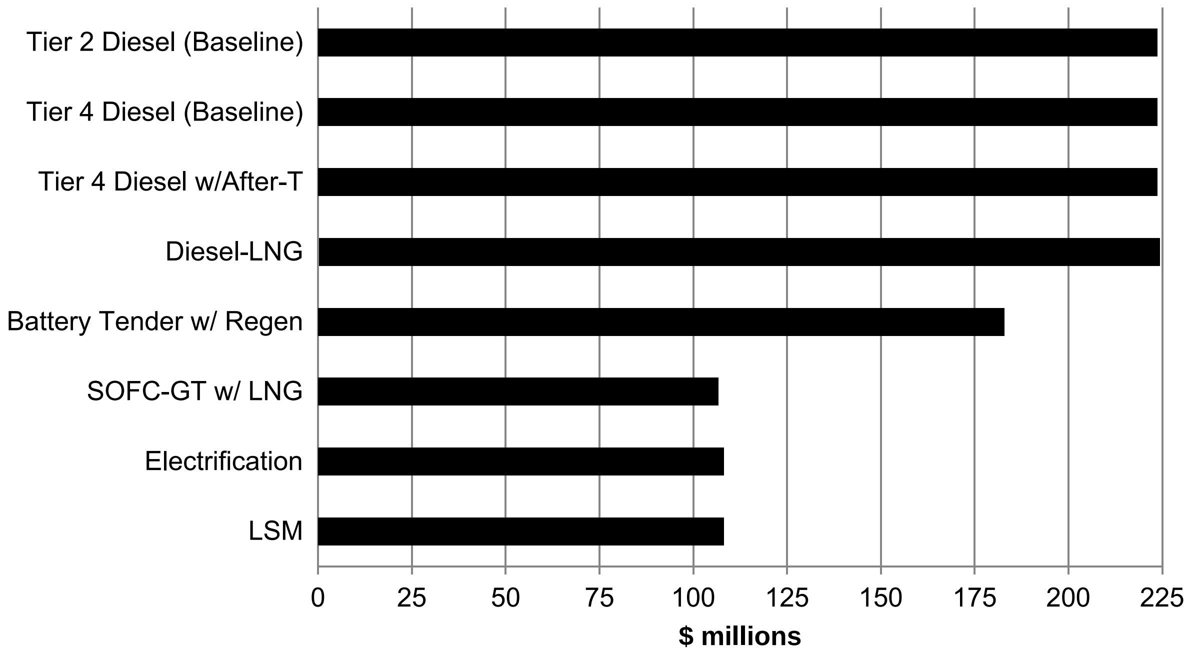

Figure S-5, Annual locomotive energy/fuel cost to South Coast exchange points

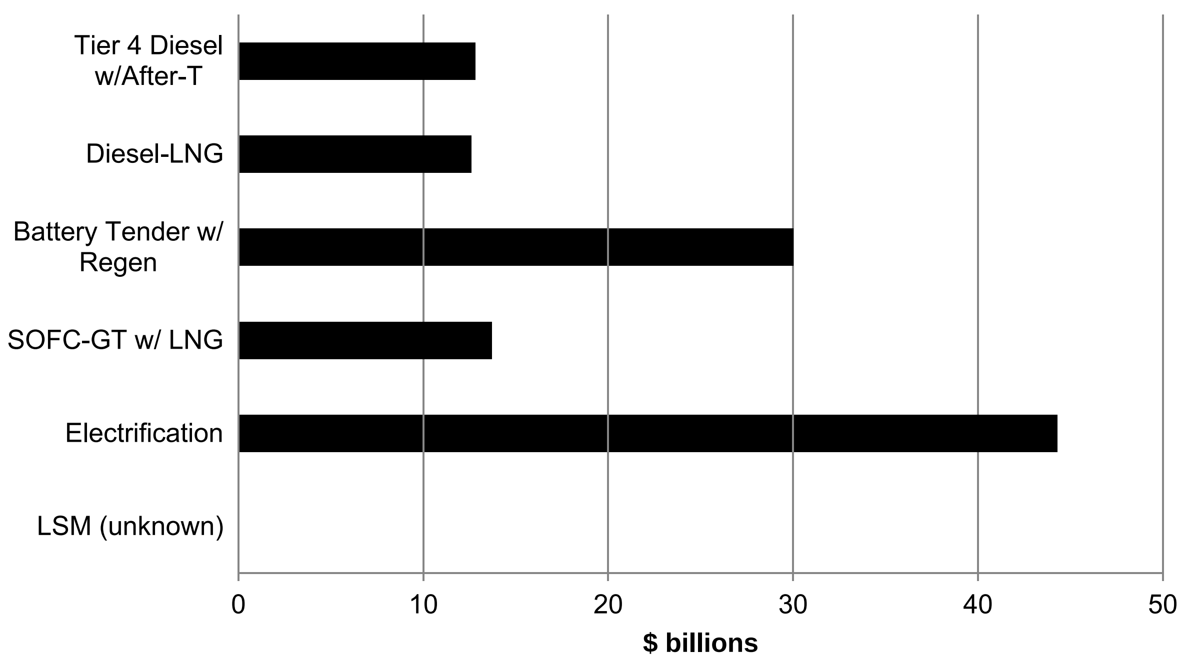

Figure S-6, Total of capital and present value costs for the South Coast scenarios

Interestingly, the three liquid fuel locomotive technologies exhibit a trade-off between total capital and present value of annual non-capital costs. Between the three liquid fuel locomotive technologies, SOFC locomotives have the highest capital cost but lowest annual cost, diesel-LNG has the lowest capital cost but highest annual cost, and Tier 4 with after-treatment falls in the middle for both capital and annual cost. This finding results in the range of total present value cost ($12.6 to $13.7 billion) narrowing compared to the range of capital costs described earlier.

Overall Findings of the Captive Fleet Scenarios

None of the studied locomotive technologies for the South Coast air basin captive fleet scenarios can generate fuel and energy cost reductions large enough to offset increases in annual non-capital costs. This is the case even when mode shift is not considered in the calculation of annual costs. When mode shift is considered, the potential for $1.1 billion in lost revenue each year dominates the annual cost calculation. When combined into a net present value calculation over 15 years, the lost revenue also dominates the economics of the three liquid fueled locomotive technologies even though the locomotive capital costs range from $1.7 to $3.2 billion.

Only for electrification and battery tender locomotives is the revenue loss not the dominant factor in the total net present value calculation. This is due to the high capital cost of both of these technologies at $20.5 billion for battery tenders and $35.5 billion for electrification.

The total present value cost of each technology can be weighed against its relative percent emissions reduction from Tier 2 and Tier 4 levels to assess its performance. Based on the calculated percent reduction in emissions per billion dollars invested, the SOFC-gas turbine locomotive with LNG has the potential to yield the best emissions reduction performance compared to the other locomotive technologies. However, the emissions produced by trucks carrying freight shifted from rail limits the potential benefits of all of the reduced-emission locomotive technologies, even those that are locally “zero emissions”.

North American Deployment Scenarios

To address the primary cost drivers of the captive fleet scenarios, two locomotive technologies were selected for analysis within the context of a North American deployment strategy: Tier 4 diesel-electric with after-treatment and onboard battery storage, and the SOFC-gas turbine locomotive with LNG. North American deployment of either technology appears to offer improved economics relative to operation with exchange points. Although North American deployment requires the purchase of more alternative technology locomotives, they can realize fuel savings over longer train runs and are not burdened by the capital cost, train delay and lost revenue associated with locomotive exchange points. North American deployment of Tier 4 diesel-electric with after-treatment and onboard battery storage technology appears to offer the best economics of any alternative in this study. In the longer-term, the SOFC-gas turbine locomotive with LNG appears to offer potential but requires extensive research and development.

The primary drawback of the North American deployment scenario is the required fleet size of approximately 6,000 units. Due to the capital cost involved and manufacturing constraints, it is likely that the required locomotives would be phased in over time. In this study it is assumed that full emissions benefits are not obtained for 15 years.

In a North American deployment scenario, the line-haul locomotive assignment process must be adjusted to ensure South Coast trains enter the air basin with reduced-emission locomotives. Poor fleet management may result in missed locomotive connections and train delay at terminals, adding cost and potential for shift of freight to other modes.

Conclusions

For the SCAB deployment scenario, with potential train delays and mode shifts, the above findings emphasize the importance of examining operational factors when evaluating new locomotive technology to reduce the emissions of line-haul freight rail in California. For several of the technologies, it is not the equipment capital cost and potential fuel savings that control the economic feasibility of the technology, but instead other factors that arise from the difficulty of integrating new locomotive technology in captive service within a highly interoperable rail network.

The economic feasibility of new locomotive technology is sensitive to the level of service demanded by shippers, the cost of train delay and potential shift of freight to other modes. This finding suggests that to properly evaluate alternatives, improved understanding of these factors is required beyond that found in the literature or developed through this study.

The results of this study are limited in part by the information available on the potential of each technology and its current state of development. To provide a better economic analysis, further research needs to be conducted to determine the exact potential benefits of each locomotive technology:

- For Tier 4 locomotives with after-treatment and diesel-LNG, this means conducting emissions testing of prototype and production units under representative field conditions to determine how much additional reduction beyond Tier 4 levels can be achieved by these technologies. Diesel-LNG tests should also quantify the amount of methane leakage expected during refueling.
- For the SOFC locomotive and LSM, working prototypes need to be developed to demonstrate the feasibility of each technology to provide the power and tractive effort required for line-haul freight operations.
- For the battery tender, working prototypes need to be developed to demonstrate the potential range and service life of the batteries under line-haul freight service conditions.

For the North American deployment scenario, the two locomotive technologies assessed (i.e., Tier 4 with after-treatment and on-board batteries and a Solid Oxide Fuel Cell with Gas Turbine) offer improved economics relative to operation with exchange points in the SCAB deployment scenario. See Conclusions in Chapter 14 for more detailed information.

1 Introduction

This research identifies and examines the operational and economic challenges and opportunities in transitioning to near-zero emission line-haul freight rail operations in California.

1.1 Background

The California Air Resources Board (ARB) believes that transitioning to a zero or near-zero emission freight transportation system is a necessary step in meeting the long-term air quality and climate change goals of California. As a significant component of the freight transportation system, rail transportation must be actively involved in this transition.

Railroads in California operate 6,842 miles of track, the third largest state rail network behind only Texas and Illinois, and moved 6,882,659 carloads of freight in 2009 (AAR, 2010). In 2011, the two major Class 1 railroads and 23 local, switching and terminal railroads in California originated 58.7 million tons of freight in the state, with 53% of that total being intermodal traffic, and terminated 97.4 million tons of freight. Intermodal traffic in particular is important to California, and has major national significance as well. The San Pedro Bay ports are the fifth busiest in the world and by far the most important on the U.S. West Coast. At these ports, along with Oakland and others, large volumes of freight are transloaded from ships to trains destined for locations throughout the U.S. The two major freight railroads employ approximately 9,000 people in California, representing 5.3% of all railroad employees and the fourth highest state total (AAR, 2010). Freight rail activities represent a substantial element of freight transportation activity in California and the nation, with corresponding impacts on air quality. Potential changes in rail operations in California have significant implications for the state and the nation.

1.2 Objective

The objective of this research, commissioned by the ARB, is to identify and examine the operational changes and economic challenges and opportunities associated with a transition from conventional diesel-electric to zero or near-zero emission line-haul freight rail operations in California.

This study is one component of ongoing ARB efforts to determine how the rail transport mode can evolve to meet air quality goals. ARB has previously implemented programs to reduce emissions at freight rail yards. Previous ARB studies have examined passenger rail electrification and taken a broad look at the potential for different locomotive technologies and alternative fuels to reach zero or near-zero emissions. This research project assesses the feasibility of implementing alternative locomotive technologies given the economics and operational requirements of line-haul freight rail transport on mainlines in California.

The results of this investigation provide an assessment of how different alternative locomotive technologies, and different deployment strategies within the North American fleet of 29,500 locomotives, may impact railway operations, economics and logistics. The quantified measures of these challenges and opportunities presented in this report allow for better understanding of the network-level costs and benefits of zero or near-zero emission freight rail operations. This better understanding can lead to more informed decisions on future policy that furthers the air quality goals of California while meeting the needs of the railroad industry and freight shippers.

1.3 Scope

This report assesses and compares the operations and economic impacts of different zero or near-zero emission locomotive technology on line-haul mainline freight railroads. This report considers six different locomotive technologies for the South Coast air basin:

- Tier 4 diesel-electric with after-treatment
- Liquefied natural gas with fuel tenders
- Diesel-electric with battery tenders and onboard battery storage
- Solid-oxide fuel cell
- Electric traction from catenary electric power supply
- Linear synchronous motors

Additionally, the solid-oxide fuel cell and Tier 4 diesel-electric with both after-treatment and onboard batteries technologies are considered for the North American deployment scenario discussed in Section 13.

The impacts of these different locomotive technologies on railroad operations and economics are analyzed in three broad steps:

1) research railroad traffic and energy demand as a basis for new locomotive technology deployment scenarios,

2) conduct a systems analysis of each locomotive deployment scenario to determine impacts to railway network operations, railway economics and freight logistics and

3) examine potential benefits from reduced energy costs of each deployment scenario and possible obstacles to establishing renewable and alternative energy supply to satisfy rail transportation demand.

The scope of this quantitative analysis is limited to mainline line-haul freight operations on the rail network in Southern California and more specifically the South Coast Air Basin. The results of the quantitative analysis in the South Coast are used to draw qualitative conclusions on the statewide effects that encompass other air basins.

For the purposes of this study, mainline line-haul freight operations are defined as trains operating on Class 1 railroad mainlines directly between origin and destination terminals. The origin and destination terminals may be classification yards, intermodal facilities, automotive facilities, ports, and large industrial shippers that load/unload entire trains. Line-haul freight trains do not make stops between origin and destination to serve individual local customers. Based on this definition, this study considers the following types of freight trains if they originate, terminate or pass through the study area on a Class 1 railroad:

- Interstate freight trains
- Intrastate freight trains between Northern and Southern California
- Hauler freight trains that operate between a major classification yard and a smaller satellite yard where railcars are further sorted for distribution to local customers

The following rail operations are not included within the scope of this study:

- Local freight trains that stop en-route to serve individual customers
- Switching operations on spur tracks, industrial leads or industrial districts
- Yard and terminal switching movements
- Freight trains operated by regional, shortline or terminal railways
- Long-distance, regional intercity and commuter passenger rail operations
- Rail transit

1.4 Organization

Each of the three quantitative analysis steps described in the previous section consists of several components described in subsequent sections of this report.

Section 2 introduces the six different locomotive technologies under consideration for the South Coast air basin and provides background on each alternative lower-emissions locomotive technology. Since several of the technologies are actively under development or still in conceptual stages, this section defines key assumptions made regarding each locomotive technology for the purposes of the analysis in this report. The discussion of each locomotive technology considers its current stage of development, potential to reduce emissions and practical implementation challenges in defining a likely deployment scenario.

Section 3 provides background on mainline freight operations in California and how they relate to the national freight rail network. Given this context, the importance of interoperability and safety to efficient freight rail operations are discussed.

In Section 4, to provide a framework for evaluation of different locomotive technologies, the demand for mainline line-haul freight rail transportation in the South Coast Air Basin is determined from a combination of public and private rail traffic data. The energy consumption of mainline freight operations is subsequently calculated from traffic demand, route alignment data and locomotive assignment rules. The analysis of freight rail traffic and energy demand is based on current rail traffic levels. No attempt is made to forecast future traffic demand in the subsequent economic and operations analysis.

Based on the calculated energy demand for mainline freight operations in the South Coast, the potential emissions benefits of each locomotive technology are evaluated in Section 5.

The number of new technology locomotives required to support mainline line-haul freight operations within the South Coast is determined in Section 6. This section also quantifies the capital cost of purchasing the new technology locomotive fleet, establishing appropriate maintenance and servicing facilities and installing trackside fuel/energy distribution infrastructure.

To integrate new locomotive technology into the existing rail network and pattern of train operations, Section 7 provides an estimate of the capital cost of constructing new "exchange point" terminal facilities where trains switch between conventional and new locomotive technology near the air basin boundary.

Section 8 analyzes the operational impact of potential rail traffic delays resulting from stops to exchange locomotives. This is accomplished through freight modal split models that consider the time sensitivity of different commodity groups shipped on individual train runs of varying length between origin and destination.

Section 9 uses the initial rail energy inventory to estimate changes in energy supply costs associated with each of the six locomotive technologies. This analysis considers the cost of new fuel sources and the relative efficiency of the traction energy conversion process associated with each new locomotive technology.

Some other potential economic and operation impacts of the new locomotive technologies are presented in Section 10 before the individual impacts of each deployment scenario are summarized in Section 11. The discussion is then extended to state-wide deployment scenarios in a qualitative manner in Section 12.

Finally, a possible North American deployment scenario is introduced for two of the locomotive technologies in Section 13.

2 Zero and Near-Zero Locomotive Technology

Since 1981, all line-haul freight rail operations in the United States have been powered by diesel-electric locomotives. While used on several passenger and commuter rail lines, electric traction for freight operations is limited to industrial shortlines and a few isolated closed-loop mining railroads that are not part of the common national network. Nationally, the average freight train is powered by 2.8 diesel-electric locomotives generating a total of 10,260 horsepower (AAR, 2012).

In 2013, diesel-electric locomotives in line-haul freight service consumed 3.7 billion gallons of diesel fuel at a cost of over $11.6 billion (AAR, 2015). Remarkably, freight rail fuel consumption has been relatively constant since 1980 despite a 101% increase in freight traffic as measured by revenue ton-miles. As a result, freight railroad fuel efficiency has doubled since 1980, up to 473 revenue ton-miles per gallon in 2013 (AAR, 2014b). While much of this increase in fuel efficiency can be attributed to heavier axle loads, alternating-current traction, distributed power and longer trains, the improved efficiency of diesel-electric locomotives over the past 35 years has also played a role. Microprocessor control and fuel injection have facilitated a 20-percent increase in the fuel efficiency of the diesel-electric locomotive itself (AAR, 2014b). Increases in fuel efficiency have been coupled with decreased emissions (Chen, 2003). All new line-haul locomotives manufactured after 2005 and prior to 2015 must meet Tier 2 standards requiring emissions 60 to 70 percent below pre-2000 levels (EPA, 1998). Tier 4 emissions standards required of all newly manufactured locomotives starting in 2015 specify emissions 50 to 70 percent below Tier 2 levels (or 80 to 90 percent below pre-2000 levels). Further efficiency gains and reductions in emissions to zero or near-zero levels will likely require further refinements to the diesel combustion process or a shift to a different locomotive technology.

2.1 Considerations for New Technologies

This study considers the economic and operational impacts of utilizing each of six different locomotive technologies to further reduce the emissions of line-haul freight rail transportation in California to zero or near-zero levels:

- Tier 4 diesel-electric with after-treatment
- Liquefied natural gas with fuel tenders
- Diesel-electric with battery tenders and onboard battery storage
- Solid-oxide fuel cell
- Electric traction from catenary electric power supply
- Linear synchronous motors

Each of the above locomotive technologies has been the subject of many individual studies and papers describing the details of the technology and its development. Recent locomotive technology scans (Stodolsky, 2002; Barton, 2012; Brecher, 2014) and testing (Frey 2012) have also evaluated the ability of each technology to reduce emissions in a theoretical or controlled operating environment. Since the focus of this study is on the operational and economic feasibility of adopting these technologies on a regional basis, a comprehensive technical review of each propulsion system is not presented here. Instead, the following sections highlight key aspects of each technology and necessary assumptions that directly relate to its practical application in a line-haul mainline freight environment.

2.1.1 Potential Energy and Emissions Reductions

Each locomotive technology may reduce energy consumption and emissions by a different amount depending on its source of energy and the efficiency of its component systems. Range limitations, dual-fuel replacement ratios, dual-mode operation and energy harvesting capability may also impact the number of reduced-emission “clean miles” that can be provided by a particular technology under different operating conditions.

Dual-fuel locomotives can operate using one or more types of liquid fuel, either alone or in combination as a blended fuel. An example of this is a locomotive that can run on diesel fuel or a mixture of diesel and natural gas. A dual-fuel locomotive can switch between these two fuel sources without physical modifications to the locomotive equipment. This is distinct from a locomotive that once converted to consume a different type of fuel can’t return to its original fuel source without additional modifications. Since each fuel may result in a different locomotive efficiency and emissions profile, the proportion of time spent consuming each type of fuel and the exact fuel blend will impact the energy and emissions performance of a dual-fuel locomotive technology.

Dual-mode locomotives can make use of two or more energy sources. An example of this is a locomotive that can generate traction energy from onboard combustion of diesel fuel or electricity supplied from overhead catenary or a third rail. A true dual-mode locomotive will have equal performance when operating in either mode. In most past applications, dual-mode locomotives exhibit reduced power and tractive effort when operating from one of the two power sources. For example, a dual-mode locomotive designed to operate primarily on electricity from overhead catenary may only have a very small diesel engine. The limited power of the diesel is not enough to move a train at full mainline speed; it is only designed to move at low speed within terminals where electric catenary traction power supply may not be installed on every track. Since the efficiency and emissions profile of each operating mode may be different, the proportion of time spent in each mode will impact the energy and emissions performance of a dual-mode locomotive technology.

Energy harvesting refers to systems that capture, store and re-use energy generated during braking with the locomotive dynamic brake. In dynamic braking, the locomotive traction motors are converted into generators that produce electrical energy while retarding the motion of the train. On conventional North American diesel-electric locomotives equipped with dynamic braking, the generated electric energy is dissipated as waste heat. Routing the generated electricity to power auxiliary equipment or to battery storage for later traction use can reduce the overall energy consumption of a particular train movement with a corresponding reduction in locomotive emissions.

This study uses the properties of each locomotive technology and train performance calculation to determine the gallons of diesel fuel consumption that can be avoided through regional implementation of a particular locomotive technology. This value can be translated into emissions savings based on the emissions of the new reduced-emissions locomotive technology relative to baseline conditions with Tier 2 or Tier 4 diesel-electric locomotives.

Although mobile source emissions (i.e. “tailpipe emissions”) are of primary concern for regional air quality, consideration is given to source emissions for technologies that rely on remote energy conversion and power generation. However, this study does not attempt to conduct a comprehensive life-cycle analysis of all upstream energy consumption and related emissions associated with fuel production, equipment manufacture and facility construction.

2.1.2 Economic and Operational Considerations

Locomotive capital, operating and maintenance costs are key economic considerations for selection of railroad motive power:

- The capital cost of a typical line-haul freight locomotive manufactured between 2000 and 2014 (and meeting Tier 0 to Tier 2 emissions standards as appropriate) was approximately $2.3 million per unit for AC traction and $1.8 million per unit for DC traction. As of 2015, the cost of a line-haul freight locomotive with the additional equipment and systems required to meet Tier 4 emissions standards is approximately $3 million per unit (Black and Clough, 2014). The capital cost of implementing new locomotive technology includes all system components: locomotives, tenders and the portion of the power/fuel supply and distribution system that will be a direct expense to the railroads.

- In the context of this study, operating costs are related to the cost of fuel/energy. In 2013, the average Class 1 railroad cost of diesel fuel was $3.12 per gallon, representing 22 percent of overall railroad operating expenses (AAR, 2015). Fuel costs vary between railroads based on location and timing of purchases, and the overall long-term fuel price hedging strategy employed by each railroad. Different energy sources will have their own operating cost profiles.
- Although there is some variation between railroads based on the composition of their locomotive fleet and maintenance practices, Class 1 railroads spend approximately $150,000 per locomotive per year on maintenance of diesel-electric locomotives (Graab, 2011). This is equivalent to $1.25 per locomotive-mile and represents approximately 5 percent of overall railroad operating expenses (AAR, 2012). Maintenance costs will vary with the complexity of the technology and its component systems, including wayside energy distribution infrastructure.

Operational considerations relate to the ability of the technology to support current train lengths and weights, the need for fuel tenders and other support railcars, possible dual-fuel and dual-mode capability and energy capture. These properties will determine the amount of inefficiency and network delay created by adoption of the new technology, and related changes in railroad operating costs. Different operational needs also impact the size, type and capital costs of facilities required at locomotive exchange points where rail lines cross the study area boundary.

2.1.3 Study Deployment Scenario

For this study, it is assumed that all line-haul freight trains operating within the South Coast basin will utilize the lower-emission locomotive technology under consideration within the basin. As defined in Section 1.3, line-haul freight trains operate on mainlines and do not make stops between origin and destination to serve individual local customers. For hauler trains operating on mainline track entirely (or predominantly) within the basin, alternative locomotive technology will be used for the entire trip from origin to destination terminal.

On intrastate and interstate line-haul freight trains, where practical, lower-emission dual-fuel or dual-mode locomotives used within the basin may continue to operate with the same train outside the basin in diesel mode (Figure 2.1b). As will be discussed in subsequent sections, dual-mode operation is not practical for all locomotive technologies. In such cases, this study assumes that the low-emission locomotives will remain captive to the air basin. All intrastate and interstate line-haul freight trains are assumed to exchange locomotives at a point on the edge of the study area when entering or exiting the South Coast basin (Figure 2.1c). This study assumes that the conventional diesel-electric locomotives will be removed from the train at the exchange point, as opposed to being deadheaded in the train consist while it is powered by the lower-emission locomotive technology. Similarly, outbound trains will have new technology locomotives removed and conventional diesel-electric locomotives added at the exchange point. This approach is used to increase locomotive utilization and avoid fuel and energy penalties associated with transporting the extra offline locomotives within the study area.

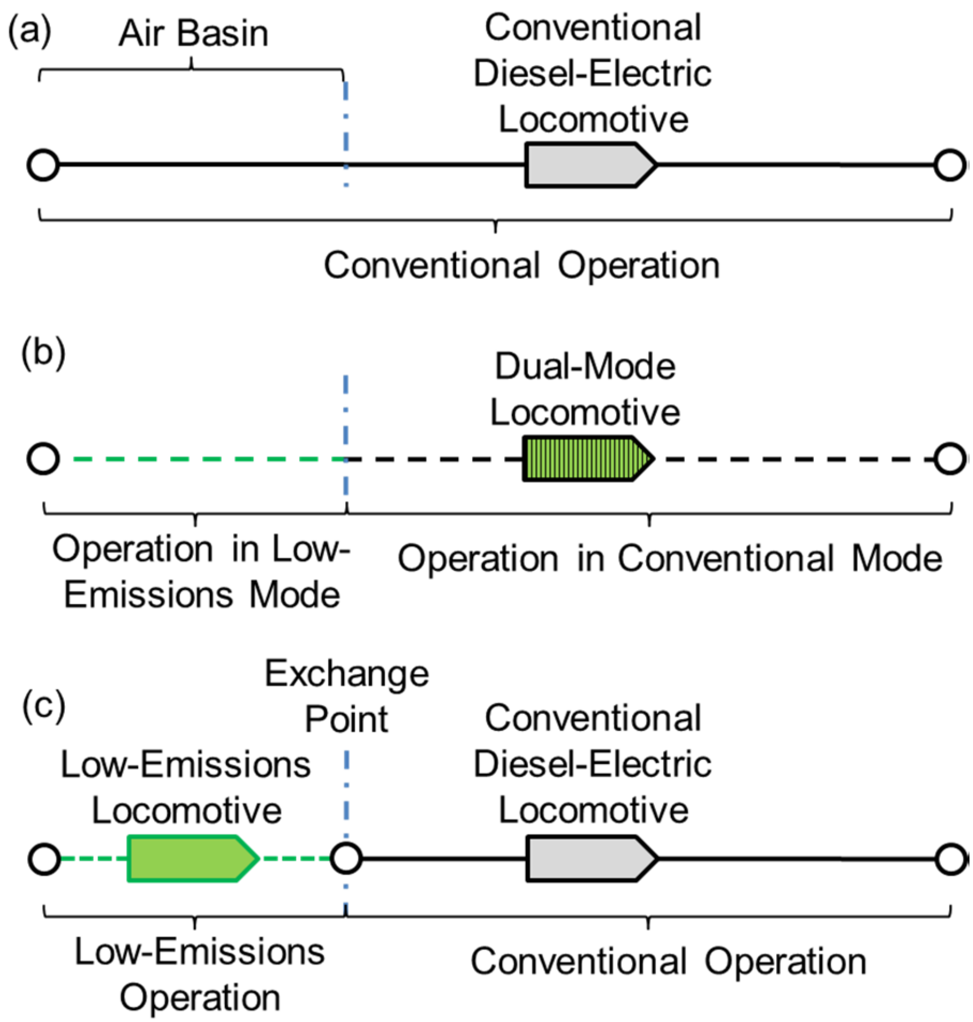

Figure 2-1, Potential locomotive deployment scenarios including (a) current conventional operations, (b) low-emissions operation in air basin with dual-mode locomotives and (c) low-emissions operation in air basin with dedicated locomotives and exchange point

In general, if technologically feasible, this study assumes that conventional diesel-electric locomotives will be replaced with new technology locomotives of equivalent horsepower and tractive effort. Where there are technical constraints, certain technologies may require a larger number of locomotive units with less horsepower or tractive effort to provide the same transportation productivity.

As discussed in the introduction, this study is limited to line-haul operations and does not consider local trains that stop to serve individual rail customers or switching activities on spur tracks and industrial leads. Thus, between terminals, the lower-emission locomotives only operate on mainline track and passing sidings. Spur tracks and industrial leads do not need to support operation of the new locomotive technology.

Although yard and terminal switching operations are not within the scope of this study, yards and terminals that are origins or destinations for line-haul freight trains must support operations of lower-emission locomotive technologies. Line-haul trains using alternative locomotive technology must be able to enter and exit the mainline to and from receiving and departure tracks. The alternative technology locomotives must also be able to move to appropriate servicing facilities or tracks used to stage motive power between train assignments.

2.1.4 State of Development

As of 2015, none of the six technologies under study are in routine operation under North American line-haul freight conditions. Further, none of the technologies are ready for immediate deployment, with each being in varying stages of development. To assess the status of each locomotive technology, the nine levels of the Technology Readiness Level (TRL) scale are used (Table 2.1). The lowest level (TRL of 1) corresponds to a concept where the basic principles underlying a technology have been observed (Mankins, 1995). The highest level (TRL of 9) corresponds to actual deployment of the technology in routine operations. The TRL assigned to each technology in the following sections is based on a literature review and the latest industry publication updates on current research and test efforts.

The TRL index only measures the technical state of new system development. After the system is proven by successful trial operations, the technology undergoes a commercialization process where actual products for purchase and revenue-service deployment are developed. Widespread deployment also requires the planning, design and construction of support infrastructure. Human infrastructure must also be developed through operating and maintenance crew training programs. These processes require substantial amounts of time and resources. Thus, even technologies that have been demonstrated in a limited operating environment can be many years from full deployment.

Table 2.1: Technology Readiness Levels (TRL) - (Mankins, 1995)

TRL	Description
9	Actual system proven by successful operations
8	Actual system qualified through test and demonstration
7	Prototype demonstrated in operational environment
6	Prototype demo in relevant environment
5	Component validation in real environment
4	Component validation in laboratory environment
3	Experimental proof of concept
2	Technology concept formulated
1	Basic principles observed and reported

2.2 Tier 4 Diesel-Electric with After-Treatment

In 2015, General Electric began production of diesel-electric locomotives for line-haul freight service that comply with EPA Tier 4 emissions standards (General Electric, 2015). The emissions standards were met through changes to the internal combustion process and additional cooling. The locomotives also use Exhaust Gas Recirculation (EGR) to meet Tier 4 Nitrogen Oxide (NOx) standards.

In order to exceed EPA Tier 4 emissions standards for line-haul freight locomotives, manufacturers of conventional diesel-electric locomotives are exploring new engine exhaust after-treatment systems (Osborne, 2012). In addition to EGR, other after-treatment technologies include Diesel Oxidation Catalysts (DOC), Selective Catalytic Reduction (SCR), and Diesel Particulate Filters (DPF).

When mature, the after-treatment technologies may be available on newly manufactured diesel-electric locomotives or as retrofit kits to modify existing diesel-electrics as they are rebuilt. Retrofit applications are constrained by the limited space available for new systems within the locomotive hood. Potential changes to the combustion process may also alter the size and footprint of the locomotive prime mover engine block. In such instances, retrofits to exceed Tier 4 standards will likely require substantial modifications to existing locomotives.

2.2.1 Potential Energy and Emissions Reductions

Depending on the exact combination of technologies selected, locomotives with after-treatment systems requiring additional onboard equipment such as pumps and fans may consume additional power normally available for traction. This increase in power drawn by onboard auxiliary systems may result in a slight decrease in fuel consumption for Tier 4 diesel-electrics with after-treatment.

Specific emissions targets beyond Tier 4 have not been established. To exceed Tier 4 standards, the improved diesel-electric locomotives must, relative to Tier 2 levels, reduce hydrocarbon emissions by more than 53 percent, NOx by more than 76 percent and particulate matter by more than 70 percent. ARB estimates that after-treatment can further reduce NOx and particulate matter emissions by an additional 75 percent below Tier 4 levels. This technology is not likely to decrease CO_2 or CO emissions unless it is accompanied by simultaneous improvements in locomotive fuel efficiency.

2.2.2 Economic and Operational Considerations

In consultation with industry experts, it is estimated that after-treatment systems will increase the cost of each new diesel-electric locomotive by $1 million relative to Tier 2/Tier 3 levels to approximately $3.5 million per unit.

Tier 4 locomotives with after-treatment can make use of the existing diesel fuel supply and distribution infrastructure. As mentioned in the previous section, Tier 4 locomotives with after-treatment may experience increased fuel consumption, increasing operating costs.

The SCR system consumes an aqueous solution of urea carried onboard the locomotive. New infrastructure to distribute urea to locomotives will be required at fueling and servicing locations if SCR is adopted. The cost of a nationwide infrastructure to supply urea to the entire locomotive fleet has been estimated at $1.5 billion (General Electric, 2014).

With additional onboard systems, the Tier 4 locomotives with after-treatment may experience increased maintenance costs. The lack of space inside test locomotives rebuilt with after-treatment systems has resulted in restricted access to conventional locomotive systems, increasing maintenance effort and costs (Iden, 2012). Periodic collection of material accumulated in the DPF will be an ongoing maintenance activity to be conducted on a cycle with other routine maintenance.

Current prototype Tier 4 locomotives with after-treatment are able to develop levels of horsepower and tractive effort required to support one-for-one replacement of conventional line-haul diesel-electric locomotives. As currently being tested, the after-treatment technologies are self-contained within the locomotive and do not require tenders or other support railcars.

2.2.3 Study Deployment Scenario

Due to the specific maintenance requirements of the specialized after-treatment systems, and the need for SCR to be supplied with urea, this study assumes that Tier 4 diesel-electric locomotives with after-treatment are likely to be deployed as a captive regional fleet within the study area. For purposes of this study, all line-haul trains operating within the South Coast basin utilize the Tier 4 locomotives with after-treatment within the basin. It is assumed that all trains exchange conventional diesel-electric and Tier 4 locomotives with after-treatment at a locomotive exchange point when entering or exiting the South Coast basin.

2.2.4 State of Development

Tier 4 diesel-electric locomotives with after-treatment have achieved TRL 6: prototype demo in relevant environment. Some examples of prototype and pre-production demonstrations of Tier 4 diesel-electric locomotives with after-treatment include:

- In 2009-10, Progress Rail tested a locomotive with SCR and DOC in mainline hauler service in California (Osborne, 2012).
- In 2012, Union Pacific began testing a fleet of experimental SD59MX locomotives equipped with DOC, DPF and EGR in short-haul mainline freight service in California (SMAQMD, 2012; Iden, 2012).
- Before starting production of their current Tier 4 locomotive design (ET44AC) in 2015, General Electric had six Tier 4 prototype 4,400-hp line-haul locomotives equipped with EGR under test at various locations (Weart, 2013). The prototype or production GE designs do not use SCR or urea (Golson, 2015).
- Electro-Motive Diesel also has a Tier 4 design and the first of five prototype SD70ACe-T4 locomotives was released in October 2015 (Trains, 2015a). To meet emission requirements, the prototype EMD Tier 4 design uses a new diesel-engine prime mover, EGR and DOC. The prototype EMD design does not use urea (Vantuono, 2015).
- In 2015, Cummins repowered an EMD SD90MAC locomotive to serve as a Tier 4 testbed for its 4,000 horsepower QSK-95 diesel prime mover (Trains, 2015b). Unlike most locomotive applications that use medium-speed diesel engines, Cummins uses a high-speed diesel prime mover. The Cummins diesel uses SCR to meet Tier 4 emissions levels (Cummins, 2015).

2.3 Liquefied Natural Gas

The recent low cost of natural gas relative to diesel fuel has led to renewed interest in the use of liquefied natural gas (LNG) as a fuel for internal combustion locomotives (Pinney, 2013). Internal combustion engines powered by LNG can make use of spark ignition or compression ignition. Spark ignition engines can operate on LNG alone by utilizing a spark to ignite the gas. Compression ignition engines must use a small amount of diesel fuel to serve as a pilot and initiate combustion of the diesel-LNG mixture during the compression cycle. In this manner, the ratio of LNG to diesel can be varied and the same engine can operate purely on diesel fuel when LNG is unavailable (i.e. dual-fuel operation). Diesel-LNG locomotives can use the same general equipment layout and engine blocks as conventional diesel-electric locomotives. Thus, in addition to manufacturing new locomotives designed for LNG, existing conventional diesel-electric locomotives can be converted to burn a diesel-LNG mixture using retrofit kits.

LNG has approximately 60 percent of the energy density of diesel fuel. Thus, a volume of LNG equivalent to a typical locomotive fuel tank will only provide a fraction of the range of a conventional diesel-electric locomotive (Stolz, 1992). An LNG tender is necessary to supply the volume of LNG required to provide an acceptable range for a line-haul freight locomotive. The LNG fuel tender includes an insulated cryogenic tank for storing the LNG and other equipment used to convert the LNG to a gas for delivery to the locomotive and combustion (Schultz, 1993). As currently being tested, each tender can supply LNG to the two locomotives it is coupled between; LNG cannot be passed through a locomotive to reach other locomotives in the train consist not directly coupled to a tender.

2.3.1 Potential Energy and Emissions Reductions

Diesel-LNG locomotives utilize the same traction system as conventional diesel locomotives but introduce new steps in the combustion process, potentially decreasing overall fuel efficiency. Although no specific data was available for line-haul rail applications, during tests of a LNG-fueled switching locomotive, an 11-percent increase in fuel consumption (equivalent diesel gallons) relative to a comparable diesel-electric was observed (Couch, 2010). Experience with heavy trucks also suggests that LNG decreases fuel efficiency by 10 percent (Love's, 2014). Thus, this study assumes that the overall efficiency of diesel-LNG locomotives will be similarly decreased, resulting in a 10-percent increase in fuel consumption (in terms of equivalent diesel gallons).

Since they provide the ability to operate as a "dual-fuel" locomotive and may be converted from existing locomotives, the locomotive manufacturers are favoring development of diesel-LNG locomotives that make use of compression ignition over spark ignition designs. Spark ignition LNG designs have the additional drawback of being sensitive to changes in environment and altitude, making them less ideal for mobile applications.

The amount of diesel gallons avoided by diesel-LNG compression ignition technology will vary with the exact ratio of LNG and diesel in the final locomotive design, the duty cycle and the time the locomotive is operated with diesel-LNG as opposed to straight diesel mode. Current prototype designs for retrofit kits substitute LNG for 60 to 80 percent of diesel fuel. EMD is developing a high-pressure direct injection design that will substitute LNG for 95 percent of diesel fuel. However, it is unclear if this design can revert to operation purely on diesel fuel (Railway Age, 2013).

Based on its chemical properties, pure LNG reduces CO_2 emissions per unit energy relative to diesel by 25 percent (EPA, 2014). In an application where LNG is substituted for 80 percent of diesel fuel, CO_2 emissions per unit energy may be reduced by 20 percent. However, since the diesel-LNG locomotive is assumed to be less fuel efficient, CO_2 emissions per unit of traction energy are only reduced by 12 percent.

The other emissions benefits of LNG in line-haul freight service are still unclear. Results from LNG tests conducted in 1991 on 3,000-horsepower mainline locomotives do not offer a good comparison to modern Tier 2 diesel-electric locomotives with higher base fuel efficiency (Caretto, 2007). Similarly, Canadian National Railway is testing retrofitted diesel-electric locomotives with a LNG conversion kit. The CN application uses a 90-10 LNG diesel mixture and is projected to decrease CO_2 and NOx emissions by 30 and 70 percent respectively relative to the base locomotive configuration (Vantuono, 2013). Current diesel-LNG prototypes under test may provide more insight on emissions benefits for line-haul service. The General Electric dual-fuel retrofit kit with port injection and 80-percent LNG substitution may achieve Tier 4 standards with the aid of after-treatment (Trillanes, 2015). Overall, the diesel-LNG configuration is not anticipated to offer emissions reductions beyond Tier 4 levels.

Liquefaction of LNG from supplied natural gas is also an energy-intensive process. A major liquefaction plant can draw over 100 MW of electricity with its associated generation emissions (Smil, 2010). Emissions benefits from LNG can also be reduced by leakage of

LNG into the atmosphere. Methane, the primary constituent of LNG, is approximately 25-times more potent as a greenhouse gas compared to carbon dioxide (EPA, 2015).

2.3.2 Economic and Operational Considerations

To implement diesel-LNG locomotive technology, railroads may purchase new purpose-built diesel-LNG locomotives or retrofit kits for current diesel locomotives. One manufacturer estimates the cost of an LNG retrofit kit at $400,000 per line-haul freight locomotive (GE, 2013). The railroads must also purchase a fleet of LNG tenders at an estimated cost of $1 million each (Railway Age, 2013). A minimum of one tender is required for every two locomotives consuming LNG.

Implementation of LNG will also require capital investment in a natural gas supply infrastructure that may include fueling stations, liquefaction plants and pipelines. A single-consist LNG fueling station is estimated to cost $700,000 plus the cost of supplying fuel to the station (Barton, 2012). At locations of high demand, railroads may elect to invest capital in liquefaction plants fed from pipeline connections. However, the capital cost of a LNG liquefaction plant is approximately $450 million per million gallons of daily LNG liquefaction capacity (Hemphill, 2015). A supply of 1 million gallons of LNG per day is enough to fill 33 tenders per day (at 30,000 gallons per tender) giving the plant the capacity to refuel approximately 25 trains per day. Given this capital investment, it is possible that LNG will be purchased from suppliers with the cost of liquefaction included in the delivered cost of the fuel as an operating expense.

Maintenance costs of diesel-LNG locomotives may be increased compared to conventional diesels due to the need for a tender, two onboard fuel systems and the additional glycol pump system used to evaporate the LNG before it is fed to the locomotive. Although data for long-term line-haul service is not available, testing of LNG switching locomotives has shown increases in the number of maintenance events (Couch, 2010). It is not clear how much of this effect is simply due to unfamiliarity with the unique test locomotives. As experience is gained with a larger fleet of LNG locomotives in routine service, there may be less disparity in maintenance compared to conventional diesel-electric locomotives.

Operating costs of diesel-LNG locomotives will be less than conventional diesel provided that the delivered cost of LNG remains below diesel fuel. Crude oil price trends in late 2014 and early 2015 have decreased the economic incentive for introducing LNG to replace diesel fuel. In April 2015, the national average price of diesel fuel was reported as $2.88 per diesel gallon while the national average price of LNG, based on limited data, was reported as $2.54 per equivalent diesel gallon (USDOE, 2015). At these prices, the 10-percent savings from 80-percent LNG substitution is offset by the suggested 10-percent decrease in locomotive fuel efficiency, providing no economic incentive for LNG. However, since 2010, LNG prices have not varied more than 10 percent above or below the April 2015 value while diesel fuel prices have been as much as 43-percent higher than the April 2015 value.

Current prototype diesel-LNG locomotives are able to develop levels of horsepower and tractive effort required to support one-for-one replacement of conventional line-haul diesel-electric locomotives. Diesel-LNG locomotives require tenders that will increase the length and tare weight of trains without adding revenue. Tender designs under development and in testing are sized such that their range will most closely match conventional diesel locomotives when supplying two diesel-LNG locomotives. As currently being tested, the tenders can only supply locomotives that they are directly coupled to; there are no fuel pass-through capabilities. In addition, LNG can only be fed to the rear of the locomotive and cannot be fed from the front where the cab is located. These restrictions introduce potential tender logistical issues when locomotive consists include more than two or an odd number of locomotives.

Compression ignition diesel-LNG locomotives with the capability to operate on a mixture of LNG and diesel or pure diesel fuel offer the possibility of dual-fuel operation. The same dual-fuel locomotive consist that originates a train and operates within the reduced-emissions study area using a diesel-LNG mixture could then switch to pure diesel mode for the remainder of the trip. Dual-fuel operation in this manner could avoid a locomotive exchange at the edge of the study area but would require the entire national fleet to be equipped for diesel-LNG operation. The train would also incur a significant fuel penalty while operating in diesel-only mode but still hauling the LNG fuel tenders. For example, consider a train using four locomotives and two LNG fuel tenders to transport 7,500 revenue tons of freight over a 2,125-mile route. The first 125 miles within a reduced emission zone require operation with diesel-LNG. If the train operates with 80-percent LNG during the initial leg of the trip, an average of 1,546 gallons of diesel fuel can be avoided. During the remaining 2,000-mile trip, transporting the two fuel tenders consumes an extra 296 gallons of diesel fuel. Thus, 19 percent of the diesel gallons saved during LNG operation is offset by transportation of the fuel tenders. Under such conditions, the railroad may elect to stop and switch the fuel tenders out of the train. The delay incurred while switching out the tenders is equivalent to a complete exchange of locomotives, minimizing any advantage of a dual-fuel application.

2.3.3 Study Deployment Scenario

Since a stop to add or drop LNG tenders is necessary to avoid fuel penalties during dual-fuel operation and to concentrate LNG fueling infrastructure and gain economies of scale in its liquefaction, this study assumes that diesel-LNG locomotives are deployed as a captive regional fleet within the study area. For purposes of this study, all line-haul trains operating within the South Coast basin utilize diesel-LNG locomotives operating at 80-percent diesel substitution within the basin. In this study, all trains exchange conventional diesel-electric and diesel-LNG locomotives with tenders at a locomotive exchange point when entering or exiting the South Coast basin. True dual-fuel capability that allows switching between diesel-and diesel-LNG operation en route is not used in this study as diesel-LNG locomotives and tenders are assumed to not leave the basin.

The assumption of this deployment scenario allows for better direct comparisons with other technologies that require a captive locomotive fleet within the South Coast (i.e. battery tenders and electrification as described in subsequent sections). In practice, to avoid exchange points, it is less likely that diesel-LNG locomotives will be captive to a region and more likely that they will be captive to certain corridors between terminals equipped with LNG fueling infrastructure. In the context of the South Coast basin, this deployment approach would eliminate the need for exchange points but limit the benefits of diesel-LNG locomotives to certain line-haul freight trains on particular routes in the basin.

2.3.4 State of Development

Diesel-LNG locomotives have achieved TRL 6: prototype demo in relevant environment. Proof-of-concept tests in line-haul freight service have been conducted on several occasions over the past 25 years (Caretto, 2007). More recent developments include:

- Canadian National had two diesel-LNG locomotives testing in regular line-haul service during 2013.
- BNSF Railway took delivery of four diesel-LNG test locomotives in late 2013 (Progressive Railroading, 2013).

- Union Pacific and CSX have announced plans to conduct diesel-LNG tests in 2015 (Weart, 2013).
- A heavy-haul iron ore railroad in Brazil has tested five diesel-LNG locomotives operating at up to 70 percent LNG. This figure includes three 4,000-horsepower GE locomotives with retrofit kits operating on 50-percent LNG since 2008 (Carvalhaes, 2013). The locomotives are supplied by three LNG fuel tenders. The Brazilian test of the 4,000-horsepower locomotives has shown that the amount of diesel that can be replaced by LNG is highly dependent on the locomotive duty cycle. A high percentage of LNG can only be used in throttle notches three through six. In lower notches or at maximum power, the locomotives operate predominantly on diesel to prevent engine knocking.

2.4 Battery Tenders

When mature as a technology, battery tenders have the potential to be the railway equivalent of the plug-in hybrid electric light-duty passenger vehicle. As currently envisioned, the technology concept consists of a railcar filled with batteries that can be mated to a properly equipped diesel-electric locomotive to supply it with electricity for traction power. While the locomotive is drawing power from the battery tender, the diesel prime mover can be idled or shut down, saving diesel fuel and reducing mobile source emissions.

When decelerating or holding speed while descending grades, diesel-electric locomotives use dynamic braking to turn the momentum of the train into electrical energy that is dissipated as waste heat. The battery tender concept is envisioned as the storage mechanism necessary for the dynamic braking energy to be captured and later reused for traction. This process, known as regenerative braking, can potentially extend the range of the battery tender under the right combination of duty cycle, operating speed and grade profile.

Under the current technology concept, locomotives must be equipped with proper connections and control software to manage energy flow to and from the battery tenders. While the electrical connections may resemble those commonly used to connect locomotives to “slug” locomotives lacking diesel prime movers, the envisioned control software and electrical considerations will be more complex. Since the battery tenders will operate most efficiently at a constant voltage, the concept will work best when connected to the constant voltage DC bus of an AC-traction locomotive. Only 21-percent of the line-haul locomotive fleet is equipped with AC traction systems that may be convertible for use with battery tenders. The remaining locomotives, including the majority of the locomotive fleet used by BNSF Railway on their priority intermodal trains, use DC traction where the DC voltage varies with the speed and tractive effort of the locomotive. This situation is not compatible with a basic battery tender concept. More complex designs using additional electrical equipment could potentially make a battery tender compatible with DC traction but this would decrease the space and weight available for batteries, reducing range.

2.4.1 Potential Energy and Emissions Reductions

A locomotive equipped with a battery tender may produce no mobile source emissions when operating in battery mode. By eliminating the combustion process, the efficiency of the fully electric traction system allows for a significant reduction in purchased energy for every gallon of diesel avoided. Given the relative efficiencies of the diesel-electric locomotive, electric traction and battery charging process, the 473 ton-miles per gallon provided by diesel-electric propulsion translates to 32 ton-miles per kWh of electric charge. Current battery tender design concepts claim a storage capacity of 6.2 MWh with 5 MWh of usable electricity (Transpower, 2014) sufficient power to provide an average of 160,000 ton-miles of freight rail transportation on a single charge.

For the freight train described earlier carrying 7,500 revenue tons over a hypothetical average route, the available storage capacity translates into 21.3 miles of reduced emissions operation per battery tender. During these 21.3 miles, 338 gallons of diesel fuel consumption are avoided. If each of the four locomotives on the train operates with one battery tender, conceptually, the train can operate for 85 miles and 1,352 gallons of fuel can be saved. This scenario represents gross averages; actual results will vary greatly with route speed and grade profiles. More detailed route-specific calculations of train performance are conducted later in the analysis.

The number of reduced-emission miles and gallons of diesel avoided can be increased through regenerative braking under certain combinations of locomotive duty cycle, operating speed and grade profile. Given the efficiency of the electric traction system to generate braking energy and then consume it again, multiplied by the efficiency of the battery storage system, less than 55 percent of the energy used to accelerate a train or overcome grade resistance can be used during the next acceleration cycle or grade ascent *given an ideal duty cycle and grade profile*. When the energy consumed overcoming inherent train resistance is factored into the calculation for a more realistic duty cycle on a route with more level terrain, potential use of regenerated energy drops quickly (Painter, 2006). Locomotive manufactures claim that depending on the exact route and duty cycle, only 10 to 30 percent of diesel gallons could be avoided through energy regeneration (Railway Gazette, 2007; Sun, 2013; Ward, 2014).

Although the battery tender concept may allow for operation with zero emissions directly from the mobile source, the batteries must be charged with electricity drawn from the regional power grid (van der Meulen, 2013). Thus, the actual emission savings are a function of the regional electric source generation profile. According to the regional electric source generation profile for California (Table 2.2), 41.5 percent of electricity consumed in California is derived from true zero-emissions sources (EIA, 2014). Natural gas is used to produce 51.1 percent of electricity consumed in California with an additional 5.0 percent produced by other sources that produce emissions from combustion.

Table 2.2: 2013 Source Generation Profile of California Electricity Consumption (EIA)

Source	Percent of Total
Natural Gas	51.1
Biomass	4.5
Coal	0.4
Petroleum	0.1
Hydroelectric	13.6
Nuclear	11.3
Geothermal	7.1
Wind	7.4
Solar	2.1
Foreign Imports	2.5

On average, 611 pounds of CO_2 are emitted per MWh of electricity generated in California (EPA, 2014). Since emissions controls can be implemented more effectively at a handful of large stationary sources, such as power generating stations, compared to numerous small distributed mobile sources, use of these fuels for power generation has less emissions impact compared to their use in mobile internal combustion engines for transportation.

2.4.2 Economic and Operational Considerations

According to one developer, the initial cost of each conceptual 5 MWh battery tender is estimated at $5 million (Transpower, 2014). Since the cost of the tender is largely driven by the cost of the batteries, costs could decrease over time with improved battery technology and as economies of scale are gained. The battery tender operational concept also requires the purchase of compatible AC traction locomotives (at $3.0 million per unit) or modifications to existing AC traction locomotives (assumed at $250,000 per unit).

Additional capital investment is required for electrical charging infrastructure to support the battery tenders. Since a typical train will require multiple battery tenders and motive power for several trains must be charged simultaneously, numerous chargers will be required at each locomotive exchange point and destination terminal within the South Coast. For highway applications, the cost of a 100kW DC fast charging station is $160,000 (Yilmaz, 2013). However, to charge a 5 MWh battery tender in six hours, the charging station must operate at higher voltage and power. The cost of such a charger is estimated at $1 million per tender being charged.

Maintenance costs may be increased due to the additional maintenance of the battery tender and electrical systems. With current battery technology, over the life of the battery tender, the batteries will need to be replaced to maintain peak performance. Battery life is estimated at 3,000 cycles before replacement. Based on communications with suppliers, it is anticipated that over a 15-year line-haul service life, battery replacement will add $6 million to the cost of each tender.

Operating cost savings will depend on the number of battery miles and the relative cost of electricity and diesel fuel. For the purposes of this study, the cost of electricity is based on the average industrial rate of $87.60 per MWh in the Pacific region (EIA, 2015)

One-for-one replacement of conventional diesel-electric locomotives with battery-tender-equipped locomotives may be possible once the technology is mature. However, the range of the battery tender is small, limiting the number of reduced-emission miles. The battery tender will increase the length and tare weight of trains without adding revenue. Unlike LNG tenders, it is envisioned that a locomotive may draw battery power from multiple battery tenders. Conceptually, it may be possible to configure either end of a conventional locomotive to mate with a battery tender or pass electrical current through to locomotives not directly coupled to the battery tender. This may allow all of the battery tenders to be grouped in one block behind the locomotives, simplifying switching and train make-up.

With their limited range, dual-mode operation is integral to the battery tender concept. When the battery is depleted, or the train is outside the reduced emissions study area, the locomotive must be able to operate purely on diesel fuel with full capability. During diesel operation, however, a fuel penalty is incurred for transportation of the heavy battery tenders. Recall the earlier example train hauling 7,500 revenue tons and four battery tenders that was able to operate in battery mode for 85 miles and save 1,352 gallons of fuel. On the remaining 2,040 miles of the route, 1,898 gallons of diesel are consumed in transporting the additional weight of the battery tender. The result is a net increase of 546 gallons of diesel fuel over the entire trip. Note that this analysis considers gross averages and does not include any additional fuel savings from regeneration energy. Given such conditions, the railroad may elect to not utilize dual-mode capability beyond the locomotive exchange point; each train stops to exchange the battery tender and specially equipped locomotives for conventional diesel-electrics.

2.4.3 Study Deployment Scenario

To concentrate battery tender charging infrastructure and maximize the number of fully-charged reduced-emission miles within the study area, this study assumes battery tenders with specially equipped locomotives are deployed as a captive regional fleet within the study area. For purposes of this study, all line-haul trains operating within the South Coast basin will utilize specially-equipped AC traction locomotives operating with battery tenders within the basin. It is assumed that all trains will exchange conventional diesel-electric locomotives for specially-equipped locomotives with battery tenders at a locomotive exchange point when entering or exiting the South Coast basin. The equipped locomotives and battery tenders will not leave the basin.

On many train routes in the South Coast, outbound trains must travel an additional 20-50 miles beyond the air basin boundary to reach the locomotive exchange point. Providing sufficient storage to operate on battery power over the extended distance to the exchange point requires an impractical number of battery tenders on several routes. Thus, for this study, it is assumed dual-mode capability is used between South Coast terminals and the exchange points (Figure 2-2). A train departing from the South Coast will use battery power from origin to the air basin boundary and then the specially-equipped locomotives will switch to diesel-electric mode for the remaining miles to the exchange point. Beyond the exchange point, the train will be powered by conventional diesel-electric locomotives from the national fleet. An inbound train will follow the same process in reverse.

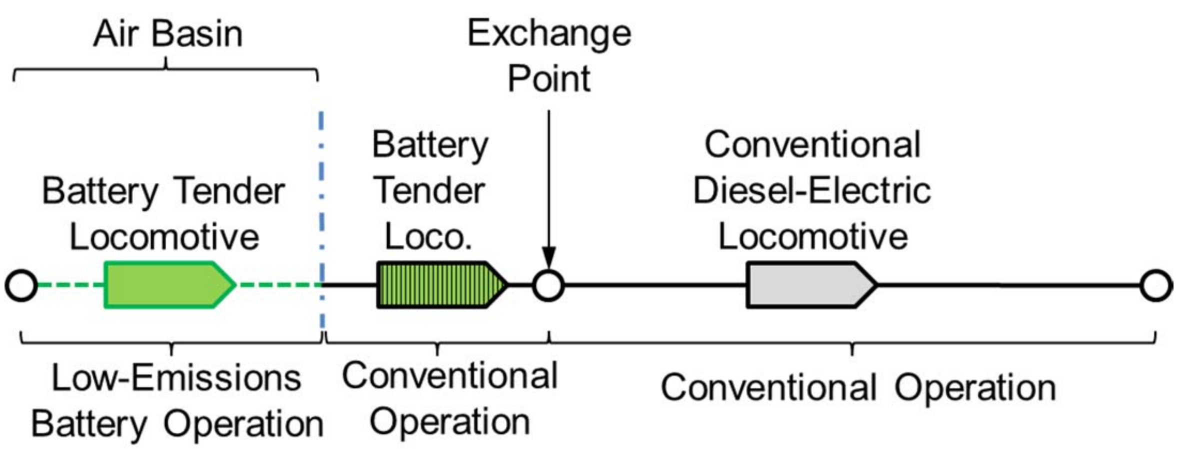

Figure 2-2, Dual-mode battery tender operation concept

2.4.4 State of Development

For line-haul freight service, battery tenders have achieved TRL 2: technology concept formulated. Recent developments include:

- Applications of battery locomotives have been limited to light-duty switching assignments. Recently produced battery switching locomotives were only moderately successful and production was stopped in favor of genset locomotives.

- The Norfolk Southern 999 battery locomotive prototype for heavier yard and transfer service has been subject to battery reliability issues during its limited operational tests (Barbee, 2013).
- General Electric developed a prototype line-haul locomotive equipped with batteries for energy regeneration (Railway Gazette, 2007) but it only saw limited service testing and is not being developed further.
- Although several concepts for battery tenders have been put forward, no working prototypes have been developed.

2.5 Solid-Oxide Fuel Cell

The solid-oxide fuel cell (SOFC) is a concept for a multi-stage power generation system that can be fueled by diesel, biodiesel or natural gas (Ormerod, 2003). Unlike fuel cells that require hydrogen as a base fuel, the solid-oxide concept considered for this study does not require hydrogen to be supplied to the locomotive. Instead, traditional hydrocarbon fuels undergo the steam reforming process where they are treated with steam to produce hydrogen and carbon dioxide. The hydrogen is then combined with oxygen to generate electricity in the fuel cell. Residual gases from the fuel cell process including hydrogen and carbon monoxide combine to form a synthesis gas that can be combusted in a turbine to generate additional electricity. The two stages of the process combine to produce more electrical energy than direct combustion of the base fuel (LaMonica, 2013). In laboratory trials, the SOFC-gas turbine process can achieve a fuel efficiency of 70 percent compared to 30-40 percent for an internal combustion engine (Calise, 2006). Although the reforming process does not eliminate emissions of carbon dioxide, emissions are potentially reduced due to the greater fuel efficiency of the conceptual process compared to internal combustion.

2.5.1 Potential Energy and Emissions Reductions

Conceptually, the increased efficiency of the conversion of fuel to electrical energy has the potential to reduce energy consumption by as much as 25-30 percent.

The increased efficiency and reduced energy consumption will likely reduce emissions but further research is needed to quantify the exact benefits. For purposes of this study, it assumed the SOFC-gas turbine concept can meet Tier 4 emissions requirements.

2.5.2 Economic and Operational Considerations

At this early stage of development, it is difficult to determine costs for SOFC locomotive technology but initial research by Schroeder (2010) suggests that it is two to three times that of a conventional diesel-electric locomotive. This corresponds to a capital cost of approximately $5 million per unit. The same research indicates that over its life cycle, the increased capital cost of a SOFC locomotive is not offset by its improved fuel efficiency unless there are substantial increases in the cost of diesel fuel. The same author indicates that maintenance costs for the SOFC locomotive will be over three times higher than a conventional diesel-electric locomotive. This is equivalent to $3.75 per locomotive-mile.

The SOFC-gas turbine locomotive concept can also use natural gas as a fuel (Martinez, 2012a; Martinez, 2012b). To take advantage of potentially lower natural gas prices, this study considers a SOFC-gas turbine locomotive operating on liquefied natural gas. To operate on LNG, the SOFC locomotives require fuel tenders and LNG fueling infrastructure, similar to that described previously for diesel-LNG locomotives.

Preliminary research suggests that it may be technically feasible to develop a SOFC locomotive with suitable horsepower and tractive effort for line-haul freight applications.

Thus one-for-one replacement of conventional diesel-electric locomotives with SOFC locomotives is assumed for this study. Since the envisioned concept involves a fundamentally different energy conversion process, there is no traditional diesel prime mover onboard the SOFC locomotive. The locomotive is powered by the SOFC at all times and dual-mode operation is not a possibility. Therefore, a locomotive exchange is required to transition between SOFC and conventional diesel-electric operations.

2.5.3 Study Deployment Scenario

Due to the specialized SOFC and gas turbine equipment that differs greatly from conventional diesel-electric locomotives, this study assumes the SOFC locomotive is deployed in a captive regional fleet within the study area. For purposes of this study, all line-haul trains operating within the South Coast basin utilize SOFC locomotives within the basin. It is assumed that all trains exchange conventional diesel-electric and SOFC locomotives at a locomotive exchange point when entering or exiting the South Coast basin.

2.5.4 State of Development

For line-haul freight service, SOFC locomotives have achieved TRL 2: technology concept formulated. Development of the SOFC concept for line-haul freight service has been extremely limited:

- There are no working prototypes of the line-haul SOFC locomotive.
- Tests of hydrogen fuel cell locomotives such as the BNSF 1205 have been limited to light-duty switching assignments.

2.6 Electrification

Electrification technology involves the transmission of electricity from remote power generation stations to electric locomotives via overhead catenary wire suspended above the tracks. The electric locomotives simply convert the power supplied by the catenary to the proper voltage for use by the locomotive traction motors. The ability of electrification to power freight trains has been demonstrated by past use in North America and by its application to heavy haul freight operations in Sweden, Australia, South Africa and India (Fisher, 2008).

2.6.1 Potential Energy and Emissions Reductions

Since the conversion of chemical energy to electricity (and its associated energy loss) no longer takes place on the locomotive but is moved upstream, the amount of energy purchased by the railroads is likely to decrease.

By implementing electrification, all diesel gallons within the study area can be eliminated. However, as with the battery tender concept, the electricity for electric operations is drawn from the regional power grid. Thus, the actual emission savings are a function of the regional electric source generation profile. As shown previously (Table 2.2), only 40 percent of electricity consumed in California is from emission-free sources (EIA, 2014).

Like the battery tender concept, regenerative braking offers the potential to further decrease electrical energy consumption and source emissions. The catenary traction power distribution system can be used to transfer energy from electric locomotives in dynamic braking to electric locomotives on other trains that are consuming traction power. Unlike the battery tender concept, however, the regenerated energy cannot be stored. Regenerated power can only be used if there is a nearby train in the same power district to absorb the energy. In Europe, where mainline electrification is common and short passenger trains tend to operate on more frequent headways, train schedules are carefully choreographed to maximize use of regenerated energy (van der Meulen, 2013). Obtaining similar levels of regeneration within the study area is likely to be difficult due to the longer headways between heavy freight trains and the greater schedule flexibility of freight train operations. Due to the substantial daily variation in freight train operating patterns, this study does not consider regeneration in its evaluation of electrification.

2.6.2 Economic and Operational Considerations

It has been over 30 years since the last new electric line-haul freight locomotives were delivered in North America. The GF6C locomotives developed for the British Columbia Railway lacked many features, such as adhesion and wheel-slip control systems, common to the modern generation of diesel-electric locomotives (Rao, 1986). The IORE electric locomotives developed for use in northern Sweden are an example of modern electric freight locomotives with capabilities comparable to requirements for line-haul freight operation in the United States (Kuchta, 2011). The small size of the IORE locomotive fleet, however, skews locomotive production costs. The cost of a production line-haul electric locomotive with the same tractive effort and equivalent horsepower of a conventional diesel-electric freight is currently estimated at $5 million per unit by industry experts. It may also be technically feasible to retrofit Tier 0 diesel-electric locomotives for operation as electric locomotives at a cost of $3 million per unit. However, such a conversion has yet to be demonstrated in practice.

Electrification requires a significant infrastructure investment in the overhead catenary traction power distribution system. Recent studies have estimated the capital cost of electrification infrastructure at $4.8 million per track-mile (Cambridge Systematics, 2012). This figure only includes the capital cost of the overhead catenary traction power distribution system. To provide vertical clearance for the overhead catenary wires, existing tunnels, overpasses and other structures must be modified or reconstructed where insufficient clearance exists. These projects increase the estimated capital cost of electrification to approximately $50 million per route-mile (Caltrain, 2015).

Owing to their decreased complexity, maintenance costs for electric locomotives are 40 to 50 percent less than the cost of maintaining a comparable fleet of diesel-electric locomotives (Baumgartner, 2001). However, the overhead catenary traction power distribution system also requires maintenance at a cost of $30,000 per route-mile per year (Metrolinx, 2010).

Operating cost savings for electrification depend on the cost of electricity relative to diesel fuel and natural gas (Pinney, 2013).

One-for-one replacement of conventional diesel-electric locomotives with electric locomotives is conceptually possible if a new generation of purpose-built electric line-haul freight locomotives are developed for the North American market. Current European designs develop sufficient horsepower but lack the number of axles, axle loads and adhesion required to match the tractive effort of a North American line-haul diesel-electric locomotive. The electric locomotives do not require tenders but a locomotive change is required where the overhead catenary system ends.

Dual-mode locomotives capable of operating as conventional diesel-electrics or by drawing electric power from the wayside have been used for passenger service to avoid locomotive changes. However, a freight locomotive that functions with equal capability in either mode is currently impractical due to space and weight constraints. Dual-mode electric locomotives developed for use in Europe lack full capability when in diesel-electric mode (Vitins, 2012). The diesel is not capable of generating full horsepower and tractive effort and is only used for reduced-speed “last-mile” situations in terminals and on industrial sidings that lack overhead catenary.

2.6.3 Study Deployment Scenario

Since they are limited by the extent of capital-intensive overhead catenary, this study assumes electric locomotives are deployed as a captive regional fleet within the study area. For purposes of this study, all line-haul trains operating within the South Coast basin utilize electrification within the basin. Since dual-mode locomotives are not practical for line-haul applications, it is assumed all trains will exchange conventional diesel-electric and electric locomotives at a locomotive exchange point when entering or exiting the South Coast basin.

2.6.4 State of Development

Electrification with straight electric locomotives has achieved TRL 8: actual system qualified through test and demonstration. Two important points for the practical implementation of electrification for line-haul freight service are:

- Several isolated electric railroads exist in the United States and other electrified heavy-haul freight railways in service globally have demonstrated the capability of the traction power and distribution system.
- Further development is required to design, test and commercialize a modern line-haul electric freight locomotive tailored for operation in the United States.

2.7 Linear Synchronous Motor

The Linear Synchronous Motor (LSM) is an electric propulsion system for fixed guideways. The LSM makes use of linear electric motors mounted on the track structure to propel LSM "locomotives" equipped with permanent magnets along the track. While LSM has been applied to transit systems with short, purpose-built, multiple-unit rail vehicle consists, LSM for freight operations using conventional railcars in free interchange is merely a concept.

2.7.1 Potential Energy and Emissions Reductions

The LSM has some potential to improve the efficiency of the traction drive system and reduce energy consumption. In transit applications, the LSM has an electric-to-mechanical efficiency of 85 to 98 percent depending on the location of the vehicle relative to the power feed within the linear synchronous motor segment (Kaye, 2004). Diesel-electric locomotives have a traction drive efficiency of 85 percent. To be conservative and recognize potential inefficiencies of line-haul freight service (compared to controlled short-haul transit applications), for this study, the drive efficiency of the LSM is assumed to be 85 percent with an electric supply efficiency of 90 percent.

Conceptually, by implementing the LSM, all diesel gallons within the study area may be eliminated. However, as with the battery tender concept and electrification, the electricity for electric operations is drawn from the regional power grid. The actual emission savings are a function of the regional electric source generation profile. As shown previously (Table 2.2), only a portion of electricity consumed in California is from emission-free sources. The current LSM technology concept does not offer any potential for regenerative braking.

2.7.2 Economic and Operational Considerations

The LSM concept requires significant infrastructure investment in a power distribution system and the track-mounted linear motors. Recent studies have estimated the capital cost of LSM component materials at $5 million to $20 million per track-mile plus the cost of design, construction and project management (Cambridge Systematics, 2012).

The cost of LSM "locomotives" is unknown. One concept envisions development of a railcar frame fitted with permanent magnet motors to develop tractive effort in place of conventional locomotives (General Atomics, 2015). The high cost of permanent magnets and uncertainty in availability may make such a concept uneconomical for freight service.

Since the technology is in the preliminary stages of development, exact operating and maintenance costs are not known. The presence of the linear motors on top of the railway crossties will complicate the use of automated track maintenance machinery. There are numerous other operational questions that must be answered before a freight LSM can be tested, such as fail-safe mechanisms for providing train braking and speed control in the event the LSM loses electrical power,

Since it uses a radically different propulsion system, a locomotive change is required to transition between LSM and conventional diesel-electric operations. From current research, it is unclear if the LSM can generate the tractive effort required to directly replace a conventional diesel-electric locomotive consist. Additional LSM "locomotives" may be necessary to move a train of conventional length and weight. In addition to a locomotive change, train length and weight constraints may require splitting and combining trains at the edge of the reduced emissions study area. Current LSM technology developed for transit applications only allows for one vehicle (or group of "locomotives" coupled together) in each segment of the linear motor (Kaye, 2004). This restriction may prevent the use of distributed power configurations and limit overall train weight. Similarly, the length of LSM segments also limits train spacing, minimum headway and operational flexibility.

2.7.3 Study Deployment Scenario

Since their range is limited by the extent of the capital-intensive linear motor, this study assumes the LSM is deployed only within the study area. For purposes of this study, all line-haul trains operating within the South Coast basin utilize the LSM within the basin. It is assumed all trains will exchange conventional diesel-electric and LSM locomotives at a locomotive exchange point when entering or exiting the South Coast basin.

2.7.4 State of Development

The LSM has achieved TRL 5: component validation in real environment. Although the LSM has been used for fixed guideway passenger transportation within the context of various transit systems, it has yet to be demonstrated for freight rail service of any kind.

2.8 Summary

There is no "off the shelf" zero or near-zero emission locomotive technology for North American line-haul freight service. All of the presented locomotive technologies require additional research, development or commercialization before they can be implemented in line-haul service:

- Line-haul Tier 4 diesel-electric locomotives entered production in 2015 but locomotives with additional after-treatment to further reduce emissions are still in experimental stages of development. It is not known how far below Tier 4 levels emissions can be reduced through a combination of further diesel combustion process refinements and additional after-treatment.
- Diesel-LNG locomotives are still in demonstration and test service and the ability of diesel-LNG to achieve additional emissions reductions below Tier 4 levels is not known. Although prototypes exist and operate under waivers, standards for LNG tenders are still under development.
- Battery tenders for line-haul freight service are a concept with no working prototypes.
- There are no working SOFC line-haul locomotive prototypes. Other types of fuel cell locomotives have only been demonstrated in switching service.

- Further development is required to design, test and commercialize a modern line-haul electric freight locomotive tailored for operation in the United States.
- Although applied to transit, LSM has not been demonstrated for freight service and it is not known if the technology has the capability to handle the length and weight of typical freight train consists.

3 Line-Haul Freight Rail Operations, Interoperability and Safety

Previous studies have shown that Class 1 mainline operation accounts for the majority of locomotive emissions in California. While shortline, terminal, industrial and passenger rail operations in the state are served by a fleet of approximately 800 locomotives that largely operate within California, ARB inventories indicate that over 10,000 different locomotives enter California on mainline freight operations each year. Thus, mainline freight movements are the most significant consideration when implementing a zero or near-zero emissions locomotive fleet.

ARB has previously implemented a Statewide Rail Yard Agreement, but locomotives captive to yard, terminal, commuter or short-haul passenger service that tend to remain within a geographic area pose less of a logistical and operational challenge to upgrades with new technologies.

Because of these factors, the scope of this analysis is limited to freight rail operations with a focus on mainline line-haul train movements. This study considers mainline train movements that originate, terminate or pass through the South Coast Air Basin in California to the extent that such movements are impacted by locomotive requirements in the South Coast Air Basin.

Line-haul train movements are those moving long distances between different mainline origin and destination terminals. These trains are distinct from local freight services that may operate on the mainline while serving multiple individual rail shippers located on adjacent rail spurs or branchlines. The latter local train movements are not considered in this analysis as they consume less than 15 percent of the fuel consumed by freight rail operations.

3.1 California Line-Haul Rail Network

The majority of line-haul mainline freight rail service in California is provided by two Class 1 railroads: BNSF Railway (BNSF) and Union Pacific Railroad (UP). These two railroads provide freight service on four general corridors: Northern California to Oregon and Washington, Northern California to eastern destinations, Southern California to eastern destinations, and between Northern California and Southern California. While there are nearly 7,000 miles of railway in California, BNSF and UP line-haul freight service is concentrated on a smaller network of intrastate and interstate mainlines (Figure 1).

The mountainous nature of California limits the number of mainline connections between California and the rest of the national rail network. Interstate freight movements on the corridors described above pass through one of seven major rail crossings of California state borders:

- UP at Klamath Falls, Oregon
- BNSF at Klamath Falls, Oregon
- UP (with BNSF trackage rights) at Reno, Nevada
- UP (with BNSF trackage rights) at Portola, California
- UP at Las Vegas, Nevada
- BNSF at Needles, California
- UP at Yuma, Arizona

Statewide, over 200 trains are operated each day by BNSF and UP. Of these, approximately two-thirds originate, terminate or pass through the South Coast Air Basin in Southern California.

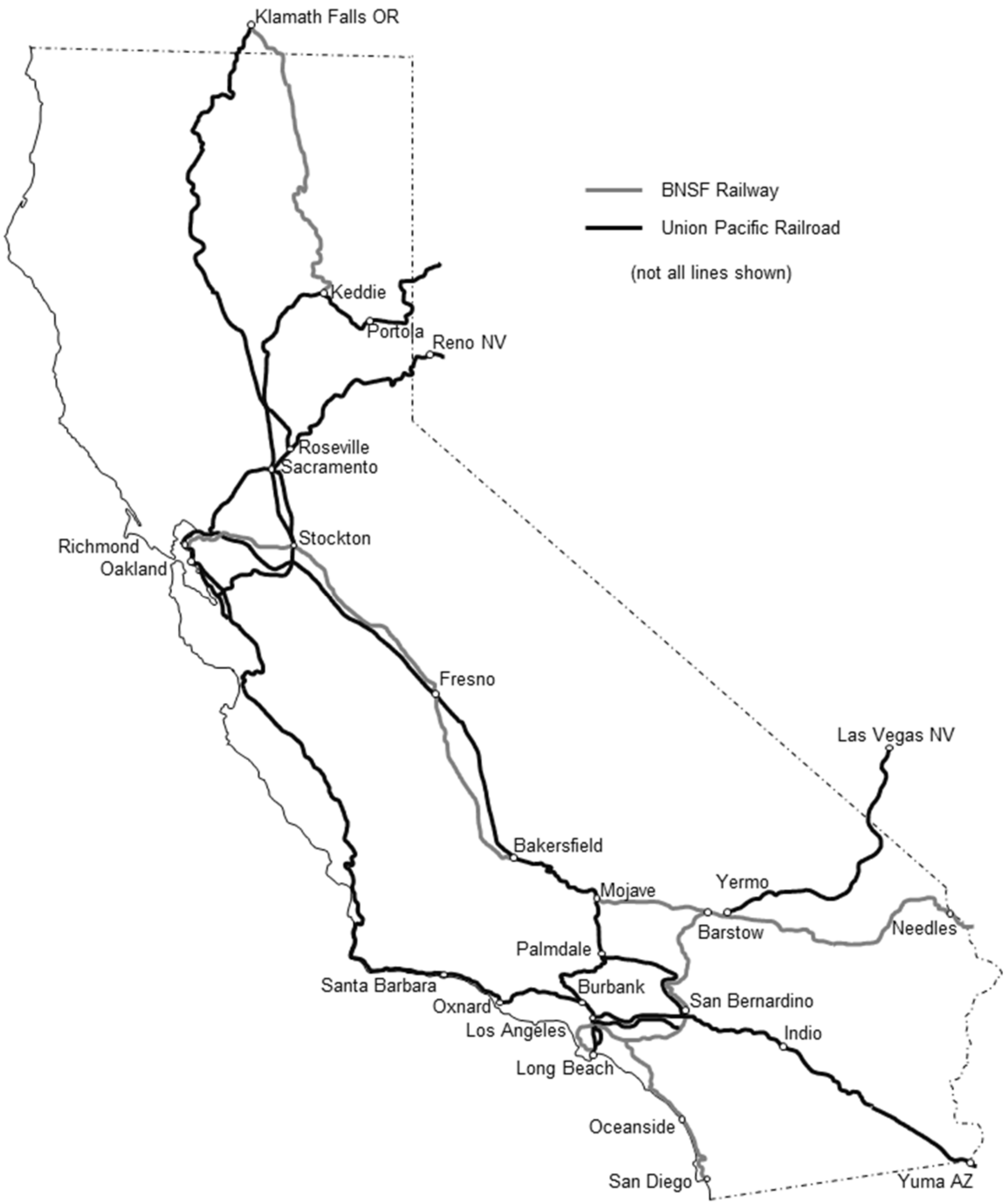

Figure 3-1, Map of line-haul freight rail network in California

3.2 Line-Haul Rail Network in Southern California

The South Coast Air Basin encompasses portions of Orange, Los Angeles, Riverside, and San Bernardino Counties in Southern California. A substantial network of freight rail mainlines exist within the basin to serve the San Pedro Bay ports of Los Angeles and Long Beach along with other key freight rail terminals located within the basin. Line-haul rail service enters and exits the basin via six different routes operated by BNSF and UP:

- Union Pacific Yuma Subdivision
- BNSF Cajon Subdivision
- Union Pacific Cima Subdivision (via trackage rights on BNSF Cajon Subdivision)
- Union Pacific Mojave Subdivision
- Union Pacific/Metrolink Valley Subdivision
- Union Pacific Santa Barbara Subdivision

BNSF also operates line-haul freight traffic to San Diego that exits the basin via track owned by the North County Transit District (San Diego Subdivision) and Southern California Regional Rail Authority (Metrolink Orange Subdivision). Approximately 60 miles at the southern end of the route to San Diego are outside the South Coast Air Basin. This portion of the route can only be reached by travelling through the South Coast Air Basin.

The routes and major rail terminal facilities served by each railroad are described in more detail in the following sections.

3.2.1 BNSF Railway

The BNSF Cajon Subdivision between Barstow and San Bernardino provides the only access for BNSF into the South Coast basin. Barstow is the location of a major hump classification yard with connections to Northern California and all eastern destinations on BNSF. Traffic between Northern California and the east does not enter the South Coast basin but may be sorted in the classification yard at Barstow. All manifest trains carrying carload traffic in the South Coast basin originate or terminate at Barstow. Although BNSF intermodal, auto and bulk trains bypass the classification yard, all trains stop in Barstow and San Bernardino to change crews. BNSF has a major intermodal terminal at San Bernardino.

From San Bernardino, there is one main BNSF route into Los Angeles (the San Bernardino Subdivision) to serve La Mirada (auto facility), Commerce (locomotive facility) and Hobart (intermodal terminal). The same line connects to the north end of the Alameda Corridor, a joint BNSF-UP route serving the ports of Los Angles and Long Beach. Altogether, the route from Barstow to the north end of the Alameda corridor is 152 miles in length.

Just west of Hobart, the San Bernardino Subdivision connects to the Harbor Subdivision. The Harbor Subdivision extends west in an arc to reach Watson and the ports. The Harbor Subdivision primarily serves local traffic except for the 2.5-mile section between Watson and the southern end of the Alameda Corridor. Line-haul freight trains moving south on the Alameda Corridor use this short segment of the Harbor Subdivision to access the BNSF yard at Watson.

Although intermodal traffic predominates, bulk trains of coal, grain, soda ash and ethanol are operated to Watson and the port. BNSF also operates daily manifest hauler trains from Barstow to San Diego, a smaller freight terminal at Kaiser and to interchange with Union Pacific at their West Colton classification yard.

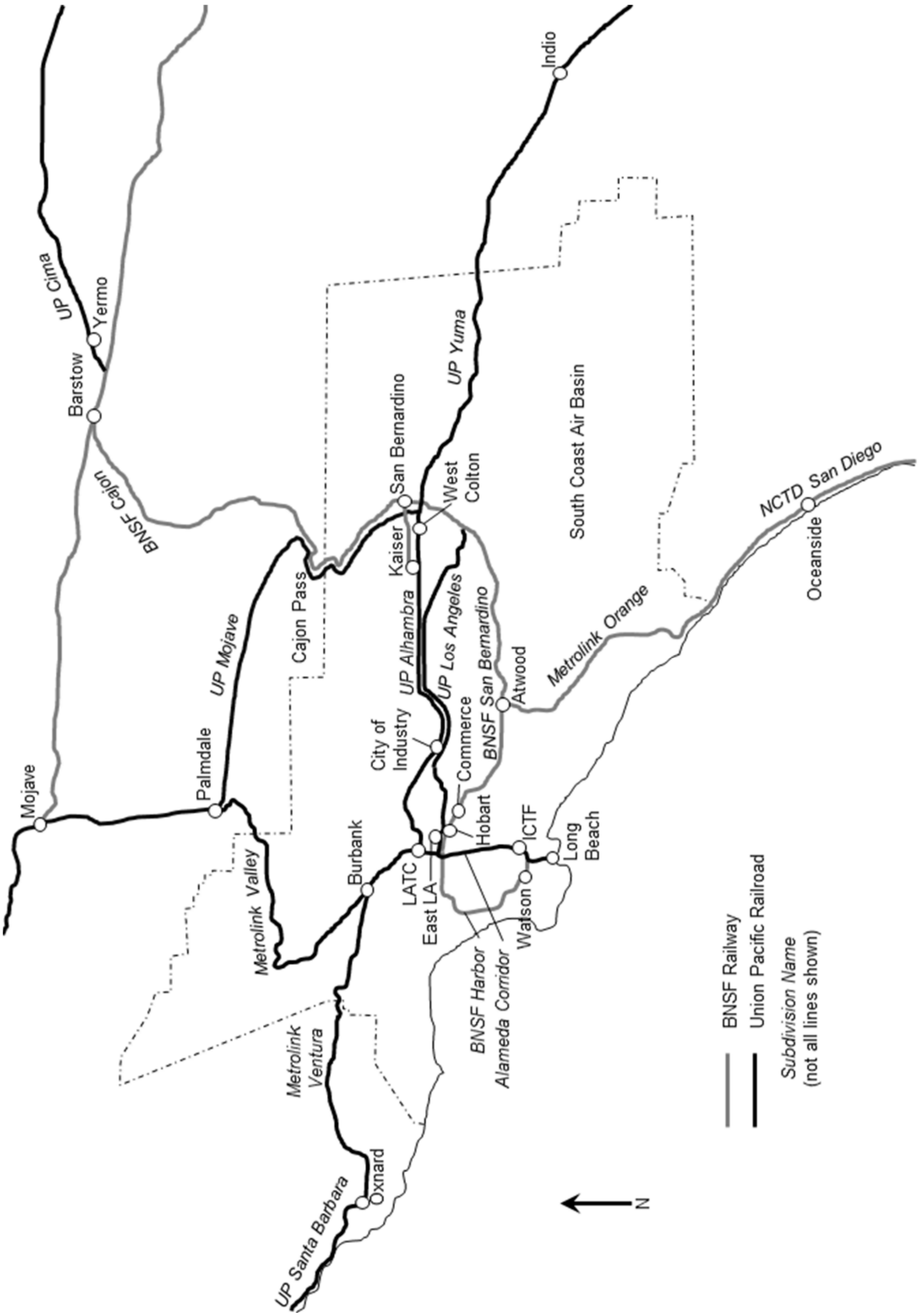

Figure 3-2, Map of line-haul freight rail network in Southern California

3.2.2 Union Pacific Railroad

The major Union Pacific hump classification yard facility is located at West Colton. The yard is served by multiple routes in and through the South Coast basin, a legacy of the 1996 merger of Southern Pacific into UP. All manifest trains carrying carload traffic in the South Coast basin originate or terminate at West Colton, including regional haulers to various smaller terminals in the basin. Unlike BNSF, traffic between Northern California and the east does enter the basin, even if it is not classified at West Colton.

The Yuma Subdivision extends east from West Colton to Indio on the "Sunset Route" through El Paso, Texas to eastern destinations. Some traffic for Midwestern destinations is routed over the Cima Subdivision to Las Vegas via trackage rights on BNSF over Cajon Pass.

Traffic for northern destinations can be routed over the Mojave Subdivision extending north from West Colton through Palmdale to Bakersfield, Northern California and destinations in the Pacific Northwest. This route is primarily used by manifest trains to points in Northern California and the Pacific Northwest. Intermodal trains to northern destinations typically follow an alternate routing via trackage rights on Metrolink through Glendale on the Valley Subdivision Saugus Route to Palmdale. Manifest trains for destinations on the Central California coast utilize the Santa Barbara subdivision Coast Line through Oxnard. This latter route handles crude oil shuttle train service between San Ardo and Dolores.

There are two main UP routes between West Colton and downtown Los Angeles. The first route, the Alhambra Subdivision, runs directly west from West Colton to the LATC intermodal terminal near downtown. The route makes connections to the Valley and Coast routes before turning south to connect to the Alameda Corridor and the ports of Los Angeles and Long Beach. Carload terminals are located along this route at Kaiser and City of Industry. An intermodal terminal is also located at City of Industry. The second route, the Los Angeles Subdivision, follows a more southerly route from a connection to BNSF trackage rights in West Riverside to a major intermodal terminal at East Los Angeles where many expedited intermodal trains originate. The route continues west to connect to the north end of the Alameda Corridor to the ports. This route also serves an auto terminal at Mira Loma.

Since portions of the Los Angeles Subdivision and most of the Alhambra Subdivision are single track with passing sidings, UP utilizes directional running to minimize delay due to train meets. Eastbound trains typically use the Los Angeles Subdivision while most westbound trains utilize the Alhambra Subdivision. Trains may need to operate against this general current of traffic to reach specific terminals.

3.3 Network Interoperability

The routes for freight rail movements in California and the South Coast basin are part of an integrated North American freight rail system that includes Mexico and Canada. The railways in North America operate under a common set of interchange rules that allow equipment from one railway to operate together in trains with equipment from any other railway. Common track standards allow railway equipment to operate on tracks owned by another railway. These industry agreements were established in the late 19th century to maintain interoperability as railways developed and adopted new rail vehicle and track technology. The concept of interoperability is central to the ability of the railway system to obtain the economies of scale necessary to provide efficient long-distance movement of freight at relatively low cost.

3.3.1 Interoperability of Locomotives

In the era of steam locomotives, when trains needed to stop every 100 miles for coal and water, it was common for a train to change locomotives multiple times while en route. Locomotives could be assigned to a particular district, and even a particular crew, operating back and forth between intermediate terminals and only handling a train for a short portion of its overall route. In this environment of frequent locomotive changes, locomotives never travelled very far from their routine maintenance facility and significant variation in motive power could exist between regions served by different terminals and between railroads.

The introduction of diesel-electric locomotives largely eliminated the need for frequent service stops. With trains no longer making extended servicing stops at frequent intervals, stops to change locomotives became an unnecessary source of delay and were gradually eliminated. As the length of locomotive assignments grew to cover multiple crew districts, it became desirable to have more uniformity across the locomotive fleet. Removing terminal-specific locomotive assignments increased locomotive utilization, decreased the size of the fleet and decreased costs. Still, railroad-specific practices introduced during the steam era of captive locomotives, such as different cab signal systems, prevented complete interoperability on the national network. During the 1970s and 1980s, to satisfy requirements for can signals and other onboard equipment, it was still common for locomotives to be changed when a run-through train was interchanged between railroads. When the number of major Class 1 railroads was reduced during the mergers of the 1990s, eliminating such incompatibilities to allow complete interoperability of locomotives across larger portions of the network was one of the economic drivers behind the creation of the larger rail systems. With large networks, railroads could make the economic business case to incur the expense of installing multiple sets of onboard signal equipment to avoid delay and inefficiencies associated with locomotive changes,

The Class 1 railroads have continually worked to remove barriers that prevent the seamless movement of freight. It is not uncommon for multiple railroads to partner on operating a single long-distance “run-through” service using a pool of locomotives and railcars from multiple carriers and private owners that traverse the entire route across track owned by different railroads. Thus, railroads that do not physically operate or own track in California may have significant numbers of locomotive and rolling stock assets in line-haul operation within the state at any time. In this manner, no part of the line-haul rail network operates in isolation and the status of the rail network in California can cause ripple effects that are felt by all rail carriers across North America.

3.3.2 Previous Experiences with Captive Regional Locomotive Technology

As stated earlier, since 1981, all line-haul freight rail operations in the United States have been powered by diesel-electric locomotives. Similar conditions have existed in Mexico since 1997 and in Canada since 2000. Prior to these dates, portions of the line-haul freight network in each country were electrified and operated with electric locomotives.

In the United States, there are many historical examples of short segments of mainline freight electrification on severe grades or through long tunnels where proper ventilation was expensive or difficult to achieve. These operations minimized train delay and locomotive utilization issues by keeping the conventional line-haul power on the train as it was pulled through the electrified zone by the electric locomotives. The process of adding electric locomotives to the front of the train consist is less complex and time consuming than a complete locomotive exchange. Despite minimal delays, all of these installations were eventually taken out of service in favor of conventional diesel-electric operations.

The most significant electrified mainline line-haul freight operation in the United States, and last to remain in service, was the route between New York, Philadelphia and Harrisburg, Pennsylvania, last operated by Conrail and now part of Norfolk Southern. Previous electrified networks operated by the Milwaukee Road and Norfolk & Western were removed from service in 1974 and 1962, respectively. Part of the reason for the longevity to the Harrisburg electrification is that it operated between two major gateway terminals at one extreme end of the Conrail network. Harrisburg was the location of Enola Yard, one of the largest hump classification yards in North America. The majority of trains traversing the electrified territory operated between an origin on the Philadelphia-New York electrified territory and Enola Yard for reclassification. With both origin and destination on the electrified territory, the trains did not need to make a mid-route locomotive change (Bezilla, 1980). The two other major electric operations that were discontinued years earlier were all located in the middle of train routes and away from major terminals, leading to locomotive changes, delay and logistical issues (Marchinchin, 2013).

In British Columbia, Canada, 84.5 miles of new mainline constructed by BC Rail to reach two new coal mines were electrified in 1984. This route segment operated with electric locomotives until 2000. Coal trains serving the mines executed a locomotive change at an exchange point located at the southern end of the electrification. The electric locomotives transported the empty trainsets to the mine for loading and return to the exchange point. During this process, the diesel-electric locomotives were staged in a siding track. The locomotive exchange facility was not placed at a crew change point; as crews completed the locomotive exchange, they continued their run with the new motive power. Since the volume of traffic never exceeded three loaded trains per day, logistical issues at the exchange point were minimized. The commodity being transported, coal for overseas export to Japan, was also not particularly sensitive to delays associated with the locomotive exchange operation. Electrified operations were terminated in 2000 as coal production at the mines was scaled back and BC Rail, previously operating as a government-owned corporation, was privatized through a lease to Canadian National.

In Mexico, a 154-mile segment of freight mainline between Mexico City and Queretaro was electrified with operations commencing in 1994. The electrification had originally been planned to extend to the major terminal in San Luis Potosi with fast, frequent shuttle train service between the two end points. Due to financial difficulties, the electrification was terminated in Queretaro, a location that was neither an existing locomotive servicing point nor a crew change point for through trains. The need for a mid-route locomotive change created delays and logistical issues with balancing motive power. When the route was privatized in 1997, electric operations were immediately terminated in favor of run-through diesel-electric locomotives.

In each case, maintenance of the overhead catenary system, and the capital cost of replacement or refurbishment at the end of its service life, is often cited as the primary reason for discontinuing electric operations. However, improved locomotive utilization and elimination of delay from locomotive changes were also significant factors.

3.3.3 European Experience

Although the rail network in Europe is interconnected and, in most countries, shares a common gage (distance between the rails), national rail systems were developed independently with different electrification and signal systems that do not support interoperability of locomotives between countries. As freight and passenger trains traverse Europe, they often stop at national frontiers to change locomotives. This lack of locomotive interoperability, and its associated increases in freight transit time, is cited as a key reason for the freight rail market share in Europe only reaching 8 percent (compared to 38 percent in the United States). Elimination of barriers to interoperability that prevent efficient long distance freight rail transport could double European freight market share to 16 percent (Fagan and Vassallo, 2005). Walker et al (2008) also stressed the need to maintain a seamless rail network in order to compete for freight market share with trucks.

In 2012, a European Union study of freight rail transport between central and southeast Europe surveyed rail service and interoperability issues at border crossings between seven different countries in Europe requiring locomotive exchanges (FLAVIA, 2012). The survey identified multiple crossings where freight was routinely delayed 60 to 120 minutes during the locomotive exchange and, where required, customs clearance procedures. Rail operations managers stationed at these points indicated that the primary source of delay was the availability of locomotives that did not arrive at the border crossing in time to connect properly with other arriving trains. Also, despite many of these crossings having eight or more parallel tracks to facilitate staging trains during the exchange, the managers indicated that they often encountered a shortage of exchange tracks. This required them to hold trains on the mainline outside the facility, causing extra congestion and further delay.

Within Britain, only 40 percent of the rail network is electrified. Diesel-electric locomotives are used to transport freight and passenger trains across the gaps in the electrification. A 2009 study by Network Rail examined the positive impacts of extending electrification across these gaps to provide interoperability and seamless movement of freight and passengers. Among the economic benefits cited was operational cost savings from avoided engine changes when able to operate an entire freight route as a completely electrified operation. The cost savings included both the direct costs of the locomotive change and also the risk of network disruptions and cascading train delays caused by missed locomotive connections. The report also indicated that moving to a single type of motive power would allow the locomotive fleet to be used more efficiently, leading to reductions in fleet size with associated capital cost savings. Finally, elimination of isolated diesel-electric locomotive operations would eliminate the cost of regional maintenance, servicing and fueling facilities in favor of larger, consolidated facilities for a single locomotive technology.

These findings are of particular interest when viewed from the perspective of creating regional locomotive fleets for reduced-emissions operations in Southern California. In such a situation, the exact opposite of the benefits highlighted by the Network Rail study should be anticipated: increased operating costs, delays and network disruption due to locomotive exchange, decreased locomotive utilization, increased locomotive fleet size and the capital cost of establishing extra regional alternative-technology locomotive maintenance, servicing and fueling facilities. According to the European experience, the net result of these outcomes will likely be a decrease in freight rail market share.

3.3.4 Regional versus Corridor-based Fleets

A 2014 report addressing sustainability strategies and air emissions of supply chains acknowledged that rail freight transportation in the United States is likely to cross multiple jurisdictions each with the ability to set their own air quality regulations (NCFRP, 2014). The report indicated that supply chain efficiency issues can arise where there are differences in the air emissions standards and the regulations applied between geographies. Dual standards or regulations can increase manufacturer costs and risks, and may cause difficulties for rail carriers. The report suggested that a corridor-based approach to freight transportation air emissions management can provide an effective way of planning, financing, and regulating freight movement. Consistent approaches allow optimal supply chain operations, keeping costs down, and maintaining certainty. The EU Green Freight Corridors concept is an example of this approach (NCFRP, 2014). Instead of regional regulations, the EU applies certain efficiency targets on specific cross-jurisdictional corridors with concentrations of freight traffic moving between major hubs. In terms of mainline freight railway emissions in California, instead of applying new locomotive technology to all trains traversing the air basin, the corridor-based approach would apply new locomotive technology to a select number of long-distance trains operating between major terminals on a particular corridor. While such an approach would alleviate the need for locomotive exchanges, the emission benefit would be global in scale along the entire route and not concentrated in the South Coast basin.

3.3.5 Regional Locomotive Fleets for Air Quality Purposes

There are few contemporary references on the feasibility of regional locomotive fleets in mainline freight service for air quality purposes. However, in the era of steam locomotives, smoke from railway operations was a major air quality concern in major cities with congested rail hubs. In the early 1900s, this was a particular concern in Chicago, Illinois and several rounds of studies were conducted to determine the feasibility of using electrification to replace all steam railway operations within city limits.

The Chicago smoke abatement and electrification study conducted between 1911 and 1915 shares many common elements with this study, including consideration of locomotive exchange points and their associated delay (Goss, 1915). In addition to both overhead and third-rail electrification of over 1,500 miles of mainline track, the study also considered the feasibility of electric locomotives with battery tenders, compressed air locomotives and early forms of locomotives using internal combustion. The study also considered the reliability of supplying the required electric power given the daily fluctuations in energy demanded by railway operations.

The economic analysis in the study included the cost of “transfer yards for the interchange of motive power on through freight and passenger train runs” at 18 different locations. The study acknowledged that the unscheduled nature of freight operations required the capability for simultaneous exchange of locomotives on multiple trains. Thus, depending on traffic volumes, each exchange point had up to four long tracks for performing locomotive exchanges. The proposed locomotive exchange yards included a total of 338 miles of track to provide sufficient staging for inbound freight trains and locomotive servicing.

The Chicago study observed that setting the boundary of electrified operations at the city limits as opposed to a strategic point for rail operations would be suboptimal due to operational convenience and potential land availability. In selecting an exchange location, the study considered the space and cost to relocate all existing steam locomotive facilities to the proposed exchange point. Where possible, the proposed exchange facilities were set at existing yards and key interchanges where trains were already stopping and locomotive and crew facilities may already be present. In some cases where a single facility served multiple mainlines owned by the same railway, the operator would need to establish multiple new facilities, one on each of the mainlines at remote locations beyond the city limits.

The study also considered the labor cost of hostlers and inspectors to perform inspections and test brakes at the exchange points. The authors concluded that at the time there was “no known method by which it is possible to estimate the cost of stopping a train, changing locomotives, testing brakes and setting the train motion again”. The authors used an industry survey to establish a value for the cost of stopping each train at exchange points. This cost included crew overtime due to train delay, damage to equipment during braking and switching, and extra fuel to restart the train.

The authors were also faced with the task of determining the required size of the captive electric locomotive fleet. The study acknowledges that the lack of freight schedules complicates the fleet sizing problem and there is a potential for train delay while waiting for locomotives to become available. To account for train bunching, on low volume lines, the fleet size was based on double the actual number of locomotive assignments, while a 25 percent buffer was used at higher volume exchange locations. In this context, the study identified the issue of run-through traffic from railroads that owned no track in Chicago but operated their trains into Chicago on the tracks of others. It was unclear to the authors of the study how these run-though operators would contribute to the cost of the captive locomotive fleet.

Finally the study considered that current steam locomotives released from service in Chicago provided some value to the railroads.

Many of these same issues and costs are addressed in the modern context of California, and the South Coast Air Basin in particular, in the subsequent sections of this report.

3.4 Safety

The railway industry in North America prides itself on delivering safe, efficient and economical freight transportation. An over-arching railway industry consideration in the selection of locomotive technology is safety. New locomotive technology, particularly those involving new fuels and sources of energy, will only be adopted after they have been satisfactorily demonstrated to not compromise the safety of train operations. Even new versions of conventional locomotive technology must undergo an extensive test and qualification program. This process may take several years and increase the timeline for adoption of new locomotive technologies, even if the associated technology is already developed. An excellent example of this is the current multi-year effort to develop new regulations and standards for liquefied natural gas fuel tenders (current tenders used in test service operate under Federal Railroad Administration waivers). Although a complete safety and risk analysis of each locomotive technology is beyond the scope of this study, the topic of safety is introduced here to acknowledge its importance. Locomotive technology decisions are not made on economic and operational factors alone; safety is also a priority.

4 Line-Haul Freight Rail Traffic and Energy Requirements

To provide a framework for evaluation of different locomotive technologies, the demand for line-haul freight rail transportation in California must be quantified. Three types of information are required on the various rail routes in California: traffic volume in tons, length of haul in miles (including the portion outside the state or study area) and commodities carried. Traffic volume in tons is required to support development of train locomotive and energy requirements. Length of haul relates to locomotive assignment. Both length of haul and commodity carried relate to the sensitivity of shipments to delay and potential mode shift.

To support later analysis of a statewide deployment scenario, this section first describes public statewide rail traffic data. This is followed by a description of more detailed data on train movements in the South Coast basin study area collected by ARB and approved by the railroads. Next an analysis of waybill data is conducted to verify the raw ARB train counts and supplement the traffic volume information with more detailed information on tonnage, length of haul and commodities involved. The information on train weight, length of haul and commodities is then used to determine the locomotive requirements for line-haul train operation in the South Coast basin. The locomotive, train and route characteristics and then used with a train performance calculator to construct an inventory of line-haul freight rail energy demand in the South Coast basin.

The energy demand calculation presented in this study, and subsequent economic and operations analysis, is based on available data and current rail traffic levels at the time of writing. No attempt is made to forecast future traffic demand.

4.1 Statewide Rail Traffic Data

Due to the competitive nature of freight rail transportation as a private business enterprise, public sources for comprehensive railroad and line-specific rail traffic data are few. Significant growth in traffic over the past decade has rendered the available sources obsolete in absolute terms (Table 4.1) but they are illustrative of relative traffic levels between routes. Intrastate movements on BNSF and UP are derived from line-haul operations on the north-south mainline corridors between northern and southern California.

The 2003 Railroad Traffic Atlas only provides traffic information on a coarse scale of million gross tons (MGT) of traffic (Ladd, 2003). More specific information on rail traffic in MGT for 2006 is provided in the 2008 California State Rail Plan (Caltrans, 2008).

Traffic volumes in gross tons have been converted to an average number of trains per day (TPD) at the rate of one train per day is equivalent to 1.8 MGT. This equivalency is based on the AAR industry average train size and average freight payload capacity per railcar (AAR, 2014).

The 2013 California State Rail Plan publishes traffic data from 2010 in a coarse MGT and trains per day format (Caltrans, 2013). The detailed, line-specific information included in 2008 is not present. On most lines, the 2010 data show traffic below 2006 levels due to economic effects that caused rail traffic to reach record levels in 2006 before declining. Rail traffic has since rebounded with intermodal traffic in 2013 eclipsing the peak levels of 2006 (AAR, 2014).

The three sets of data in Table 4.1 are largely consistent in their relative ranking of the various routes by traffic density and trains per day. The predominance of traffic on the three routes through Needles, Yuma and Las Vegas further supports the emphasis of this study on line-haul freight rail emissions in the South Coast basin.

Table 4.1: Historical Rail Traffic in Million Gross Tons (MGT) and Trains per Day (TPD) on Key Routes in California

Route	2003 MGT	2006 MGT	2010 MGT	2003 TPD	2006 TPD	2010 TPD
UP at Klamath Falls, Oregon	35	30	15	19	17	8
BNSF at Klamath Falls, Oregon	15	11	15	8	6	8
UP (BNSF track rights) at Portola, California	27	25	15	15	14	8
UP (BNSF track rights) at Reno, Nevada	25	35	30	14	19	17
UP at Las Vegas, Nevada	>40	44	30	>22	24	17
BNSF at Needles, California	>40	170	>100	>22	94	>60
UP at Yuma, Arizona	>40	85	75	>22	47	42
BNSF Intrastate	>40	48	50	>22	27	28
UP Intrastate	32	34	30	18	19	17

As a proxy for length of haul, origin-destination data from the 2007 Commodity Flow Survey (BTS, 2007) was analyzed to illustrate the distribution of rail traffic between California and various regions in the United States (Table 4.2). The table displays the fraction of interstate shipments, as measured in tons, moving to each region. The average length of haul is calculated by dividing the total number of ton-miles in a region by the total tons in that same region. The data for shipments from and to California include both “Rail Only” shipments and “Truck and Rail” intermodal shipments, as labelled in the Commodity Flow Survey.

Approximately 40 percent of shipments from California are moving less than 1,000 miles to states in neighboring regions. Due to competition from trucks, these short-haul shipments are particularly sensitive to increases in transit time and transportation cost. Over 13 percent of shipments from California are moving more than 3,000 miles. These are mainly intermodal shipments to major centers in the Northeast.

Table 4.2: Distribution of California Rail Shipments by Origin/Destination Region, 2007 Commodity Flow Survey

Origin/Destination Region	From California		To California	
	% Tons	Avg Haul (Miles)	% Tons	Avg Haul (Miles)
Pacific Northwest (OR, WA)	22	767	10	962
Mountain (AZ, CO, ID, MT, NM, NV, UT, WY)	18	709	16	998
West South Central (AR, LA, OK, TX)	12	1,628	20	1,789
West North Central (IA, KS, MN, MO, ND, NE, SD)	4	2,127	32	1,881
East South Central (AL, KY, MS, TN)	1	2,667	7	2,477
East North Central (IL, IN, MI, OH, WI)	17	2,390	13	2,299
South Atlantic (DE, FL, GA, MD, NC, SC, VA, WV)	12	2,952	2	2,907
Middle Atlantic (NJ, NY, PA)	13	3,139	<1	2,875
New England (CT, MA, ME, NH, RI, VT)	1	3,344	<1	3,200

Fewer inbound rail shipments to California are moving such long distances. Approximately 98 percent of inbound rail shipments to California are moving less than 2,500 miles. Just over one-half of the inbound rail shipments originate in the West South Central and West North Central regions. It is assumed that most of these shipments are related to agricultural and food production activities.

From a ton-mile perspective, the dominant rail traffic flows are outbound shipments to the East North central region surrounding Chicago and inbound shipments from the West North Central region on the Great Plains and Upper Midwest. Although the commodity flow survey does not provide mode-specific commodity information, these movements are consistent with intermodal traffic from California ports to the Chicago hub and inbound agricultural traffic and ethanol shipments.

The above differences in commodity flows are corroborated by rail shipment data for 2010 from the Association of American Railroads grouped by commodity type (Table 4.3). Outbound intermodal shipments are the single largest commodity movement by rail from and to California, accounting for half of outbound rail tons and three-quarters of outbound carloads. However, the state is a net importer of rail freight as measured by tons and carloads. Intermodal shipments, with their lower weight per carload shipment, make up a disproportionately larger share of carloads compared to bulk commodities.

Two commodities that comprise 81 percent of carloads from California and 51 percent of carloads to California, intermodal and food products, are particularly sensitive to transit time and operating cost. Increases in either of these parameters may cause these shipments to be diverted from rail to truck, particularly for shorter shipment distances.

Table 4.3: California Rail Shipments by Commodity (AAR, 2010)

Originated Commodity	Tons (million)	Tons (% of Total)	Carloads (thousand)	Carloads (% of Total)
Intermodal	29.1	52	2,311	75
Food Products	7.0	12	198	6
Chemicals	3.2	6	54	2
Stone, Sand, Gravel	2.3	4	37	1
Primary Metal Products	2.2	4	24	1
All Other	12.4	22	468	15
Total	56.3	--	3,093	--
Terminated Commodity	Tons (million)	Tons (% of Total)	Carloads (thousand)	Carloads (% of Total)
Intermodal	24.4	26	1,401	43
Farm Products	14.5	15	286	9
Food Products	14.0	15	268	8
Chemicals	11.6	12	177	5
Pulp and Paper	4.5	5	120	4
All Other	26.1	27	997	31
Total	95.1	--	3,249	--

4.2 South Coast Basin Rail Traffic Data

Since the majority of line-haul freight rail traffic in California is operating, from, to or through the South Coast basin study area, these rail movements are described in more detail.

4.2.1 Public Data and Previous Studies

Rail traffic counts in trains per day from two previous studies on lines transiting the South Coast basin (Table 4.4) were found in the literature. The 2006 data were based on tonnage maps in the 2008 California State Rail Plan (Caltrans, 2008). The 2010 data are based on several months of actual train counts supplied by BNSF and UP to the authors of a 2011 goods movement study (Leachman, 2011). The 2010 data only cover a subset of the most congested lines in the South Coast basin so information on some routes is not available.

The relative differences in train counts between the two studies exhibit the national decline in freight rail traffic between 2006 and 2010. In both cases, rail traffic flow through the South Coast is dominated by movements on the three main routes to the east with fewer trains exiting the basin on the routes to the north.

Table 4.4: Historical Rail Traffic in Trains per Day (TPD) on Routes Transiting the South Coast Basin (Caltrans, 2008; Leachman, 2011)

Route	2006 Caltrans	2010 Leachman
Union Pacific Santa Barbara Subdivision	4	N/A
Union Pacific /Metrolink Valley Subdivision	4	N/A
Union Pacific Mojave Subdivision	9	6.0
Union Pacific Cima Subdivision (via Cajon)	20	17.2
BNSF Cajon Subdivision	77	58.7
Union Pacific Yuma Subdivision	50	38.5
BNSF/NCTD San Diego Subdivision	N/A	N/A

N/A = these routes were not included in this report

4.2.2 ARB South Coast Basin Train Counts

To support more detailed analysis of train movements in the South Coast, ARB provided the research team with data on trains per day by route compiled from their own investigation of public sources and railroad reporting to ARB. Unlike previous studies aimed at capturing more widespread rail traffic patterns, this data was more focused on determining train counts on line segments near the air basin boundary to support analysis of potential locomotive exchange points. For each route, additional information on train type and train origin-destination pairs were collected and provided to the research team. The train types, origins and destinations allow the commodities and length of haul on each route to be characterized. This information is required to support analysis of operating cost and mode shift due to exchange point delay.

The train counts by train type on each route (Table 4.5) were verified by BNSF and UP for use in this study. Non-integer values of average trains per day are caused by trains that only operate on certain days of the week. In the train count data, priority (or expedited) intermodal trains are counted separately from medium and low priority intermodal traffic since they have a different sensitivity to delay and operating cost. Medium and low-priority intermodal traffic are both included in the intermodal category. Manifest trains handle carload traffic between major classification yards and smaller terminals where local trains serving individual shippers are based. The "Other" category includes unit train shipments of coal, soda ash, crude oil and ethanol, along with dedicated trains of automobile traffic.

The train counts in Table 4.5 are carried forward as the basis for the exchange point analysis in later sections of this report.

Table 4.5: Average Trains per Day in 2013 by Train Type on Routes Transiting the South Coast Basin

Route	Priority Intermodal	Intermodal	Manifest	Other	Total
Union Pacific Santa Barbara Subdivision	--	--	--	1.0	1.0
Union Pacific /Metrolink Valley Subdivision	5.1	0.5	--	--	5.6
Union Pacific Mojave Subdivision	--	--	6.8	0.9	7.7
Union Pacific Cima Subdivision (via Cajon)	0.6	3.6	4.0	1.0	9.1
BNSF Cajon Subdivision	18.0	37.7	8.0	3.2	66.9
Union Pacific Yuma Subdivision	11.4	14.2	10.0	4.3	39.9
BNSF/NCTD San Diego Subdivision*	--	--	4.0*	--	4.0*

*San Diego trains transit the BNSF Cajon Subdivision and are also included in that total.

4.2.3 ARB South Coast Basin Train Configurations

Distributed power locomotive technology allows the crew in the lead locomotive at the front of a train to remotely control locomotives located at the middle and rear of a train consist. By better managing in-train forces and train braking, distributed power can facilitate operation of longer, heavier trains that lower operating cost through economies of scale. Distributed power train configurations are an important consideration for this study since locomotives on the rear or middle of a train can complicate the locomotive exchange process, leading to additional train delay. Additional locomotive exchange point track infrastructure is required to accommodate exchanges of mid-train locomotives, increasing the cost of these facilities. Additional hostler crews may also be required to exchange multiple sets of locomotives on a single train in a timely manner. Thus, in addition to raw train counts, knowledge of the locomotive power configuration used on each train is required to adequately assess delay and infrastructure requirements at each exchange point.

Not all trains operate with distributed power. Train weight, length, make-up, route grade profile, power requirements and operating rules are all considered in to the decision to operate a train with a distributed power configuration. Distributed power operation is also subject to locomotive availability as not all locomotive units are equipped with the necessary radio control equipment. Each group of coupled locomotives distributed throughout the train must have at least one locomotive equipped with distributed power technology. The lead locomotive of the train must also be equipped with the distributed power control technology. These constraints further complicate the locomotive exchange process as additional switching may be required to obtain the correct grouping and orientation of locomotives when motive power is removed from one train to another. Turning facilities in the form of a wye or balloon track may be necessary at the locomotive exchange points.

ARB provided the research team with data on distributed power train configurations in the South Coast by railroad and train type (Table 4.6). The data was verified by both BNSF and UP for use in this study. Since the data for each railroad covers all train operations in the basin, and UP trains move on multiple routes, it is assumed that the ratios of train configurations for each train type hold constant on the various UP routes. Since BNSF traffic is concentrated on a single route, the distribution of BNSF train configurations can be applied directly to the BNSF route.

It is apparent from the collected data that UP makes more extensive use of distributed power in the South Coast basin compared to BNSF. The most significant difference between the two railroads is the configuration of priority intermodal trains. Almost 90 percent of BNSF priority intermodal trains operate as conventional train consists without distributed power. On UP, approximately 75 percent of the priority intermodal trains operate with distributed power on the rear of the train.

Very few trains were observed with mid-train distributed power and neither railroad was found to use distributed power locomotives at the middle and rear of the train simultaneously. However, both railroads indicate that they plan to increase train length and use of distributed power in the future. As more double track and longer passing sidings are installed on key routes, UP plans to more frequently operate longer intermodal trains that, according to air brake rules, will require mid-train distributed power locomotives.

Table 4.6: BNSF and UP Distribution of Train Configuration in percent by Train Type on Routes Transiting the South Coast Basin

BNSF Train Configuration	Priority Intermodal	Intermodal	Manifest	Other	Total
Front Only (X-0-0)	88.9	62.9	75	62.5	71.6
Front and Rear (X-0-X)	11.1	37.1	25	37.5	28.4
Front and Middle (X-X-0)	0.0	0.0	0.0	0.0	0.0
Front, Middle and Rear (X-X-X)	0.0	0.0	0.0	0.0	0.0
UP Train Configuration	Priority Intermodal	Intermodal	Manifest	Other	Total
Front Only (X-0-0)	24.9	42.1	21.7	73.8	34.1
Front and Rear (X-0-X)	75.1	58.5	76.3	26.2	65.2
Front and Middle (X-X-0)	0.0	0.0	2.0	0.0	0.7
Front, Middle and Rear (X-X-X)	0.0	0.0	0.0	0.0	0.0

4.3 South Coast Train Traffic from Waybill Data

Although it includes train counts for specific types of trains, the rail traffic data discussed above does not include information on train length, train weight specific commodities and length of haul outside the South Coast basin. Both of these items are required to support the analysis of locomotive requirements, energy cost and modal shift due to exchange point delay. This study, information on length of haul and specific commodity movements was obtained from the Surface Transportation Board 2011 Carload Waybill Sample (STB, 2012).

4.3.1 South Coast Rail Commodity Analysis

The STB Carload Waybill Sample provides data on individual rail shipments in North America, including commodity shipped, origin, destination, junctions, railroads involved, weight, type of railcar, and type of service. Since different commodities traveling different distances have varying sensitivity to delay, the ARB train counts for UP and BNSF are supplemented with information from the waybill data on specific commodities handled and overall shipment distance.

Origin and destination data is provided at several levels in the waybill sample, including state, county and Freight Station Accounting Code (FSAC). Since the boundaries of the South Coast Air Basin include parts of different counties, creation of a subset of waybills for shipments originating and terminating in the South Coast basin required development of a FSAC list for the basin. The Railinc Centralized Station Master File contains geographic information for each rail shipping point, including zip code and FSAC (Railinc, 2013). A list of zip codes within the South Coast basin was cross referenced against the station master file to generate the South Coast FSAC list.

The waybill sample records were then filtered by origin, destination and interchange FSAC according to the South Coast FSAC list to create a subset of rail shipments transiting the study area. Inspection of the data revealed that multiple non-basin shipments had been captured by the filtering process due to errors in the FSAC field or multiple locations in different states being assigned the same FSAC within the station master file. The data was filtered again by state and county to remove these records.

Each waybill record includes the Standard Transportation Commodity Code (STCC) identifying the product designation for the commodity being transported. The first two digits (including leading zeroes) of the STCC identify a high-level commodity grouping. For purposes of this study, the two-digit STCC commodity types are further aggregated into nine commodity groups based on similar groupings used in the Freight Analysis Framework (FAF). The FAF-based commodity groups are created to aggregate different commodities on the basis of the value of each product shipped. Since product value is one of the parameters used to determine freight modal split, the FAF-based groups (Table 4.7) are of more utility in this study.

The carload waybill data does not include every shipment in 2011. Instead, the waybill data is a structured stratified statistical sample of shipments, with sampling rates that vary between 1-in-2 and 1-in-40, depending on the type of shipment. Thus, each record in the database represents a larger number of actual shipments. Any statistics derived from the waybill sample, such as tons and number of carloads, must be inflated according to an expansion factor to produce true values. The expansion factor is the inverse of the sampling rate for each waybill strata. Since the expansion factor varies for each individual waybill, the expansion must be done at the lowest level of analysis before individual waybill shipments are aggregated.

The waybill sample data includes information on shipment distance. The total rail miles for each waybill shipment are not reported directly by the railroads as part of the waybill sampling process. Instead, shipment distance is derived from routing information developed when the waybills are processed to create the STB carload waybill sample. Using the derived shipment distance included in the waybill data, a commodity-shipment distance profile was created for rail shipments transiting the South Coast in 2011 (Table 4.8).

Table 4.7: STCC Codes and Descriptions Corresponding to Value-Based Commodity Groups Used in the Study

Commodity Group	Two-Digit STCC	STCC Commodity Description
1	01 09	Farm Products Fresh Fish or Other Marine Products
2	21 20	Tobacco Products; except Insecticides Food or Kindred Products
3	10 32	Metallic Ores Clay, Concrete, Glass or Stone Products
4	11 13 29	Coal Crude Petroleum, Natural Gas or Gasoline Petroleum or Coal Products
5	28 30 48 49	Chemicals or Allied Products Rubber or Miscellaneous Plastics Products Hazardous Wastes Hazardous Materials
6	08 22 24 26 27 31	Forest Products Textile Mill Products Lumber or Wood Products; except Furniture Pulp, Paper or Allied Products Printed Matter Leather or Leather Products
7	14 19 33 34 35 36	Non-metallic Minerals; except Fuels Ordnance or Accessories Primary Metal Products, including Galvanized Fabricated Metal Products; except Ordnance Machinery; except Electrical Electrical Machinery, Equipment or Supplies
8	37 38	Transportation Equipment Instruments, Photographic Goods, Optical Goods, Watches or Cl
9	23 25 39 40 41 42 43 44 45 46 47 50	Apparel, or Other Finished Textile Products or Knit Apparel Furniture or Fixtures Miscellaneous Products of Manufacturing Waste or Scrap Materials Not Identified by Producing Industry Miscellaneous Freight Shipments Containers, Carriers or Devices, Shipping, Returned Empty Mail, Express or Other Contract Traffic Freight Forwarder Traffic Shipper Association or Similar Traffic Miscellaneous Mixed Shipments Small Packaged Freight Shipments Bulk Commodity Shipments in Boxcars

Table 4.8: South Coast Basin Rail Shipments in 2011 by Commodity Group and Shipment Distance (Thousands of Tons)

Commodity Group	Distance (miles)					
	0-500	500-1,000	1,000-1,500	1,500-2,000	>2,000	All
1	76	5	146	546	4,554	5,327
2	1,547	291	348	429	1,413	4,027
3	173	14	19	137	78	421
4	462	2,428	200	68	12	3,170
5	4,911	248	1,190	1,214	2,336	9,852
6	1,381	59	310	694	1,044	3,488
7	6,899	56	153	200	1,033	8,311
8	41	15	357	44	424	566
9	469	3,726	8,566	12,692	39,759	64,769
All Groups	15,959	6,841	11,288	16,024	50,623	99,931

Based on the waybill analysis, in 2011, 99.9 million tons of rail freight originated or terminated in the South Coast basin. This corresponds to roughly two-thirds of the approximately 150 million tons of freight shipped by rail to and from California as reported by the AAR. Approximately one half of shipments are moving over 2,000 miles by rail. Short-haul shipments less than 500 miles in length account for 16 percent of tons shipped by rail. These short-haul movements can be particularly sensitive to transit time and delays.

Commodity Group 9, corresponding to most intermodal shipments, accounts for 65 percent, nearly two-thirds, of all tons shipped by rail. None of the other commodity groups alone account for more than 10 percent of tons shipped.

The single largest commodity movement by distance is the combination of Group 9 (intermodal) transported more than 2,000 miles by rail, with approximately 40 percent of all tons shipped by rail to and from the South Coast basin falling into this category. Although these long-distance intermodal shipments have less competition from trucks compared to short-haul movements, due to the value of the goods transported, inventory costs and service penalties, they are still sensitive to transit time and delay.

4.3.2 Traffic to Train Assignment

While the previous section provides a general breakdown of commodities and shipment distances for all South Coast rail shipments, finer detail is required for this study since different trains on different routes may experience differing amounts of delay under scenarios involving locomotive exchange. Thus, the South Coast waybill data was subjected to further analysis to create a commodity and shipment distance profile for each specific train type and origin-destination movement (train symbol).

The South Coast waybills were first divided between BNSF and UP shipments for separate analysis. Once divided by railroad, the waybills were further split into intermodal (truck-rail) and non-intermodal shipments using the service type field in the carload waybill sample database. This creates four pools of traffic for assignment to trains: BNSF Intermodal, BNSF Non-Intermodal, UP Intermodal and UP Non-Intermodal.

Based on the train symbols in the train count data for each railroad and route provided by ARB, a list of train runs by train type and origin-destination pair was created. For each train origin/destination outside the South Coast basin, a local capture area was defined based on the type of train service. Waybills with origin/destinations within each capture region were then assigned to the corresponding train run origin/destination. For simplicity and ease of analysis, the local capture areas were defined according to state boundaries. For states with multiple train run origin/destinations, traffic was apportioned to each capture area based on train frequency. Similarly, within the South Coast, the waybills were assigned to individual yard and terminal origin/destinations based on FSAC county, service type and commodity. Splitting the waybills in this manner creates a pool of shipments for each railroad and service type between each origin-destination pair. These waybills are then assigned to the appropriate train run to create a commodity-type profile for that train.

A single waybill can represent a single carload of freight or a shipment involving multiple carloads moving together. Individual trailers or containers on intermodal trains typically have their own waybill, even if they share the same multi-platform railcar. Thus, care must be taken when translating the number of waybills into the length, number of carloads and tare weight of each train. For non-intermodal freight, the waybill data specifies the number of railcars moving under that waybill. For intermodal shipments, it is rare for a single waybill to correspond to a single trailer or container on a single railcar. A 5-unit well car carrying ten containers may involve ten separate waybills, each listing the same railcar and the entire tare weight of all five articulated units. If, in calculating the weight of a train, the tare weight listed on each waybill is summed, the tare weight of the same 5-unit well car would be included ten times, grossly overstating the tare weight of the train.

To avoid counting intermodal railcars multiple times, the waybill sample fields specifying equipment type (single platform or well car) and number of articulated units are used to determine the number of available container/trailer slots for the railcar listed on a particular waybill. Based on the number of available slots, each container or trailer waybill is then assigned an appropriate fraction of the tare weight of the railcar.

A shortcoming of the carload waybill sample is that it lacks any data on empty car movements. Although not needed for the usual analysis of transportation productivity conducted with the waybill sample, not every train is fully loaded and energy is required to move empty railcars. Thus, to construct a line-haul freight rail transportation energy inventory for the South Coast, appropriate numbers of empty cars must be added to each train run.

Following the methods of other researchers, the study team used empty railcar ratios to estimate the number of empty railcars to assign to each corresponding train movement (Cambridge Systematics, 2007, Tolliver, 2014). For each railcar type, an empty railcar ratio is calculated from the number of empty and loaded car-miles published in the Analysis of Class 1 Railroads R-1 data (AAR, 2012). Multiplying the appropriate empty railcar ratio by the number of loaded railcars of a particular type on a train run provides an estimate of the number of empty cars of that type to include on the reverse train movement. For example, consider a case where the train from A to B (AB) has 50 loaded railcars, the train from B to A (BA) has 30 loaded railcars and the empty car ratio is 0.5 (Figure 4-1). The 50 loaded railcars on AB generate 25 empty railcars assigned to train BA, and the 30 loaded railcars on BA generate 15 empty railcars assigned to train AB. Through this assignment, train AB will have 50 loaded and 15 empty railcars for a total of 65 while train BA will have 30 loaded and 25 empty railcars for a total of 55.

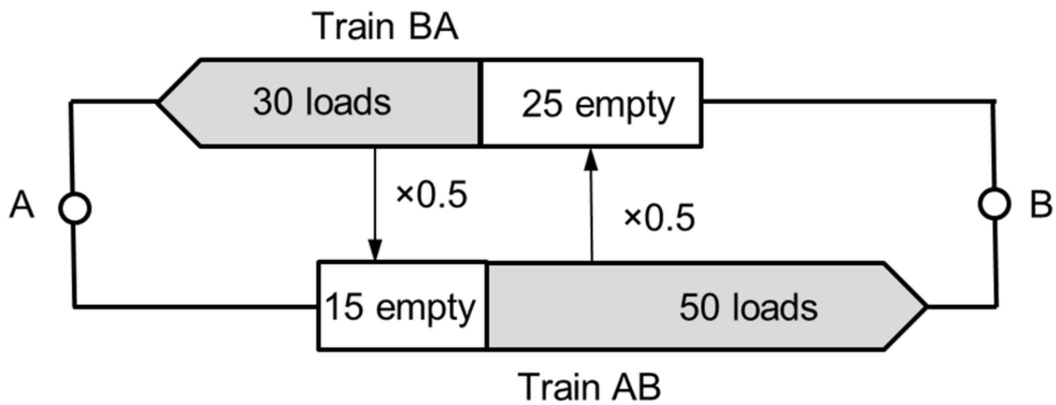

Figure 4-1, Example derivation of empty railcar movements with empty railcar ratio

Once the empty cars were assigned, the total empty and loaded railcar weights were added to determine the total weight of shipments assigned to a particular train run. The aggregated traffic was then transformed into an average individual train movement for a particular train symbol by dividing the annual totals by the number of train runs each year. This average train movement retains its commodity group make-up to support later delay and mode shift analysis.

At the conclusion of the train assignment process, the calculated train sizes were examined for reasonableness. The train frequency of a small number of overly-long and overly-short trains was adjusted slightly to provide acceptable values for train length and weight. Overall the majority of train runs fell within the expected range, providing additional verification to the train counts by origin-destination provided by ARB in Table 4.5.

4.4 Locomotive Requirements

The next step in the analysis of rail traffic data is to determine the number of locomotives required to power line-haul freight trains that transit the South Coast.

4.4.1 Locomotive Assignment Methodology

Once total tonnage is known for each train, a number of locomotives are assigned to each train based on horsepower per trailing-ton (HP/TT) methodology. For use with this study, UP and BNSF both provided horsepower-based locomotive assignment factors for routes in California (Table 4.9). In practice, UP uses a more complicated route-specific tons-per-axle locomotive assignment methodology.

Table 4.9: Horsepower per Trailing Ton by Railroad and Train Type

	Train Type			
Railroad	Premium Intermodal	Intermodal	Manifest	Bulk
UP	3.5	3.5	2.5	0.9
BNSF	4.0	3.0	3.0	3.0

The total number of trailing tons is the sum of the tons of freight hauled by the train and the tare weight of all loaded and empty railcars in the train. For purposes of this study, it is assumed that all mainline line-haul locomotives produce 4,400 horsepower. Thus the number of locomotives is calculated as follows:

Number of Locomotives = (Trailing Tons) × (Horsepower per Trailing Ton Factor) ÷ 4,400

To avoid assigning excessive numbers of locomotives to some of the heavier trains generated by the waybill data, for purposes of this study, trains are restricted to a maximum of six locomotives or 26,400 horsepower.

4.4.2 Fleet Sizing Methodology

After calculating the number of locomotives assigned to each train, the instantaneous number of trains en route between each train symbol origin-destination involving the South Coast was estimated. The number of trains and locomotives per train can be multiplied to provide an estimated “fleet size” for current line-haul freight train operations involving the South Coast. This metric is not a true “fleet size” as locomotives are not dedicated to operation on trains serving the South Coast (ARB data shows that thousands of unique locomotives transit the South Coast basin each year). Instead, this metric is the typical instantaneous number of locomotives that must be allocated to operation of trains serving the South Coast. This value serves as a baseline for comparison to later calculation of new technology locomotive fleet sizes.

To calculate the allocated number of locomotives, the entirety of all train runs involving route segments within the South Coast basin are considered in isolation from the rest of the rail network. This effectively creates a large hub-and-spoke network centered on the South Coast with the ends of the spokes at train symbol destinations such as Chicago, Kansas City, Dallas etc. In the calculation, locomotives are assumed to cycle within this network, moving from the South Coast to a remote terminal and then returning on the next train departing from that terminal back to the South Coast. This simplified approach does not allow locomotives arriving at a remote terminal to be repositioned to a different terminal or depart for other destinations on trains that do not transit the South Coast. Thus there may be some inefficiency in locomotive assignment where trains operate to a remote terminal at less than daily frequencies. However, by not taking advantage of these opportunities, the approach is conservative and will result in a larger fleet size. Similar assumptions are made within the South Coast. For example, locomotives arriving at Long Beach from Chicago are assumed to be held for the next train to Chicago from Long Beach and are not repositioned to depart on a train from West Colton.

The fleet size calculation is accomplished via Little’s Law where, for each train symbol run:

Number of trains online = Train travel time (days) × Average train frequency (trains per day).

Number of locomotives online = Number of trains online × Number of locomotives per train

For example, if a train symbol requiring four locomotives is scheduled to depart twice per day and each departure requires 72 hours (three days) to complete its one-way journey, at any instant there would be six editions of this train online requiring a total of 24 locomotives. Assuming locomotive availability of 85 percent, a pool of 28 locomotives would be allocated to support this train movement at any given time.

Train frequency is based on the train symbol frequencies provided by ARB as reconciled with the train frequencies indicated by the waybill data. The travel time for each train was estimated using the one-way rail distance between origin and destination terminal and average train speed. The values for average train speed are specific to each railroad and three different types of trains (Table 4.10), representing an average for train operations during the 2013 calendar year (Railroad Performance Measures, 2014).

Table 4.10: Average Train Speed in Miles per Hour by Type (Railroad Performance Measures, 2013)

Railroad	Intermodal	Manifest	Bulk Unit
BNSF Railway	31.5	18.5	18.8
Union Pacific Railroad	30.5	21.3	25.5

4.4.3 Baseline Locomotive Demand

According to the baseline diesel-electric locomotive fleet size calculation (Table 4.11), a total of 2,022 diesel-electric locomotives (4,400 horsepower each) are required to support operations of all line-haul trains transiting the South Coast basin at a given instant. Only a portion of these 2,022 locomotives are actually operating within the South Coast basin at any given time. The remainder is operating outside the South Coast basin as trains continue their run to remote terminals.

As mentioned in the previous section, in practice, locomotives are not specifically allocated to operation on trains serving the South Coast. To increase utilization by making the most efficient connections between trains, locomotives arriving from the South Coast at a remote terminal may not immediately return to the South Coast. Instead the locomotives may be assigned to several other trains and pass through multiple remote terminals before once again being assigned to a train bound for the South Coast. Thus, the 2,022 locomotives required to operate all line-haul trains transiting the South Coast at any given moment must be drawn from a much larger fleet of locomotives that serve other freight corridors in addition to the South Coast. Assuming that each locomotive spends one-third of its time operating on trains serving the South Coast, a fleet of over 6,000 locomotives is required to supply the South Coast trains with 2,022 locomotives at any given time. If specific locomotive modifications were required for freight trains to transit the South Coast, the railroads must either equip all of the over 6,000 locomotives in this larger fleet with the necessary modifications to maintain current operating patterns or utilize the exchange point concept (Section 2.4.3) and modify a smaller number of locomotives captive to the South Coast.

Section 6 will transform this baseline fleet calculation into conventional and alternative technology locomotive fleet sizes for operation of the South Coast trains under study with exchange points.

Table 4.11: Baseline Conventional Locomotive Fleet Size and Allocation by Route

Route	Locomotives
Union Pacific Santa Barbara Subdivision	8
Union Pacific /Metrolink Valley Subdivision	29
Union Pacific Mojave Subdivision	47
BNSF Cajon Subdivision	1,242
Union Pacific Cima Subdivision (via Cajon)	151
Union Pacific Yuma Subdivision	534
BNSF San Diego	11
Total	2,022

4.5 Baseline Energy Requirements

Train energy consumption is often estimated with gross annual average metrics of fuel efficiency. However, previous research has shown train energy consumption can vary greatly by type of train and route (Sierra Research, 2004; Fullerton, 2015). Intermodal trains, the dominant type of traffic in the South Coast, can be particularly inefficient (Sierra Research, 2004; Lai, 2008). Since train operations involving the South Coast include a diverse set of train types and sizes operating over mountainous terrain, the study team used route data and a train performance calculator to determine the energy consumption of individual train runs within the South Coast basin. The approach of using computer train performance simulation to improve transportation energy efficiency was first used for this purpose by Hopkins (1975).

4.5.1 Route Data

Engineering data for the seven mainline Class 1 routes that provide access to the South Coast basin and additional mainline routes to destination terminals within the basin were extracted from track charts provided by the railroads. The track charts provide detailed information on grade, curvature, and speed limits required to calculate the energy consumption of each train.

4.5.2 Train Performance Simulation

A Visual Basic (VBA) train performance simulation software program was used to calculate the energy consumption of each train movement within the South Coast basin. The train performance calculator (TPC) uses the CN version of the Davis Equation to calculate train resistance based on locomotive, railcar and route characteristics (AREMA, 2014).

Simulation of each train considered its number of assigned locomotives, overall weight, number of railcars, train type and commodity distribution derived from the waybill data. For each railcar, weight was derived from the waybill data while length and aerodynamic drag coefficient characteristics were assigned based on the typical railcar type used to transport a specific commodity.

Each outbound train was simulated in detail over a route from an origin terminal within the basin to a proposed locomotive exchange point outside the air basin boundary. The route data was compiled from grade, curvature and speed limit data from multiple subdivisions. In conducting the train performance simulation, the TPC compares the allowable speed limit to the train resistance and available tractive effort of a train. Although a train may be permitted to travel at a posted speed limit, the weight, length, and available locomotive power may limit the actual train speed. This is particularly important on routes such as Cajon Pass with steep grades and many sharp curves. The instantaneous force required to overcome train resistance at a given speed is translated into energy consumed and summed over small segments to determine the total energy required to transit the route. The same procedure is followed for each inbound train starting at the exchange point and ending at the destination terminal in the basin.

The TPC also calculates the amount of dynamic braking energy available for regeneration, storage and reuse on a mile-by-mile basis over the length of the route.

4.5.3 Energy Demand

Since train performance calculation extended past the South Coast air basin boundary to the proposed exchange points, only a portion of the energy consumed by each train should be considered in calculating baseline energy consumption and emissions. Since the train performance calculation provides mile-by-mile energy consumption for each train run, the portion between terminals within the basin and the basin boundary was extracted, multiplied by the annual train frequency and summed across all trains for each of the seven mainline routes. The annual energy consumption of line-haul mainline freight rail operations within the South Coast (Table 4.12) is presented in terms of energy "at the wheels". The required input energy has not been factored up to account for the efficiency of the traction drive or any internal combustion or other energy generation processes onboard the locomotive. Values in the table include all line-haul traffic within the South Coast basin, both inbound and outbound. These baseline numbers are used in subsequent sections to estimate the emissions and energy cost benefits of alternative locomotive technologies.

Table 4.12: Annual Train Energy Consumption within South Coast Basin by Route

Route	Terajoules	MWh
Union Pacific Santa Barbara Subdivision	13	3,500
Union Pacific /Metrolink Valley Subdivision	15	4,200
Union Pacific Mojave Subdivision	12	3,200
BNSF Cajon Subdivision	921	255,700
Union Pacific Cima Subdivision (via Cajon)	59	16,500
Union Pacific Yuma Subdivision	529	146,900
BNSF San Diego	18	4,900
Total	1,566	435,100

4.6 Summary

UP and BNSF operate approximately 130 line-haul freight trains in the South Coast basin each day. At any moment, over 2,000 locomotives from a much larger pool of nearly 10,000 locomotives are allocated to operating trains that originate, terminate or transit the South Coast basin. Trains originating or terminating in the South Coast transport approximately 99 million tons of freight each year and consume approximately 435,000 MWh of energy at the locomotive wheel.

5 Emissions Benefits in South Coast Basin

This section determines the potential local emissions benefits of each alternative locomotive technology when applied to line-haul mainline freight rail operations within the South Coast basin. The first section describes the process of modifying the train energy inventory for the different locomotive deployment scenarios and translating the energy demand into fuel and electricity consumed. The second section reviews emissions factors for the different energy sources. The third section combines consumption with the emissions factors to evaluate the reduction in emissions relative to baseline conditions.

5.1 Energy and Fuel Consumption of Alternative Technologies

The baseline energy consumption in Table 4.12 is valid for locomotive technologies that do not modify the train consist through the addition of tenders. These include Tier 4 diesel-electric with after-treatment, electrification and linear synchronous motor.

In the liquefied natural gas and solid-oxide fuel cell scenarios, train weight, resistance and energy consumption are increased by the addition of LNG fuel tenders. To account for this increase, the original train performance calculations were adjusted by adding tenders to each train consist at the rate of one tender for every two locomotives. Each tender is assumed to weigh 286,000 pounds.

In the battery tender scenario, train weight, resistance and energy consumption are increased by the addition of battery tenders. To account for this increase, the original train performance calculations were adjusted by adding tenders to each train consist at the rate of one tender for every 2.12 MWh of train energy demand (50-percent discharge of the 4.25 MWh tender at the wheels). Each tender is assumed to weigh 286,000 pounds. However, energy consumption is also reduced by reuse of stored regenerated braking energy. Based on a traction drive efficiency of 85 percent and a battery charging and discharge efficiency of 90 percent, only 58 percent of regenerated energy at the wheels is available to offset train energy consumption. The calculation also checks that the amount of regenerated energy input to the battery does not exceed the available storage capacity.

The adjusted energy consumption (Table 5.1) is then converted into fuel and energy consumption (within the air basin, not all the way to the exchange points) according to the relative efficiencies introduced in Section 2:

- The locomotive traction drive and linear synchronous motor drive are assumed to have an efficiency of 85 percent.
- Baseline Tier 2 and Tier 4 locomotive engines are assumed to be 39-percent efficient.
- The diesel-LNG engine is assumed to be 35-percent efficient (10-percent decrease relative to diesel engines).
- The battery tender charging and discharge process are each assumed to be 90-percent efficient for a combined charge-discharge cycle efficiency of 81 percent.
- The SOFC-gas turbine system is assumed to be 70-percent efficient.
- The electric and LSM power supply is assumed to have an efficiency of 90 percent.

In conversion of energy to fuel, the LNG locomotive operates on 20-percent diesel and 80-percent LNG by energy. Diesel is assumed to have an energy density of 142,926 kJ/gallon of diesel. LNG is assumed to have an energy density of 87,194 kJ/gallon of LNG. The volume of LNG is presented in both gallons of LNG and diesel-equivalent gallons.

Table 5.1: Annual South Coast Alternative Locomotive Energy and Fuel Consumption

	Energy (TJ)			Electricity	Diesel	LNG	
Technology	At Wheels	Traction	Fuel/ Electricity	MWh	Gallons	Gallons	Diesel-Gallon-Equivalent
Tier 2 Diesel-electric (baseline)	1,566	1,842	4,724	--	33,052,000	--	--
Tier 4 Diesel-electric (baseline)	1,566	1,842	4,724	--	33,052,000	--	--
Tier 4 Diesel-electric with After-treatment	1,566	1,842	4,724	--	33,052,000	--	--
Diesel-Liquefied Natural Gas (LNG)	1,689	1,987	5,677	--	7,944,000	52,089,000	31,005,000
Battery Tender w/ Regeneration	1,470	1,729	2,135	593,100	--	--	--
SOFC-Gas Turbine with LNG	1,689	1,987	2,839	--	--	32,556,000	19,378,000
Electrification	1,566	1,842	2,047	568,600	--	--	--
Linear Synchronous Motor (LSM)	1,566	1,842	2,047	568,600	--	--	--

In examining Table 5.1, the benefit of regeneration to the battery tender locomotives is apparent from the lowest traction energy consumption. However, the inefficiencies of the battery charging process result in more electricity consumption than electrification or LSM.

For the liquid fuel alternatives, diesel-LNG locomotives face a penalty both from the energy required to haul the LNG tenders but also reduced efficiency of the diesel-LNG combustion process. The increased efficiency of the SOFC-gas turbine allows it to consume the least liquid fuel despite the need for LNG tenders.

5.2 Local Emissions Factors

Local emissions factors for the different energy sources (Table 5.2) were developed from EPA guidelines for locomotives (EPA, 2009). ARB estimates that after-treatment can further reduce NOx and PM emissions by an additional 75 percent below Tier 4 levels. LNG locomotives are assumed to meet Tier 4 emissions but with per-diesel-equivalent-gallon factors adjusted to account for the decreased fuel efficiency of diesel-LNG engines. This adjustment results in the diesel-LNG engine producing the same emissions as a Tier 4 diesel for the same amount of output traction energy. Electricity is assumed to have no local emissions within the South Coast.

Table 5.2: Local Emissions Factors for Locomotives

Energy Source	CO_2 (kg/diesel-g-e)	PM (g/diesel-g-e)	HC (g/diesel-g-e)	NOx (g/diesel-g-e)	CO (g/diesel-g-e)
Tier 2 Diesel	10.21	3.74	5.41	103.0	26.6
Tier 4 Diesel	10.21	0.31	0.83	20.8	26.6
Tier 4 Diesel w/ After-T	10.21	0.08	0.83	5.2	26.6
LNG (Tier 4 Equivalent)	7.49	0.28	0.75	18.7	24.0
Electricity	0	0	0	0	0

5.3 Annual Emissions Benefits in the South Coast Basin

The alternative locomotive fuel consumption and emissions factors are combined to calculate the expected annual line-haul mainline freight locomotive emissions within the South Coast air basin (Table 5.3). The change in emissions are investigated relative to two different baseline conditions: one with Tier 2 diesel-electric locomotives and a second with Tier 4 diesel-electric locomotives. The Tier 2 diesel emissions are presented to estimate baseline emission levels before the delivery of Tier 4 locomotives in 2015 and serve as a baseline for emission reductions relative to “current” levels (Table 5.4). The Tier 4 diesel emissions are presented to estimate baseline emissions at a future date once the current mainline fleet has been completely renewed with new Tier 4 diesel-electric locomotives. This Tier 4 scenario serves as a baseline for emissions reductions relative to “future” levels in 2030 (Table 5.5). Although representative of the future locomotive fleet in 2030, the “future” Tier 4 scenario is still based on traffic from the 2011 waybill data; no attempts are made to forecast future traffic volumes and commodity group distributions in 2030.

Since this analysis considers local emissions, the three technologies that utilize electricity as an energy source are considered to be zero-emissions, resulting in 100-percent reduction of all criteria pollutants. For both the Tier 2 and Tier 4 baselines, over 743 million pounds of CO_2 emissions are potentially eliminated each year within the South Coast basin by either of these three technologies.

Implementation of Tier 4 diesel-electric locomotives with after-treatment does not change CO_2 or CO levels, but the other criteria pollutants are reduced by 80 to 90 percent relative to Tier 2 levels. Over 243,000 pounds of particulate matter emissions are eliminated each year relative to the Tier 2 baseline. Since further study is needed to determine the exact effectiveness of various after-treatment systems at achieving emissions reductions beyond Tier 4 levels, reductions shown for Tier 4 diesel-electric locomotives with after-treatment are based on an ARB estimate of 75-percent reduction in NOx and PM relative to Tier 4 levels.

The diesel-LNG locomotives decrease CO_2 emissions due to the lower carbon content of LNG but increases CO due to decreased fuel efficiency. Approximately 53 million pounds of CO_2 emissions are potentially eliminated each year within the South Coast basin by diesel-LNG technology.

The efficiency of the SOFC-gas turbine with LNG allows this technology to provide the greatest emission benefits of the liquid fuels. The SOFC-gas turbine has the potential to eliminate 423 million pounds of CO_2 emissions each year, representing a 57-percent reduction from either the Tier 2 or Tier 4 baseline (Figure 5-1 and Figure 5-2).

Table 5.3: Annual South Coast Basin Alternative Locomotive Emissions (pounds)

Technology	CO_2	PM	HC	NOx	CO
Tier 2 Diesel (Baseline)	743,970,000	272,900	394,200	7,502,000	1,940,000
Tier 4 Diesel (Baseline)	743,970,000	22,700	60,600	1,514,000	1,940,000
Tier 4 Diesel w/After-T	743,970,000	5,700	60,600	379,000	1,940,000
Diesel-LNG	690,800,000	24,700	65,700	1,645,000	2,103,000
Battery Tender w/ Regen	0	0	0	0	0
SOFC-GT w/ LNG	320,000,000	12,000	32,000	800,000	1,023,000
Electrification	0	0	0	0	0
LSM	0	0	0	0	0

Table 5.4: South Coast Alternative Locomotive Emissions (% Reduction from Tier 2)

Technology	CO_2	PM	HC	NOx	CO
Tier 2 Diesel (Baseline)	--	--	--	--	--
Tier 4 Diesel w/After-T	0.0	97.9	84.6	94.9	0.0
Diesel-LNG	7.1	91.0	83.3	78.1	-8.5
Battery Tender w/ Regen	100.0	100.0	100.0	100.0	100.0
SOFC-GT w/ LNG	57.0	95.6	91.9	89.3	47.2
Electrification	100.0	100.0	100.0	100.0	100.0
LSM	100.0	100.0	100.0	100.0	100.0

Table 5.5: South Coast Alternative Locomotive Emissions (% Reduction from Tier 4)

Technology	CO_2	PM	HC	NOx	CO
Tier 4 Diesel (Baseline)	--	--	--	--	--
Tier 4 Diesel w/After-T	0.0	75.0	0.0	75.0	0.0
Diesel-LNG	7.1	-8.5	-8.5	-8.5	-8.5
Battery Tender w/ Regen	100.0	100.0	100.0	100.0	100.0
SOFC-GT w/ LNG	57.0	47.2	47.2	47.2	47.2
Electrification	100.0	100.0	100.0	100.0	100.0
LSM	100.0	100.0	100.0	100.0	100.0

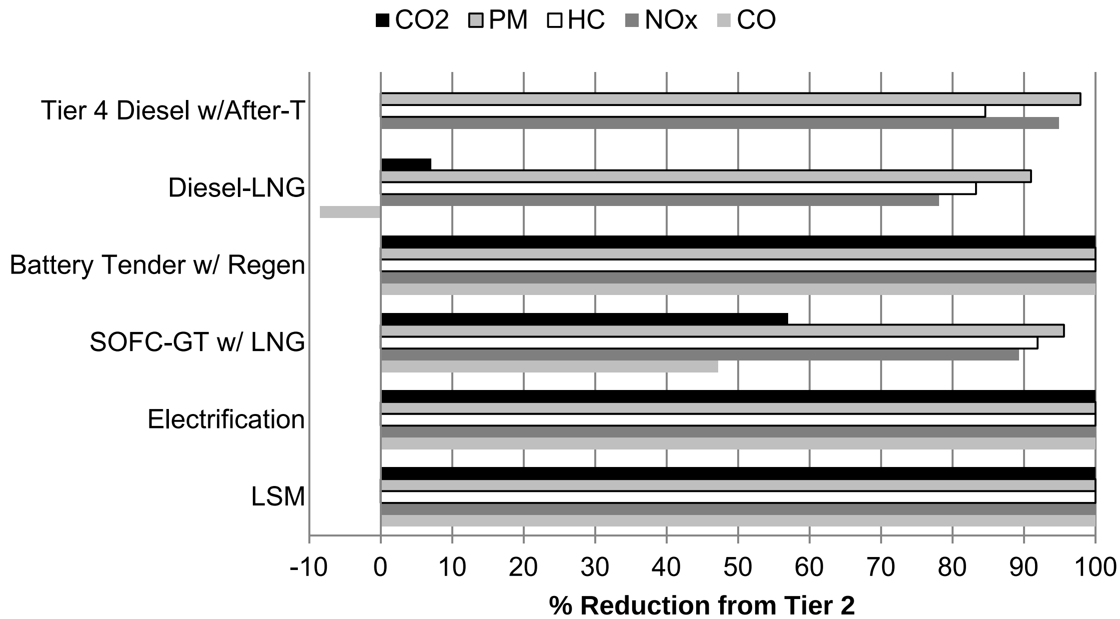

Figure 5-1, Potential reduction in South Coast line-haul locomotive emissions from Tier 2 baseline

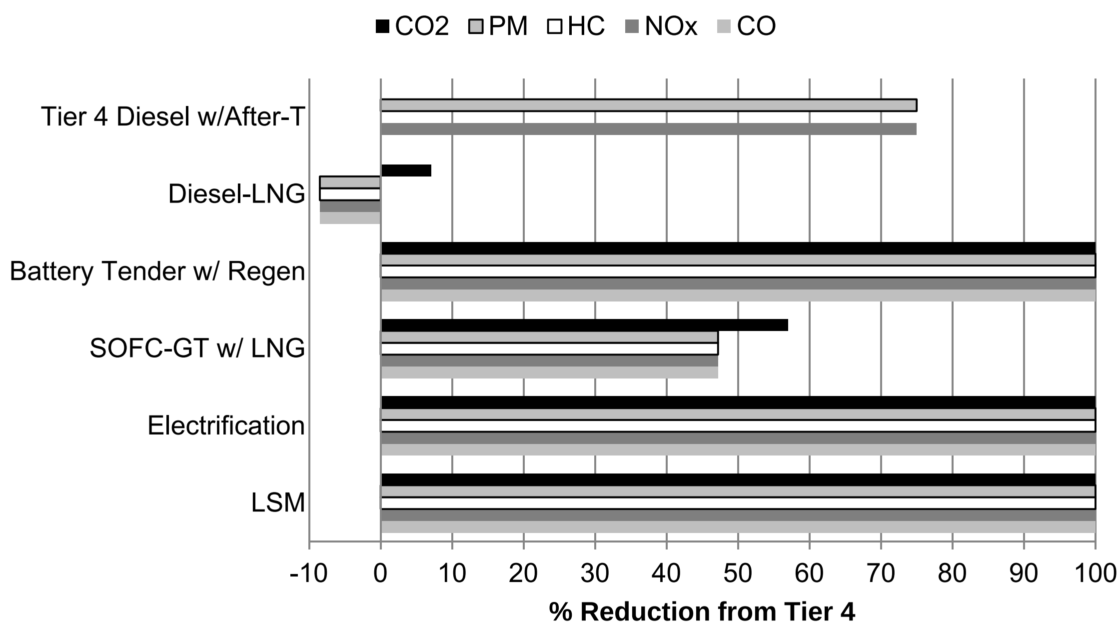

Figure 5-2, Potential reduction in South Coast line-haul locomotive emissions from Tier 4 baseline

6 Locomotive Capital, Energy Supply Infrastructure and Maintenance Costs

This portion of the study examines the cost of obtaining new locomotive technology and energy supply infrastructure required to support operations, plus the cost of maintaining these capital investments. The first section determines the required number of new technology locomotives and tenders required to support operation of all trains transiting the South Coast. The second section calculates the capital cost of the new technology locomotives. This is followed by the capital cost of energy supply infrastructure. The final sections consider the capital cost of a heavy repair shop for the new technology locomotives and the ongoing cost of locomotive maintenance.

6.1 Locomotive Fleet Size with Locomotive Exchange

As discussed in Section 4.4.3, only a portion of the locomotives allocated to trains transiting the South Coast basin are actually within the basin at a given time. Properly sizing the fleet of new technology locomotives to support operation of these trains within the basin is essential to maintaining operational fluidity. Creating captive fleets of locomotives within the South Coast basin and executing a locomotive exchange has the potential to alter the overall locomotive fleet size and lead to trains delays (Figure 6-1).

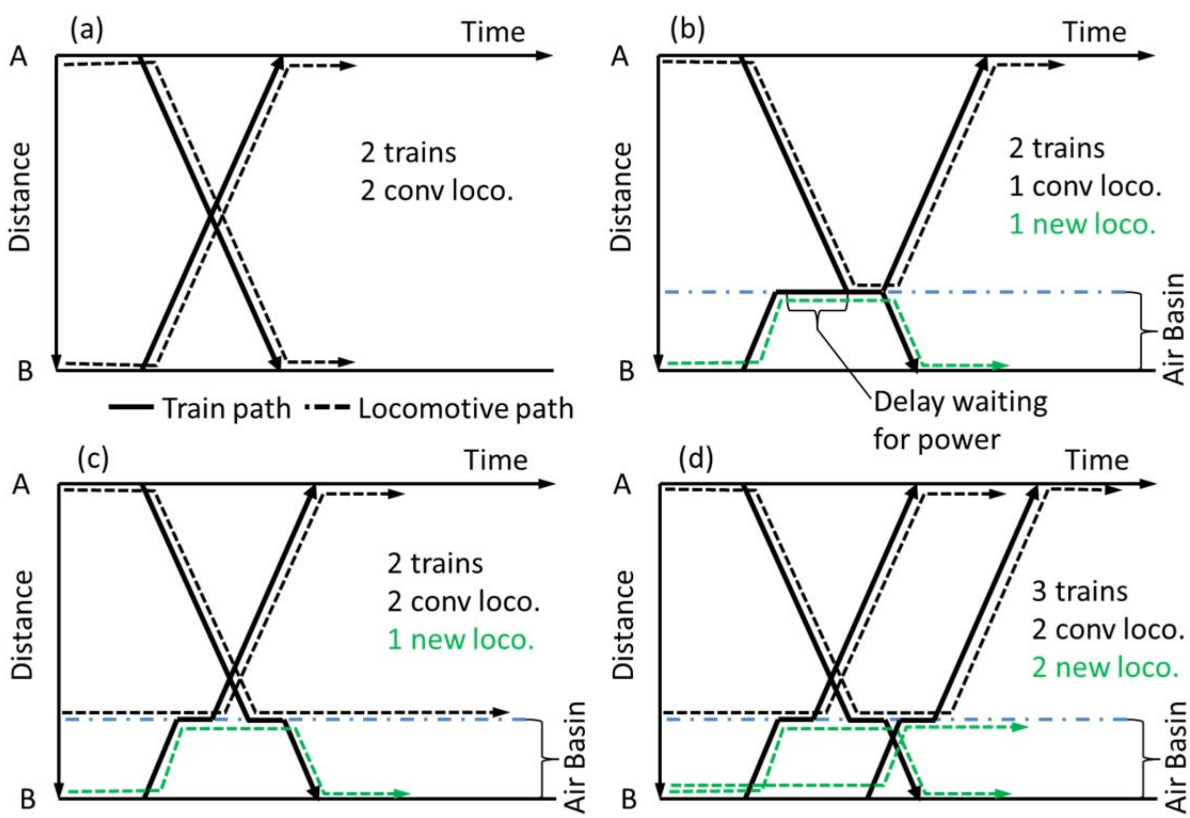

Figure 6-1, Impact of locomotive exchange on fleet size and train paths

In the example baseline condition (Figure 6-1a), two trains are scheduled to operate with conventional locomotives, one per train, for total fleet size of two locomotives. If the same fleet size is maintained but one locomotive is converted to new technology and restricted to operation within the air basin, the operation is disrupted (Figure 6-1b). The outbound train is delayed at the locomotive exchange point until the inbound train arrives with the only conventional locomotive and the exchange can begin. The overall time required for both trains to reach their destination is increased, decreasing equipment utilization and increasing costs. To remedy the situation, the second conventional locomotive may be retained along with the new technology locomotive for a total fleet of three locomotives (Figure 6-1c). By increasing the locomotive fleet size by 50 percent, the two trains are no longer delayed for power. However, the trains still experience delay time to execute the locomotive exchange.

If a third train is added, to avoid delays, a second new technology locomotive must be added for a total fleet size of four (Figure 6-1d). This is a 33-percent increase in fleet size compared to the three conventional locomotives required to move three trains in the original unrestricted case (not shown). As the number of trains increases, there are more opportunities to cycle new locomotives within the air basin and make timely connections to inbound and outbound trains. Under these more optimal conditions, the increase in total fleet size is not as great as when there are fewer trains and locomotives in the original conventional fleet.

Also, as the number of trains increases, the probability that all of the trains will be operating outside the basin at the same time decreases rapidly. Consider an original conventional locomotive fleet sized at ten locomotives to handle ten different trains in the unrestricted case. If, after creation of the exchange point, only nine trains will ever be operating outside the basin at the same time, then the size of the conventional locomotive fleet can be decreased to nine locomotives. One conventional locomotive is made surplus and can be reassigned to other duties. The overall fleet size may still increase as it is likely that more than one train will be within the air basin at a time, necessitating the purchase of multiple new technology locomotives and increasing the fleet size beyond the original ten locomotives.

6.1.1 Methodology

To capture these locomotive assignment patterns, the approach of considering locomotive assignments on individual train runs in Section 4.4.1 is expanded. Instead of considering trips between origin and destination, the closed loop operation of each train symbol is divided into two segments, one with conventional locomotives outside the air basin and one with new technology locomotives within the air basin. This is somewhat illustrated in Figure 6-1b where the locomotives cycle back and forth in their own clean or conventional portion of the route.

The project team developed a spreadsheet tool to generate and track several weeks of train movements through each exchange point according to the origin-destination train frequencies provided by ARB. The spreadsheet tracks location of train movements according to the average speeds (Table 4.10) to determine which trains en route require conventional or new technology locomotives and the number of locomotive units assigned to each train. Hourly conventional and new technology locomotive demand is tracked over two weeks of operations to determine the peak value controlling conventional and new technology fleet size.

To account for variation in North American freight operations and avoid schedule bias, the day of each origin-destination departure is determined according to the reported train frequency. Then trains are dispatched to depart a terminal randomly over that 24-hour period according to a uniform distribution. A total of 25 trials were conducted with different randomized departure patterns to determine the maximum conventional and new technology locomotive demand.

The locomotive demand from the spreadsheet calculation is increased to account for locomotive availability of 85 percent. For the non-base cases with locomotive exchange, an additional utilization factor of 92 percent is applied to account for delay at the exchange point for a total utilization of 78 percent.

6.1.2 Required Locomotive Fleet

Operation with exchange points requires the purchase of 570 new technology locomotives to power trains within the South Coast (Table 6.1). To operate outside the air basin beyond the locomotive exchange points, the train movements require the instantaneous allocation of 1,925 conventional diesel-electric locomotives for a total of 2,495 locomotives assigned. As discussed in Section 4.4.3, the number of conventional locomotives represents the required allocation at any moment in time. In practice, 1,925 individual conventional locomotives are not dedicated to service on South Coast train movements; instead, the required allocation is drawn from a much larger locomotive fleet. If locomotives in this fleet spend one-third of their time on South Coast train movements, then a fleet of just under 6,000 conventional locomotives is required to support operations outside the exchange points.

Table 6.1: Required Locomotive Fleet Size and Allocation by Route

Route	Baseline	With Exchange				
	Conventional Locomotives	Conventional Locomotives Retained	New Technology Locomotives Purchased	Overall Fleet Total	Fleet Total Increase (%)	Surplus Conventional Locomotives
Union Pacific Santa Barbara Subdivision	8	8	8	16	100.0	--
Union Pacific /Metrolink Valley Subdivision	29	29	20	49	69.0	--
Union Pacific Mojave Subdivision	47	42	30	72	53.2	5
BNSF Cajon Subdivision	1,242	1,202	274	1,476	18.8	40
Union Pacific Cima Subdivision (via Cajon)	151	146	51	197	30.5	5
Union Pacific Yuma Subdivision	534	492	175	667	24.9	42
BNSF San Diego	11	6	12	18	63.6	5
Total	2,022	1,925	570	2,495	23.4	97

Compared to the current fleet of diesel-electric locomotives required to operate the trains under study, the 23.4% increase in total fleet size illustrates the inefficiencies of the locomotive exchange. The 570 new technology locomotives purchased for operation within the air basin only allow 97 conventional locomotives to be withdrawn from the fleet. One-for-one replacement cannot be obtained because additional locomotives are required to balance power, maintain fluidity at the exchange point and connect to each inbound and outbound train.

6.1.3 LNG Tender Fleet

A similar exercise was conducted for the LNG tender fleet. For each train, one LNG tender was allocated for every two locomotives assigned to the train. The number of LNG tenders is rounded up for trains with an odd number of locomotives. The spreadsheet tool is then used to track the movement of LNG tenders on each route between the exchange points and terminals within the South Coast. Considering 25 random schedule iterations, the peak number of tenders required is then increased to account for tender maintenance (85-percent availability) and fueling time (83 percent availability) for an overall utilization factor of 70 percent.

Overall, a total of 364 LNG tenders are required to support diesel-LNG and SOFC-gas turbine locomotive operation within the South Coast (Table 6.2).

Table 6.2: Required Tender Fleet Size and Assignment by Route

Route	Fleet Size	
	LNG Tenders	Battery Tenders
Union Pacific Santa Barbara Subdivision	7	31
Union Pacific /Metrolink Valley Subdivision	16	39
Union Pacific Mojave Subdivision	25	62
BNSF Cajon Subdivision	162	658
Union Pacific Cima Subdivision (via Cajon)	35	153
Union Pacific Yuma Subdivision	111	647
BNSF San Diego	8	23
Total	364	1,613

6.1.4 Battery Tender Fleet

The number of battery tenders for each train run is based on the calculated energy demand at the wheels within the South Coast basin for that train and the capacity of the battery tender. Each battery tender has the capacity to provide 4.25 MWh at the wheels. However, to preserve the life of the battery, it is assumed that each tender is only discharged to 50 percent of its energy storage capacity. Because of this limitation, the number of battery tenders is calculated on the assumption that each tender can provide 2.12 MWh at the wheels. To avoid an impractical number of tenders, the battery tenders are allocated to only provide enough energy for operation within the air basin, and not for the extended trip from the air basin boundary to the exchange point. Also, to be conservative, regenerated energy is not considered when allocating the battery tenders.

Once the number of tenders per train is determined, the spreadsheet tool is then used to track the movement of battery tenders on each route between the exchange points and terminals within the South Coast. Considering 25 random schedule iterations, the peak number of tenders required is then increased to account for tender maintenance (85-percent availability) and charging time (6-hour charge for every 12 hours of operation or 67-percent availability) for an overall utilization factor of 57 percent.

Overall, a total of 1,613 battery tenders are required to support train operation within the South Coast air basin (Table 6.2).

6.2 Equipment Capital Cost

Capital cost of locomotives and tenders considers the costs discussed in Section 2 and the fleet sizes developed earlier in this section (Tables 6.1 and 6.2). Where feasible, it is assumed that only the 97 conventional locomotives made surplus are available for retrofit to satisfy the demand for 570 new technology locomotives. The remaining 473 new technology locomotives are assumed to be purchased new.

6.2.1 Unit Costs

To summarize information on locomotive and tender capital costs presented in Section 2:

- Tier 4 diesel-electric locomotives with after-treatment are estimated at $3.5 million per unit.
- Diesel-LNG retrofit kits are estimated at $400,000 per locomotive plus $1 million per LNG tender. Since the total fleet size must be increased, not all locomotives can be retrofits. New diesel-LNG locomotives are estimated at $2.7 million per unit (based on the combined cost of a Tier 2 locomotive and retrofit kit) plus the cost of LNG tenders.
- Battery tenders are estimated at $11 million per tender. Battery tender operation requires locomotive conversions at $200,000 per unit or new locomotives at $3 million per unit.
- SOFC-gas turbine LNG locomotives are estimated at $5 million per unit plus $1 million per LNG tender.
- Electric locomotives are estimated to cost $5 million per unit.
- The cost of LSM “locomotives” is unknown given the current state of research and technology development.

6.2.2 Total Locomotive and Tender Cost

The locomotive fleet size and unit costs are used to estimate locomotive and tender capital costs (Table 6.3). Re-equipping a captive South Coast basin fleet with 570 Tier 4 diesel-electric locomotives with after-treatment requires a capital investment of nearly $2 billion. For operation with battery tenders, the cost of the tenders themselves dominates the equipment capital cost. The ability to retrofit surplus locomotives allows diesel-LNG to have the lowest equipment capital cost despite the need for LNG tenders.

Table 6.3: Capital Cost of New Technology Locomotive and Tender Fleets ($ million)

Technology	BNSF Locomotives	BNSF Tenders	UP Locomotives	UP Tenders	Total
Tier 4 Diesel w/After-T	1,001.0	--	994.0	--	1,995.0
Diesel-LNG	668.7	170.0	647.2	194.0	1,679.9
Battery Tender w/ Regen	732.0	7,491.0	706.4	10,252.0	19,181.4
SOFC-GT w/ LNG	1,430.0	170.0	1,420.0	194.0	3,214.0
Electrification	1,430.0	--	1,420.0	--	2,850.0
LSM	unknown	--	unknown	--	unknown

6.3 Energy Supply and Delivery Infrastructure

Existing line-haul mainline freight rail operations in the South Coast are supported by a diesel fuel supply and delivery infrastructure. A change to a new locomotive technology utilizing a different fuel type or energy source will require a new supply and delivery infrastructure. For LNG, this may involve storage tanks and liquefaction plants. For LSM and electrification, this includes electricity distribution infrastructure required trackside or on rail property such as overhead catenary, primary traction power substations and the synchronous motor.

These costs do not include secondary supply infrastructure such as long distance pipelines, or enhancements to the electric grid such as new transmission, distribution and generation facilities. These facilities would be developed and owned by supplying utilities or energy providers at their capital expense.

This section does not include fueling and electric charging stations located at locomotive exchange points. These facilities are discussed in Section 7.

6.3.1 Electrification and Linear Synchronous Motor Infrastructure

To provide all line-haul freight rail operations in the South Coast with electric overhead catenary or linear synchronous motor infrastructure between terminals in the basin and the locomotive exchange points, 630.6 route-miles must be developed (Table 6.4). Several of these lines have relatively low traffic volumes and other lines are predominantly located outside the air basin but between the South Coast air basin boundary and the proposed locations of the locomotive exchange points. To reduce capital cost, these segments could be left as conventional diesel routes while investment is focused on a select few higher-volume routes.

As discussed in Section 2, the estimated capital cost of electrification infrastructure is $50 million per route mile for a total of $31.5 billion (Table 6.5). Linear Synchronous Motor infrastructure is estimated to cost $20 million per route-mile for a total of $12.6 billion.

6.3.2 Liquefied Natural Gas

To reduce capital costs, it is assumed that the railroads do not invest in their own dedicated LNG liquefaction plants. Instead, the cost of establishing these facilities is included in the market price for LNG. Thus there are no capital costs shown for LNG liquefaction in Table 6.5.

Table 6.4: Required Route-Miles of Electrification and LSM Infrastructure

Route	Route-Miles	
	Total to Exchange	Within Basin
BNSF Cajon Subdivision	81.3	18.5
BNSF San Bernardino Subdivision	67.6	67.6
Alameda Corridor	18.1	18.1
BNSF Harbor Subdivision	2.5	2.5
Metrolink Orange Subdivision	42.0	42.0
NCTD San Diego Subdivision	19.0	0.0
UP Yuma Subdivision	72.5	37.7
UP Alhambra Subdivision	55.7	55.7
UP Los Angeles Subdivision	56.6	56.6
UP Mojave Subdivision	78.3	23.4
UP Cima Subdivision	11.0	0.0
Metrolink Valley Subdivision	67.5	57.0
Metrolink Ventura Subdivision	39.5	20.2
UP Santa Barbara Subdivision	19.0	0.0
Total	630.6	399.3

Table 6.5: Capital Cost of Energy Supply and Delivery Infrastructure ($ million)

Technology	Electric Overhead Catenary System	Linear Synchronous Motor	LNG Liquefaction
Tier 4 Diesel w/After-T	--	--	--
Diesel-LNG	--	--	--
Battery Tender w/ Regen	--	--	--
SOFC-GT w/ LNG	--	--	--
Electrification	31,500	--	--
LSM	--	12,600	--

6.4 Heavy Locomotive Repair and Central Maintenance Shop

Currently, neither BNSF nor UP has a heavy locomotive repair and central maintenance shop located within the South Coast basin. While routine servicing and inspection of conventional diesel-electric locomotives is performed at light servicing facilities within the basin, the locomotives must be sent outside the basin for more involved activities and heavy repair.

This poses a challenge for a fleet of new technology locomotives captive to the South Coast basin. Deadheading locomotives to shops outside the basin decreases locomotive utilization and increases expense. Also, the remote locomotive shops are accustomed to maintenance of diesel-electric locomotives and may not have the expertise or equipment to work on some of the locomotive systems associated with the new technology.

For this reason, it is assumed that each railway will need to establish a single heavy locomotive repair and central maintenance shop that is specially equipped for the new technology locomotives. The cost of a heavy repair shop can be estimated as 10 percent of the total value of the locomotives assigned to the shop for heavy maintenance (Baumgartner, 2001). The cost of the UP and BNSF shops is calculated with this approach for each alternative new locomotive technology (Table 6.6).

Table 6.6: Capital Cost of Heavy Locomotive Repair Shop ($ million)

Technology	BNSF Shop	UP Shop	Total
Tier 4 Diesel w/After-T	100	99	199
Diesel-LNG	67	65	132
Battery Tender w/ Regen	55	54	109
SOFC-GT w/ LNG	143	142	285
Electrification	143	142	285
LSM	unknown	unknown	unknown

Additional light servicing, fueling and charging infrastructure are required at the locomotive exchange points and terminals in the basin as discussed in Section 7.

6.5 Annual Locomotive Maintenance Expense

Locomotives require routine maintenance and inspection to operate in a safe and efficient manner. The annual cost of this maintenance varies with the distance each locomotive travels (Table 6.7). To summarize information on annual locomotive maintenance costs presented in Section 2:

- Tier 2 diesel-electric locomotive maintenance expenses are estimated at $1.25 per locomotive-mile based on current industry cost data.
- Tier 4 diesel-electric locomotive maintenance expenses are estimated at $1.32 per locomotive-mile based on the added maintenance expense of additional cooling and EGR systems required to achieve Tier 4 emissions levels.

- Tier 4 diesel-electric locomotives with after-treatment maintenance expenses are estimated at $1.50 per locomotive-mile based on the added maintenance expense of the after-treatment systems.
- Diesel-LNG locomotive maintenance expenses are estimated at $1.75 per locomotive-mile based on the requirements of the tender, dual-fuel system and glycol pump systems.
- Battery tender locomotive maintenance expenses are estimated at $2.00 per locomotive-mile. To provide dual-mode capability, the battery tender locomotive must maintain a fully functioning diesel prime mover in addition to the battery tender and its electrical systems. Battery replacement costs are factored into the capital cost of the battery tender locomotive.
- SOFC-gas turbine LNG locomotive maintenance expenses are estimated at $3.75 per locomotive-mile based on published estimates of maintenance expenses three times that of conventional locomotives.
- Electric locomotive maintenance expenses are estimated at $0.75 per locomotive-mile based on published experience with the relative maintenance costs of diesel and electric locomotive fleets in Europe. Additional expenses are incurred for maintenance of the overhead electric catenary system.
- The maintenance cost of LSM “locomotives” is unknown given the current state of research and technology development.

Table 6.7: Assumed Annual New Technology Locomotive Expenses

Technology	Assumed Maintenance Expense ($ per locomotive-mile)	Increase Relative to Tier 2 Diesel Baseline ($ per locomotive-mile)	Increase Relative to Tier 4 Diesel Baseline ($ per locomotive-mile)
Tier 2 Diesel (Baseline)	1.25	--	--
Tier 4 Diesel (Baseline)	1.32	--	--
Tier 4 Diesel w/After-T	1.50	0.25	0.18
Diesel-LNG	1.75	0.50	0.43
Battery Tender w/ Regen	2.00	0.75	0.68
SOFC-GT w/ LNG	3.75	2.50	2.43
Electrification	0.75	-0.50	-0.57
LSM	unknown	unknown	unknown

Each year, the captive locomotive fleet in the South Coast is projected to accumulate 25.7 million locomotive-miles with an associated cost for maintenance of the new technology locomotives. However, at the same time, these same 25.7 million locomotive-miles required to move line-haul freight trains in the South Coast will no longer be accumulated by the conventional diesel-electric locomotive fleet (in both the Tier 2 and Tier 4 baseline scenarios). Thus the incremental per-locomotive-mile maintenance expense of the new locomotive technology deployed as a captive fleet is the difference in maintenance cost between the baseline Tier 2 or Tier 4 locomotive and the new technology locomotive (Table

6.7). Multiplying the increase (or decrease) in maintenance cost per locomotive-mile by the 25.7 million locomotive miles accumulated within the South Coast results in the incremental annual locomotive maintenance expense for each alternative locomotive technology (Table 6.8).

The overhead catenary traction power distribution system also requires maintenance at a cost of $30,000 per route-mile per year (Metrolinx, 2010) or $18.9 million annually for the electrification scenario.

Not enough information is known about the LSM technology in mainline freight applications to calculate maintenance expenses for the LSM locomotives or in-track infrastructure.

Table 6.8: Annual New Technology Locomotive and Catenary Maintenance Expenses

Technology	Incremental Locomotive Maintenance Relative to Tier 2 Diesel Baseline ($ million)	Incremental Locomotive Maintenance Relative to Tier 4 Diesel Baseline ($ million)	Catenary Maintenance ($ million)
Tier 4 Diesel w/After-T	6.4	4.6	--
Diesel-LNG	12.8	11.0	--
Battery Tender w/ Regen	19.3	17.5	--
SOFC-GT w/ LNG	64.2	62.4	--
Electrification	-12.8	-14.6	18.9
LSM	unknown	unknown	unknown

6.6 Summary

Operation of a captive locomotive fleet within the South Coast requires 570 new technology locomotives. Depending on the technology, these locomotives are supported by 364 LNG tenders or 1,613 battery tenders. Purchase cost of new locomotives and tenders, and cost of modifications to conventional locomotives for the captive new technology locomotive fleet within the South Coast, ranges from $1.7 to $19 billion depending on the locomotive technology.

The installed cost of the overhead catenary traction power distribution system for electrification is $31.5 billion and LSM infrastructure is $12.6 billion. The study assumes that the capital cost of infrastructure to liquefy LNG is included in the delivered cost of LNG from third-party suppliers.

The construction cost of new locomotive shop facilities for new technology locomotives within the South Coast ranges from $109 to $285 million depending on the locomotive technology.

The change in annual locomotive maintenance expense from the Tier 2 baseline ranges from a decrease of $12.8 million per year for electrification to an increase of $64.2 million per year for SOFC locomotives. However, electrification requires an additional $18.9 million per year for catenary maintenance. Changes from the Tier 4 baseline are slightly less due to the additional maintenance expense of the baseline Tier 4 diesel-electric locomotives.

Not enough is known about potential freight applications of LSM to develop complete cost data.

7 Exchange Point Process, Infrastructure and Costs

As described in Section 2, operation of alternative locomotive technology on mainline freight movements within the South Coast basin will requires trains entering or exiting the basin to stop at a location near the basin boundary to exchange locomotives. This study considers the following exchange points:

- Union Pacific Yuma Subdivision (near Indio)
- BNSF Cajon Subdivision (near Barstow with UP facility at Yermo)
- Union Pacific Mojave Subdivision (near Palmdale)
- Union Pacific/Metrolink Valley Subdivision (near Palmdale)
- Union Pacific Santa Barbara Subdivision (near Oxnard)
- BNSF/NCTD San Diego Subdivision (near Oceanside)

Due to the time and equipment movements required, particularly where trains operate with distributed power locomotives, locomotive exchanges cannot take place on the mainline. Instead, at each of the above locations, dedicated siding tracks must be constructed to facilitate locomotive exchange. In addition to the siding tracks, additional support tracks and infrastructure must be constructed to service, inspect and stage both diesel-electric and alternative technology locomotives. The size of these exchange point facilities is a function of the traffic volumes on each particular route and the time that each train will spend at the facility to complete the locomotive exchange.

7.1 Exchange Point Process and Time Requirements

Exchanging the locomotives on a line-haul freight train for a new set is not a trivial process. The exchange involves multiple time-consuming steps that are necessary to ensure the safety of the process and comply with the operating rules and federal regulations.

7.1.1 Exchange, Inspection and Test Requirements

Once stopped at the exchange facility, before the current locomotives can be removed from the train consist, the train must be secured by applying several handbrakes. A crew member must walk back along the train and apply the handbrakes in succession on multiple railcars. On each railcar, the handbrake is applied by turning a wheel or crank that manually applies the brakes through a series of rods and levers. The number of handbrakes that must be applied will vary depending on the length of the train and the vertical alignment grade profile of the exchange track. Once the handbrakes are applied, the train crew must attempt to move the locomotives forward to test the ability of the handbrakes to hold the train in place. Only then is the train considered secured.

Before the locomotives are uncoupled, the angle cock valve on the train line supplying compressed air to the braking system must be closed to isolate the railcars from the locomotives. This is accomplished by a member of the train crew on the ground. The same crew member also lifts the uncoupling lever that allows the locomotives to be moved away from the train. Once the locomotives are separated from the train, they are moved to an adjacent track or the servicing facility. This may involve the member of the train crew on the ground manually throwing several turnouts to route the locomotives to the required track. Once positioned, the locomotives must be secured by applying their own handbrakes.

If they are continuing past the exchange point, the crew then transfers their gear to the replacement locomotives. Unless they have been prepositioned by a hostler crew at the exchange point, the replacement locomotives must be started and brought to operating temperature. The locomotive handbrakes must be removed and an independent brake test conducted before the locomotives can be moved. Once moving, the locomotives may need to negotiate several hand-throw turnouts before coupling to the train. Both of these steps require a member of the crew to be walking on the ground. After coupling, the crew member will reconnect the train line so that the locomotives can begin restoring air pressure in the train. Depending on how long the railcars have been standing and the ambient temperature, it may take many minutes to fully restore the train line to the desired brake pipe pressure. The crew member on the ground will also remove the handbrakes.

Prior to departure, the train crew must link the new lead locomotive with the end-of-train (EOT) device and perform any required air brake tests and inspections. Provided that the railcars have not been standing without a source of compressed air for more than four hours (i.e. it has been less than four hours since the original locomotives were uncoupled from the train), the crew only needs to perform an intermediate terminal air brake test. This test involves the crew making a reduction in train line brake pressure and waiting for a signal from the EOT indicating that the pressure reduction has propagated to the end of the train. The appropriate signal from the EOT indicates that the continuity of the train line has been restored over the length of the train. This ensures that all of the railcars will receive braking instructions from the crew in the lead locomotive. The "set-and-release" process can typically be accomplished in ten minutes if no anomalies are encountered. After confirming the brakes have applied, the train can depart upon receiving movement authority from the dispatcher. Typically, while the train departs the yard, it will be observed by an employee standing trackside to determine that all of the brakes have properly released.

If more than four hours have elapsed since the original locomotives were uncoupled from the train and the railcars have not been connected to another source of compressed air, the train must complete a full initial terminal air test prior to departure. This test is more involved than that described in the preceding paragraph. The initial terminal air test requires the crew to first fully charge the train air line and monitor it to ensure air leakage is within prescribed limits. The crew must then apply the train brakes and walk the entire length of the train to ensure all brakes have applied and inspect the condition of the running gear and critical safety appliances. Under ideal conditions, this process can consume two minutes per railcar or approximately two hours for a typical line-haul freight train. Once the inspection is complete, the brakes can be released and a visual confirmation of the brake release made while the train departs the exchange point.

Since the additional two hours required to perform the initial terminal air test would only add to the delay experienced at the exchange point, it is desirable to provide a source of compressed air to the standing railcars at all times. Thus it is assumed that a yard air system that connects the standing railcars to a central compressor system via piped connections to each exchange track will be provided at each locomotive exchange point. The yard air system will ensure that no railcars stand more than four hours without a source of compressed air even in the event that the locomotive exchange process is interrupted due to locomotive availability or mechanical failure.

7.1.2 Field Simulation of Locomotive Exchange

The time to complete all of the locomotive exchange activities described in the previous section is a key input to the design of the exchange point and analysis of its operational impact. Unfortunately there are no comparable line-haul freight locomotive exchanges taking place within North America to serve as a reference. To provide reference data, Union Pacific arranged for simulated locomotive exchange at their Global III Intermodal Facility in Rochelle, Illinois on August 11, 2014.

To simulate a locomotive exchange, a train in the support yard was crewed and configured as if the train had just arrived at the terminal with one locomotive on either end in a front and rear distributed power configuration. The train crew performed all of the steps necessary to secure the train and move each locomotive to an adjacent track. Once the locomotives were secured on the adjacent track, the crew simulated the exchange for alternative technology locomotives by restarting the locomotives and performing required single-unit brake tests. The crew then moved the locomotives back to the original track and recoupled them to the train in the same front and rear distributed power configuration. The simulation concluded with the crew relinking the locomotive distributed power. The distributed power relinking process includes a pre-departure air test to establish train line continuity. Event times from the simulation were recorded in the field (Table 7.1).

Table 7.1: Timing of Simulated Locomotive Exchange by UP at Rochelle, Illinois

Location	Activity	Minutes	Notes
Front of Train	Secure and Decouple	10	Additional walking time for extra locomotives
	Move to Adjacent Track and Secure	5	Varies with distance to lead/crossover and track availability
	Transport Crew to Rear	10	Varies with train length and transport mode
Rear of Train	Secure and Decouple	10	Additional walking time for extra locomotives
	Move to Adjacent Track and Secure	5	Varies with distance to lead/crossover and track availability
Subtotal	*Inbound*	*40*	Does not include deceleration delay or queueing
Rear of Train	Locomotive Start-up and Brake Test	10	Additional 7 minutes per locomotive
	Move to Train and Couple	5	Varies with distance to lead/crossover and track availability
	Transport Crew to Front	10	Varies with train length and transport mode
Front of Train	Locomotive Start-up and Brake Test	10	Additional 7 minutes per locomotive
	Move to Train and Couple	5	Varies with distance to lead/crossover and track availability
	Distributed Power Link and Air Test	20	Extra 10 minutes for mid-train
Subtotal	*Outbound*	*60*	
Total	**Exchange**	**100**	
	Crew Experience Allowance	10	10 percent of total time
	Weather Allowance	10	10 percent of total time
Grand Total	**Exchange**	**120**	

The simulation did not include acceleration and braking delay for arrival and departure from the mainline. Discussion with the crew performing the simulation suggested a ten percent increase to account for crew experience and an additional ten percent increase to account for variability in weather conditions. The simulated train only had one locomotive at each end of the train; additional locomotives will increase the time required for certain steps. The time to secure the train by walking and setting handbrakes will depend on local handbrake rules established by the track gradients in each particular yard.

7.1.3 General Locomotive Exchange Times

The time required to perform the locomotive exchange will be a function of the number and distribution of locomotives in the train consist. With reference to the times for individual steps in the simulated locomotive exchange, exchange times for different distributed power configurations are estimated (Table 7.2).

The configuration with locomotives solely at the front of the train is the most straightforward process with an estimated exchange time of 60 minutes. As observed during the UP simulation, a front-and-rear distributed power configuration can be exchanged in 120 minutes. However, if the rear distributed power locomotives are moved to the middle of the train, the exchange time is increased to 150 minutes. Removing the locomotives from between the two segments of the train requires additional steps to secure different portions of the train. Additional time is required to pull the lead portion of the train forward to allow the mid-train distributed power to escape via a crossover. A full front-middle-rear distributed power configuration is the most complex, consuming just under four hours to complete.

The exchange times in Table 7.2 represent the critical path of the locomotive exchange process in that they only include tasks that cannot be done concurrently by a single train crew. For example, although assembling, conducting a locomotive air brake test and moving a new set of locomotives from the servicing facility to the exchange tracks takes a substantial amount of time, it should be done prior to train arrival. With the locomotives pre-positioned, these locomotive movements do not contribute to the train delay created by the locomotive exchange. For the cases involving distributed power, the assignment of additional hostler crews to the exchange process could allow some of the steps to be completed simultaneously at the expense of additional labor cost.

The general locomotive exchange times also represent an ideal case where the headway between trains is no less than the time it takes to process the train before it or the facility is large enough to accommodate every incoming train and avoid queueing delay. There is also an implicit assumption that the locomotive movements always have immediate access to the required leads and tracks. There is no allowance for time spent waiting for conflicting movements to clear the desired route or for an exchange track to open up when another train departs. In practice, this is never the case as trains arrive at closer intervals on a semi-random basis depending on service demands and delays elsewhere in the system. With multiple trains exchanging locomotives simultaneously, conflicts within the facility are inevitable. The additional exchange point delay arising from these latter effects will be addressed in Section 8 of this report.

Table 7.2: General Locomotive Exchange Times for Different Distributed Power Configurations

Location	Activity	Time (minutes)			
		Front Only (2-0-0)	Front and Rear (2-0-2)	Front and Middle (2-2-0)	Front Middle Rear (2-2-2)
Middle	Secure and Decouple	--	--	10	10
	Pull Front Section Forward	--	--	5	5
	Transport Crew to Front	--	--	5	5
Front	Secure and Decouple	10	10	10	10
	Move to Adjacent Track and Secure	5	5	5	5
	Transport Crew to Rear	--	10	--	10
Rear	Secure and Decouple	--	10	--	10
	Move to Adjacent Track and Secure	--	5	--	5
	Transport Crew to Middle	--	--	5	5
Middle	Move to Adjacent Track and Secure	--	--	5	5
Subtotal	*Inbound*	*15*	*40*	*45*	*70*
Middle	Locomotive Start-up and Brake Test	--	--	10	10
	Move to Train and Couple	--	--	5	5
	Transport Crew to Rear	--	--	--	5
Rear	Locomotive Start-up and Brake Test	--	10	--	10
	Move to Train and Couple	--	5	--	5
	Transport Crew to Front	--	10	5	10
Front	Locomotive Start-up and Brake Test	15	10	10	10
	Move to Train and Couple	5	5	5	5
	Front Section Air Test	--	--	15	15
	Shove Front Section Back to Couple	--	--	10	10
Front	Distributed Power Link and Air Test	15	20	20	30
Subtotal	*Outbound*	*35*	*60*	*80*	*115*
Total	**Exchange**	**50**	**100**	**125**	**185**
	Crew Experience Allowance	5	10	12	18
	Weather Allowance	5	10	13	19
Grand Total	**Exchange**	**60**	**120**	**150**	**222**

7.2 Design Train Flow Rates

The locomotive exchange points must be designed with enough track infrastructure to support traffic volumes on the route. According to Little's Law, the expected number of trains in the locomotive exchange facility at any time is the product of the train flow rate through the facility and the average processing time per train:

Expected Trains in Facility = Hourly Flow Rate (trains/hour) × Processing Time (hours)

Section 4.2.2 provided average daily train counts for the various routes crossing the study area boundary. The daily train counts can be converted into hourly flow rates by dividing by 24. However, these flow rates assume an even distribution of train traffic through the course of the day. Rail traffic is subject to temporal variation on the seasonal, daily and hourly scale. Thus to ensure an exchange point facility of adequate size, the hourly flow rate should be adjusted to account for peak traffic volumes.

7.2.1 Seasonal Variation

The AAR publishes national rail traffic data on a weekly and monthly basis. Historically, the peak month exceeds the average month by nine percent.

7.2.2 Daily Variation

Ports, intermodal facilities and other railroad shippers tend to generate more rail traffic on weekdays than weekends. As this traffic flows over the rail network, it combines to produce daily variation within each week. According to rail operating service design personnel and previous study, the peak day within a week exceeds the daily average by 15 percent. (Caltrans, 2012)

7.2.3 Hourly Variation

Rail terminals operate most efficiently when the incoming and outgoing train flows are evenly distributed and very predictable. This allows the terminal to be optimally sized for traffic and the operating plan to be precisely planned for the minimum amount of track infrastructure. However, it is observed that within a given day, rail traffic is not distributed evenly. Windows for track maintenance, customer service demands, train speed heterogeneity, fleeting dispatching strategies and the natural flow of traffic on single and double track all help contribute to train bunching and uneven flow. A time-space string diagram of actual train movements on the UP Yuma Subdivision (Figure 7.1) illustrates these concepts. Portions of the diagram exhibit train fleeting at a minimum headway while others show spans of time with no train operations for track maintenance. A rail terminal such as a locomotive exchange point will need to be increased beyond its minimum size to handle simultaneous exchange of the observed bunches of trains. The facility must also have adequate servicing and staging tracks to temporarily store cycling locomotives during the longer stretches between arriving and departing trains.

As an example, Figure 7.1 documents 44 train movements in 24 hours, for an average flow rate of rate of 1.8 trains per hour. However, looking at the flow of trains past a particular milepost, there are instances of five or more train movements per hour sustained over a two-hour period. A locomotive exchange point sized to handle 1.8 trains per hour would quickly become saturated during these peak periods. Trains would be held on the mainline outside the facility, increasing delay. This would also interrupt the flow of inbound locomotives to the exchange point, causing additional delay as trains are held waiting for appropriate locomotive power to complete the exchange and resume their trip. This could quickly escalate to a situation where the exchange point becomes full of trains waiting for outbound locomotives but the full exchange tracks prevent any additional trains, with their much-needed inbound locomotives, from entering the facility. Unless more locomotives are deadheaded to the facility, operations can spiral downwards and the deteriorating level of service can quickly spread across the network.

To avoid this scenario, in discussion with rail operating and service design personnel, it is typical for the peak hourly train flow rate to be approximated by twice the average hourly train flow rate for the peak day within the peak month.

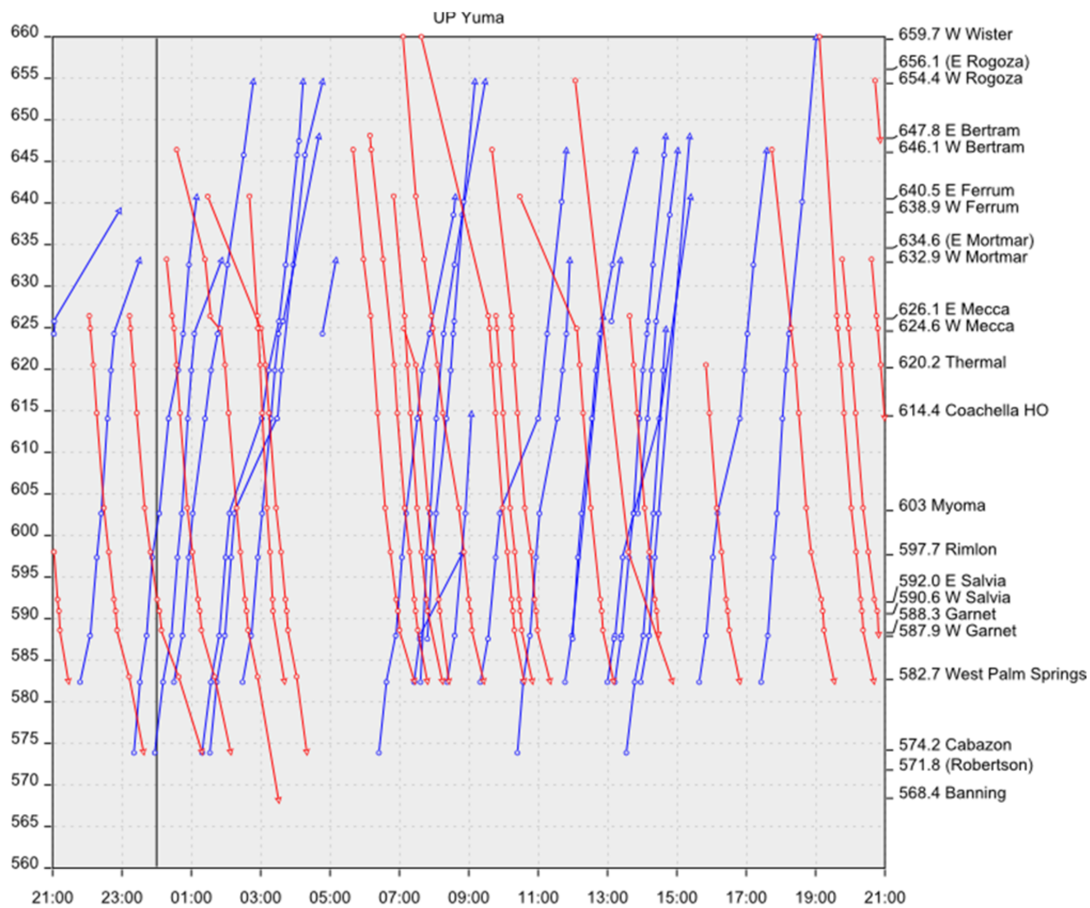

Figure 7-1, Sample time-space diagram of train movements on the UP Yuma Subdivision near Indio, California

7.2.4 Peak Train Flow Rates

Based on the discussion in the previous sections, the train flow rate during the peak hour of the peak weekday during the peak month can be calculated as follows:

Peak Factor = Monthly Peaking Factor × Weekly Peaking Factor × Hourly Peaking Factor

Peak Factor = 1.09 × 1.15 × 2.00 = 2.5 times average train flow rate.

Therefore, to provide a “compliance margin” for exchange point operations, this study uses 2.5 times the average hourly train flow rate for sizing exchange facilities. The duration of this peak flow will be a function of the exchange point dwell time.

7.2.5 Final Design Values

Certain train movements will not enter the exchange point and must be removed from the design train flow rates. For example, it is assumed that manifest trains originating or terminating at Barstow will be made up with new technology locomotives at the current classification yard facility and not use the exchange point.

The final design train flow rates were calculated for each exchange point location (Table 7.3). Since the Valley and Mojave Subdivisions rejoin each other near the air basin boundary, they are assumed to be served by a single exchange point near Palmdale. Thus their train flows combine at this facility (Table 7.4).

Table 7.3: Design Train Flow Rates on Routes Transiting the South Coast Basin

Route	Trains per Day	Exchanged Trains per Day	Average Trains per Hour	Design Trains per Hour	Trains During Peak 2-Hour Period
Union Pacific Santa Barbara Subdivision	1.0	1.0	0.04	1.0	1.0
Union Pacific /Metrolink Valley Subdivision	5.6	5.6	0.23	1.0	2.0
Union Pacific Mojave Subdivision	7.7	7.7	0.32	1.0	2.0
Union Pacific Cima Subdivision (via Cajon)	9.1	9.1	0.38	1.0	2.0
BNSF Cajon Subdivision	66.9	58.9	2.45	6.1	13.0
Union Pacific Yuma Subdivision	39.9	39.9	1.66	4.2	9.0
BNSF/NCTD San Diego Subdivision	4.0	4.0	0.17	1.0	2.0

Table 7.4: Design Train Flow Rates at Prospective South Coast Basin Locomotive Exchange Points

<table>
<tr><th>Route</th><th>Location</th><th>Design Trains per Hour</th><th>Trains During Peak 2-Hour Period</th></tr>
<tr><td>Union Pacific Santa Barbara Subdivision</td><td>Oxnard</td><td>1.0</td><td>1.0</td></tr>
<tr><td>Union Pacific /Metrolink Valley Subdivision</td><td rowspan="2">Palmdale</td><td rowspan="2">1.4</td><td rowspan="2">3.0</td></tr>
<tr><td>Union Pacific Mojave Subdivision</td></tr>
<tr><td>Union Pacific Cima Subdivision (via Cajon)</td><td>Yermo</td><td>1.0</td><td>2.0</td></tr>
<tr><td>BNSF Cajon Subdivision</td><td>Barstow</td><td>6.1</td><td>13.0</td></tr>
<tr><td>Union Pacific Yuma Subdivision</td><td>Indio</td><td>4.2</td><td>9.0</td></tr>
<tr><td>BNSF/NCTD San Diego Subdivision</td><td>Oceanside</td><td>1.0</td><td>1.0</td></tr>
</table>

As previously discussed, railroads are moving to even broader use of distributed power to operate trains in the South Coast basin. It is estimated that a front-rear distributed power configuration will require two hours for a locomotive exchange. To provide sufficient track capacity to support distributed power exchanges on all trains during peak periods, the expected number of trains in the facility over the course of two hours at the peak train flow rate is used for design (Table 7.4).

7.3 Conceptual Design

To operate efficiently and avoid becoming a bottleneck for train operations, the locomotive exchange point must be designed carefully. However, the amount of track infrastructure must not be excessive to avoid unwarranted capital expenditures.

7.3.1 Conceptual Layout and Design Considerations

The first potential bottleneck at the exchange point is the leads connecting the exchange tracks to the mainline. An appropriate number and arrangement of leads will help minimize train conflicts. If each train is assumed to be 2 miles in length, each trains requires 12 minutes to clear the lead at 10 mph, plus 12 minutes to depart the facility. During the locomotive exchange, each train requires a clean engine movement and a diesel engine movement on the lead track consuming 3 minutes each. In total, each train processed through the facility occupies 30 minutes of lead time.

The standard yard has two leads (the west and east end) providing 120 minutes of available yard time per hour. If each train consumes 30 minutes of lead time, a maximum of four trains per hour can be processed with single leads at each end of the yard. Exchange points with a flow rate of more than four trains per hour (Barstow and Indio) will require dual leads at each end of the exchange point yard. At a flow rate of four trains per hour, any bunching or variability in train spacing will result in additional train delay for the arrangement with single leads.

The overall design concept (Figure 7.2) features a paired track arrangement: one track is used for the train during an exchange and the adjacent track is used for staging and spotting locomotives. The general shape of the yard allows for both long and short exchange track pairs for distributed power and conventional train configurations. The short tracks are extendable as train length increases over time.

To improve flow in and out of the facility, the yard leads are extended along the mainline. This effectively creates additional double track near the exchange point and reduces the likelihood of trains incurring additional delay while trapped in the exchange tracks waiting for access to the mainline.

Based on discussions with UP operating personnel, the exchange tracks are designed around the “herringbone concept” (Figure 7.3). Every second track in the body of the yard is a locomotive escape track connected by crossovers to an exchange track. Since the leads at either end of the yard are saturated with train movements, crossovers near the end of each track allow locomotives to cross between the tracks without using the yard lead. The short tracks have a crossover pocket to the adjacent track for pre-positioning locomotives, while long tracks have a herringbone layout with multiple crossovers for pre-positioning locomotives. With these features, the exchange process can be self-contained on each track-pair without interference from other inbound and outbound train movements. Additional crossovers in the middle and at one-third of the track length from either end facilitate exchange of mid-train distributed power locomotives.

To exchange locomotives on the herringbone tracks, new technology locomotives are pre-positioned on the adjacent track as the train enters the exchange facility with conventional locomotives (Figure 7.3). The train is split around the crossovers with the uncoupled conventional locomotives pulling ahead through the crossovers the adjacent track.

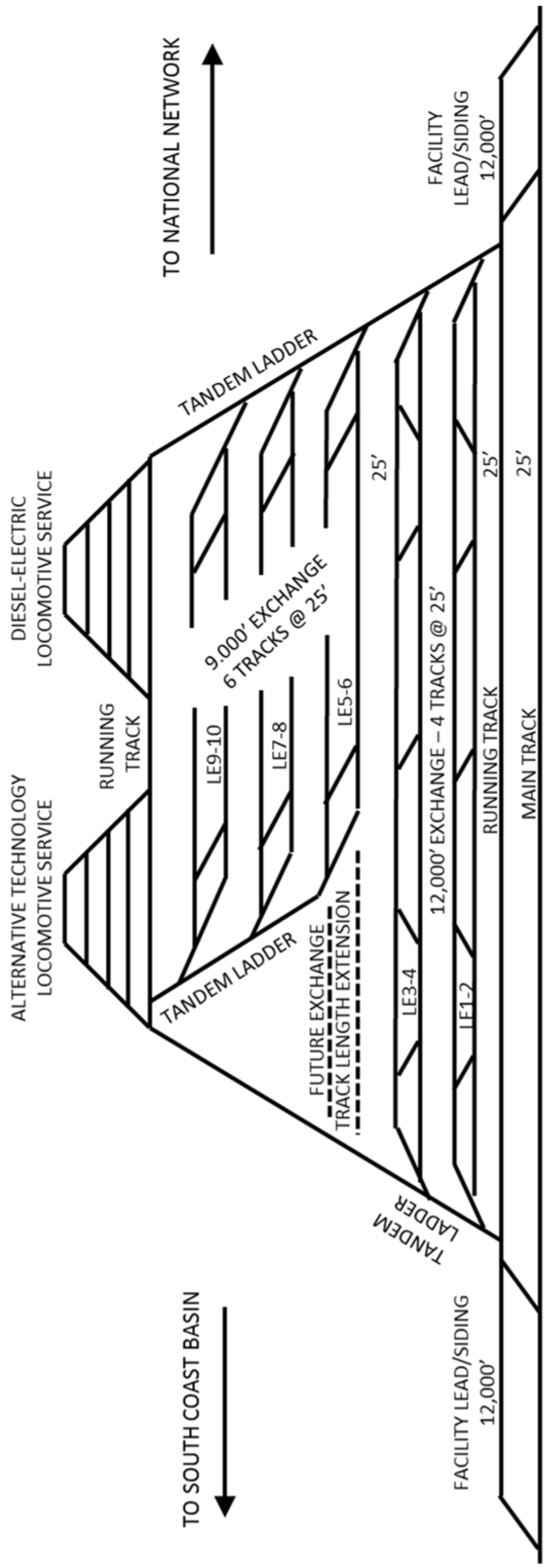

Figure 7-2, Locomotive exchange point conceptual design schematic

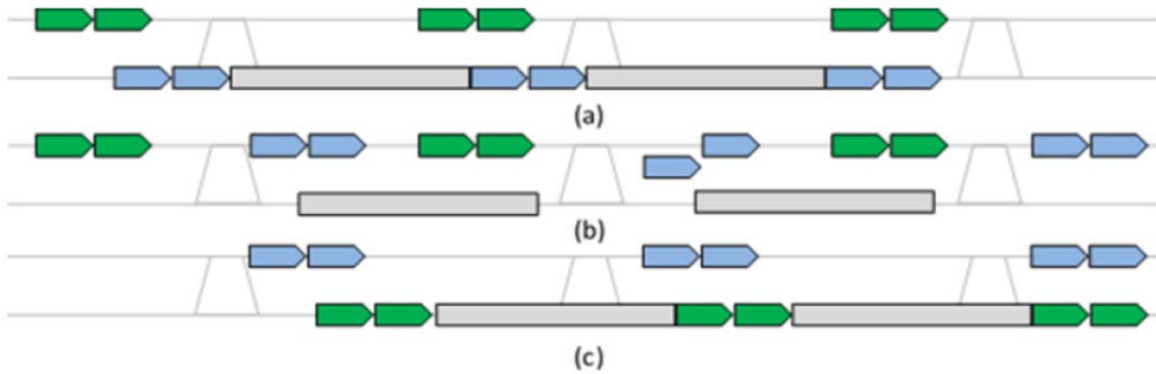

Figure 7-3, Exchange point operations on paired "herringbone" exchange tracks

Once the conventional locomotives are secured, the new technology locomotives move back and forth through the crossovers and couple to the waiting railcars. The three portions of the train are then recoupled for an air test and departure.

Track length within the exchange facility is governed by the current 9,000-foot (150-railcar) standard design train. However, UP runs several 12,000-foot trains from Rochelle to Long Beach each week with the number and length of these trains limited by the length of passing sidings on the route between Salt Lake City and Las Vegas. The train air brake rules specify that no railcar within a DPU train can be more than 5,000 feet of brake pipe distance away from a locomotive. Thus all trains over 10,000 feet in length require mid-train distributed power. To accommodate these longer trains, the conceptual layouts include several 12,000-foot tracks in addition to the 9,000-foot tracks for conventional trains. When provisions for lead tracks and crossovers are made, the exchange facility ideally requires a 3-mile stretch of mainline track without grade crossings or bridges.

7.3.2 Exchange Yard Size

Based on the previous discussion of traffic volume, peaking factor, frequency and complexity of DPU train configurations on each route, suggested locomotive exchange point sizes were prepared (Table 7.5). Queueing models, such as those discussed in Section 8 can help identify the need for additional tracks to minimize train delay while waiting to access the locomotive exchange facility.

Table 7.5: Prospective South Coast Locomotive Exchange Point Size

Location	Trains During Peak 2-Hour Period	Peak Dwelling Locomotives	12,000-foot Exchange Tracks	9,000-foot Exchange Tracks
Oxnard	1	4	0	2
Palmdale	3	20	0	6
Yermo	2	14	4	0
Barstow	13	90	4	22
Indio	9	60	4	14
Oceanside	1	8	0	2

The locomotive facility is sized according to the peak number of dwelling locomotives. This value is derived from six hours of train operations (four average hours plus two peak hours) and an average of 4 locomotives per train. Each dwelling locomotive requires 75 feet of service track space.

7.3.3 Preliminary Layouts

Preliminary layouts corresponding to the required configuration at each exchange point were developed (Figure 7-4 through 7-9). The layouts are intended to show the general arrangement of the exchange point and facilitate scale measurements of track lengths for purposes of estimating construction costs. The layouts are not intended to correspond to the local geometry and other physical constraints of specific project sites.

7.4 Locomotive Exchange Point Yard Capital Cost

Capital cost estimates were developed for the conceptual layouts based on typical unit costs used for railway capital projects (Table 7.6). The estimated construction cost includes capital cost of locomotive exchange tracks, support facilities and right-of-way. The estimate does not include fueling and servicing infrastructure (covered in Section 7.5) but does include:

- Appropriate lead tracks and mainline connections, including signal control points.
- Paved yard access roads and parking areas based on the overall area and number of tracks in the facility.
- Yard office and crew welfare facility (15,000 square feet).
- Compressed air system for maintaining break pipe pressure during the locomotive exchange process. There is a minimum fixed cost for the compressor station and then the cost increases with the number of tracks in the facility.
- Yard lighting, fire protection, utilities and drainage are a function of the area covered by the facility.
- Communications and signal costs are increased according to the number of tracks.
- Each estimate includes a contingency of 20 percent.

Table 7.6: Prospective South Coast Locomotive Exchange Point Yard Capital Costs

Location	Capital Cost ($ million)
Oxnard	49
Palmdale	110
Yermo	121
Barstow	268
Indio	227
Oceanside	49
Total	824

Total cost of exchange point facilities (excluding fueling and servicing) is $824 million. This estimated cost includes 20 percent contingency. Grade separations and relocations will likely increase this cost based on the exact location of facility. Tables 7.6-7.11 provide details for each exchange point.

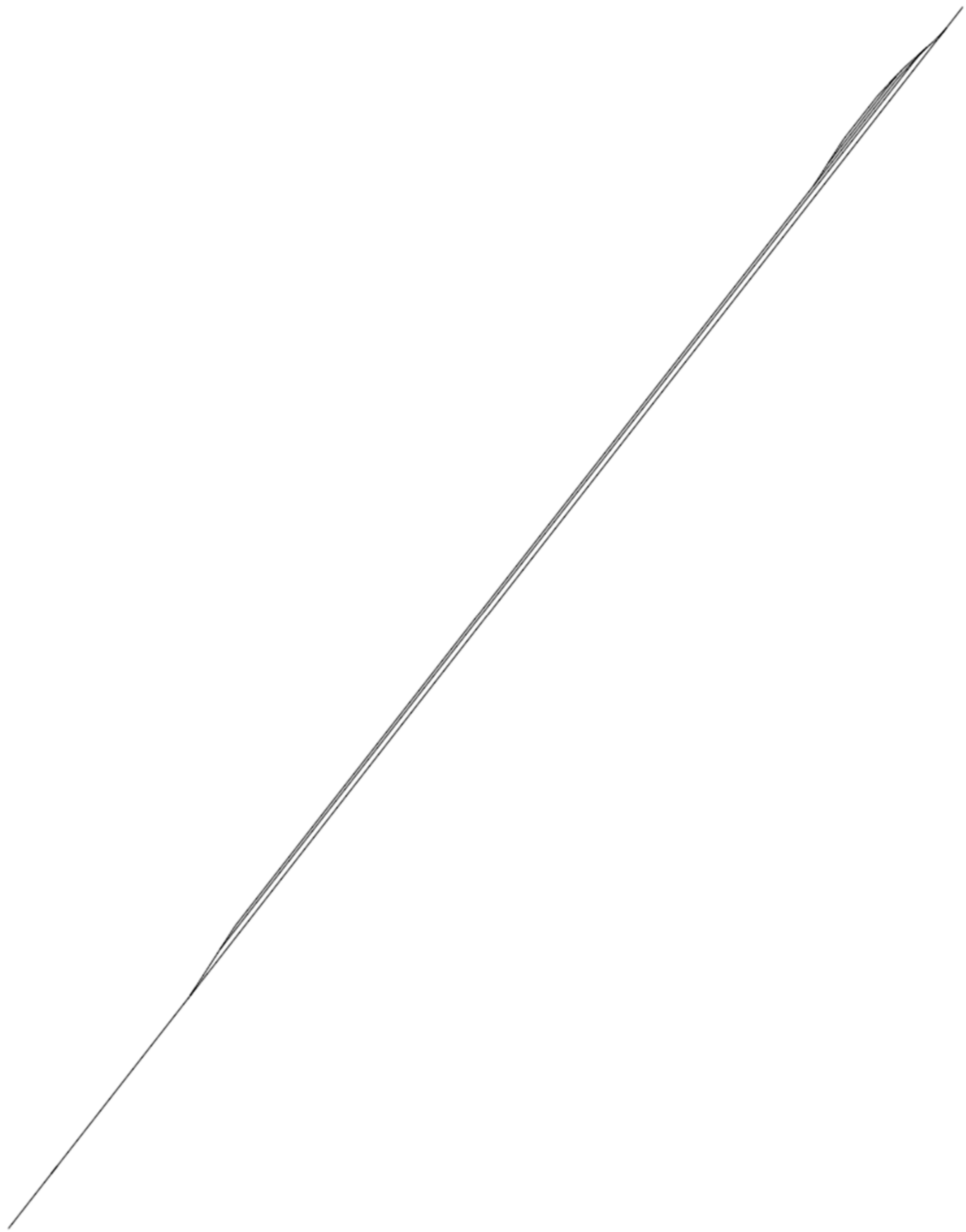

Figure 7-4, Preliminary Oxnard exchange point layout

Figure 7-5, Preliminary Palmdale exchange point layout

Figure 7-6, Preliminary Yermo exchange point layout

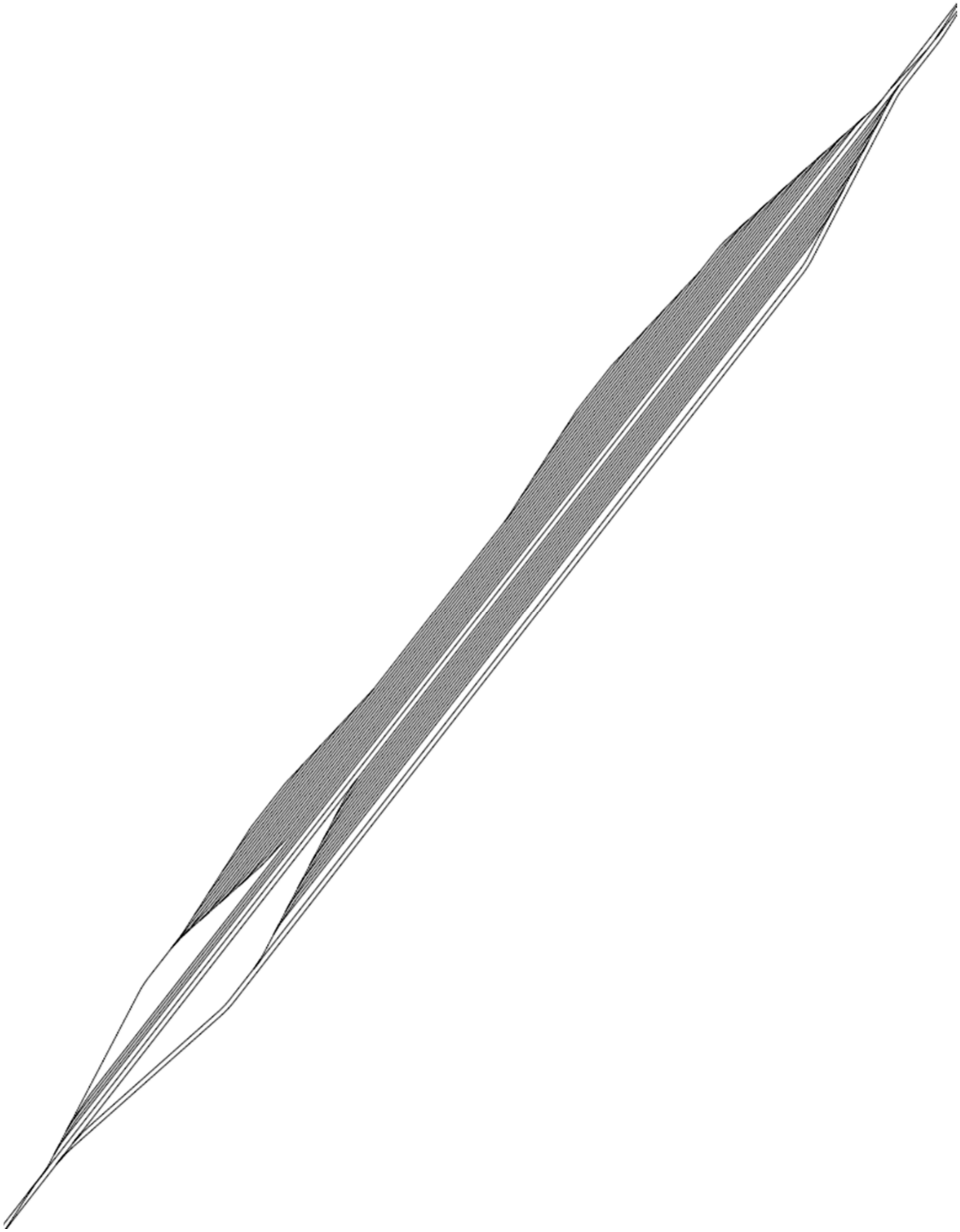

Figure 7-7, Preliminary Barstow exchange point layout

Figure 7-8, Preliminary Indio exchange point layout

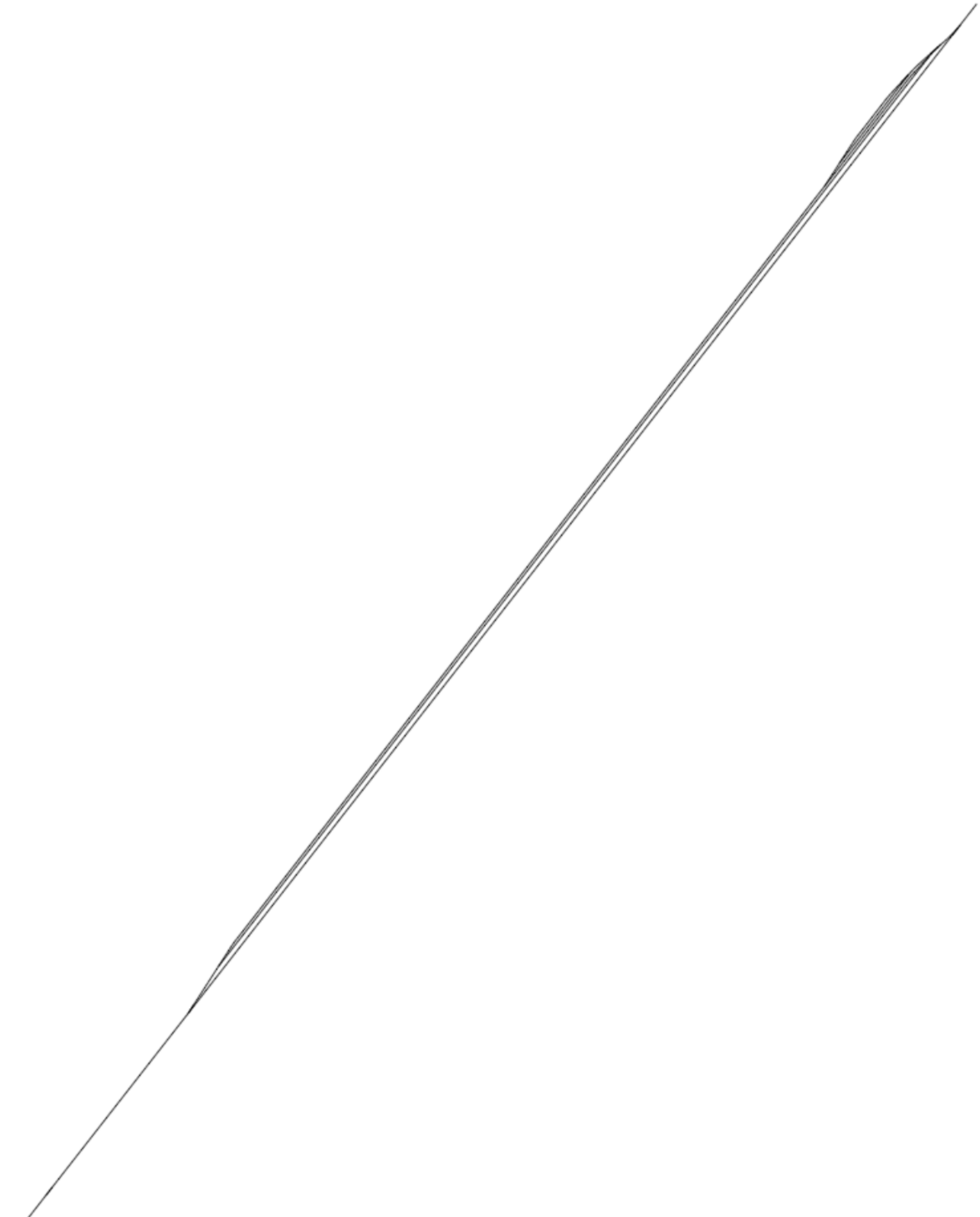

Figure 7-9, Preliminary Oceanside exchange point layout

Table 7.7: Oxnard Exchange Point Yard Capital Cost Estimate

Locomotive Exchange Point - Oxnard				
Preliminary Order of Magnitude Estimate - July 2015				
Description	**Quantity**	**Unit**	**Cost/ Unit**	**TOTAL**
Sitework				
Mobilization	1.00	LS	$1,500,000.00	$1,500,000
Clearing and Grubbing	51.00	AC	$2,500.00	$127,500
Embankment	410,000.00	CY	$5.00	$2,050,000
Excavation	250,000.00	CY	$4.00	$1,000,000
Subballast	27,000.00	CY	$35.00	$945,000
Perimeter Fence	24,800.00	LF	$30.00	$744,000
Paved Yard Roads (24') and Parking - HMAC	67,000.00	SY	$45.00	$3,015,000
Buildings & Facilities				
Yard Office and Crew Facility	5,000.00	SF	$100.00	$500,000
Yard Air	1.00	LS	$540,000.00	$540,000
Yard Lighting	1.00	LS	$1,500,000.00	$1,500,000
Site Utilities and Fire Protection	1.00	LS	$2,500,000.00	$2,500,000
Drainage				
Yard Site Estimate	1.00	LS	$7,000,000.00	$7,000,000
Track - 136# CWR New - Wood Ties & Ballast				
Install Main/Running Track	0.00	TM	$900,000.00	$0
Install Lead/Yard Track	5.02	TM	$725,000.00	$3,639,500
No. 11, RBM Turnout - Manual	6.00	EA	$175,000.00	$1,050,000
No. 11, RBM Turnout - Power	6.00	EA	$235,000.00	$1,410,000
No. 20, RBM Turnout - Manual	0.00	EA	$240,000.00	$0
No. 20, RBM Turnout - Power	0.00	EA	$305,000.00	$0
Remove Track	0.00	TF	$10.00	$0
Remove Turnout	0.00	EA	$16,000.00	$0
Signal and Control				
Mainline Signal Control Points	2.00	EA	$1,750,000.00	$3,500,000
Communications and Signals - General	1.00	LS	$2,000,000.00	$2,000,000
Subtotal				**$33,021,000**
ROW Acquisition	51.00	Acres	$150,000.00	$7,650,000
Relocation Expenses	0.00	EA	$1,250,000.00	$0
Subtotal				**$7,650,000**
Design, Environmental & Contingency		% of Total	20.00%	$8,134,200
Subtotal				**$8,134,200**
TOTAL				**$48,805,200**

Table 7.8: Palmdale Exchange Point Yard Capital Cost Estimate

Locomotive Exchange Point - Palmdale				
Preliminary Order of Magnitude Estimate - July 2015				
Description	**Quantity**	**Unit**	**Cost/ Unit**	**TOTAL**
Sitework				
Mobilization	1.00	LS	$1,500,000.00	$1,500,000
Clearing and Grubbing	112.00	AC	$2,500.00	$280,000
Embankment	900,000.00	CY	$5.00	$4,500,000
Excavation	550,000.00	CY	$4.00	$2,200,000
Subballast	113,000.00	CY	$35.00	$3,955,000
Perimeter Fence	23,700.00	LF	$30.00	$711,000
Paved Yard Roads (24') and Parking - HMAC	96,000.00	SY	$45.00	$4,320,000
Buildings & Facilities				
Yard Office and Crew Facility	15,000.00	SF	$100.00	$1,500,000
Yard Air	1.00	LS	$610,000.00	$610,000
Yard Lighting	1.00	LS	$1,830,000.00	$1,830,000
Site Utilities and Fire Protection	1.00	LS	$6,500,000.00	$6,500,000
Drainage				
Yard Site Estimate	1.00	LS	$12,400,000.00	$12,400,000
Track - 136# CWR New - Wood Ties & Ballast				
Install Main/Running Track	4.54	TM	$900,000.00	$4,086,000
Install Lead/Yard Track	16.73	TM	$725,000.00	$12,129,250
No. 11, RBM Turnout - Manual	22.00	EA	$175,000.00	$3,850,000
No. 11, RBM Turnout - Power	16.00	EA	$235,000.00	$3,760,000
No. 20, RBM Turnout - Manual	0.00	EA	$240,000.00	$0
No. 20, RBM Turnout - Power	2.00	EA	$305,000.00	$610,000
Remove Track	0.00	TF	$10.00	$0
Remove Turnout	0.00	EA	$16,000.00	$0
Signal and Control				
Mainline Signal Control Points	2.00	EA	$1,750,000.00	$3,500,000
Communications and Signals - General	1.00	LS	$6,200,000.00	$6,200,000
Subtotal				**$74,441,250**
ROW Acquisition	112.00	Acres	$150,000.00	$16,800,000
Relocation Expenses	0.00	EA	$1,250,000.00	$0
Subtotal				**$16,800,000**
Design, Environmental & Contingency		% of Total	20.00%	$18,248,250
Subtotal				**$18,248,250**
TOTAL				**$109,489,500**

Table 7.9: Yermo Exchange Point Yard Capital Cost Estimate

Locomotive Exchange Point - Yermo				
Preliminary Order of Magnitude Estimate - July 2015				
Description	**Quantity**	**Unit**	**Cost/ Unit**	**TOTAL**
Sitework				
Mobilization	1.00	LS	$1,500,000.00	$1,500,000
Clearing and Grubbing	161.00	AC	$2,500.00	$402,500
Embankment	1,300,000.00	CY	$5.00	$6,500,000
Excavation	780,000.00	CY	$4.00	$3,120,000
Subballast	112,000.00	CY	$35.00	$3,920,000
Perimeter Fence	29,700.00	LF	$30.00	$891,000
Paved Yard Roads (24') and Parking - HMAC	112,000.00	SY	$45.00	$5,040,000
Buildings & Facilities				
Yard Office and Crew Facility	15,000.00	SF	$100.00	$1,500,000
Yard Air	1.00	LS	$570,000.00	$570,000
Yard Lighting	1.00	LS	$1,710,000.00	$1,710,000
Site Utilities and Fire Protection	1.00	LS	$6,000,000.00	$6,000,000
Drainage				
Yard Site Estimate	1.00	LS	$11,400,000.00	$11,400,000
Track - 136# CWR New - Wood Ties & Ballast				
Install Main/Running Track	4.54	TM	$900,000.00	$4,086,000
Install Lead/Yard Track	16.50	TM	$725,000.00	$11,962,500
No. 11, RBM Turnout - Manual	24.00	EA	$175,000.00	$4,200,000
No. 11, RBM Turnout - Power	18.00	EA	$235,000.00	$4,230,000
No. 20, RBM Turnout - Manual	0.00	EA	$240,000.00	$0
No. 20, RBM Turnout - Power	2.00	EA	$305,000.00	$610,000
Remove Track	0.00	TF	$10.00	$0
Remove Turnout	0.00	EA	$16,000.00	$0
Signal and Control				
Mainline Signal Control Points	2.00	EA	$1,750,000.00	$3,500,000
Communications and Signals - General	1.00	LS	$5,800,000.00	$5,800,000
Subtotal				**$76,942,000**
ROW Acquisition	161.00	Acres	$150,000.00	$24,150,000
Relocation Expenses	0.00	EA	$1,250,000.00	$0
Subtotal				**$24,150,000**
Design, Environmental & Contingency		% of Total	20.00%	$20,218,400
Subtotal				**$20,218,400**
TOTAL				**$121,310,400**

Table 7.10: Barstow Exchange Point Yard Capital Cost Estimate

Locomotive Exchange Point - Barstow				
Preliminary Order of Magnitude Estimate - July 2015				
Description	**Quantity**	**Unit**	**Cost/ Unit**	**TOTAL**
Sitework				
Mobilization	1.00	LS	$1,500,000.00	$1,500,000
Clearing and Grubbing	331.00	AC	$2,500.00	$827,500
Embankment	2,700,000.00	CY	$5.00	$13,500,000
Excavation	1,600,000.00	CY	$4.00	$6,400,000
Subballast	358,000.00	CY	$35.00	$12,530,000
Perimeter Fence	31,500.00	LF	$30.00	$945,000
Paved Yard Roads (24') and Parking - HMAC	148,000.00	SY	$45.00	$6,660,000
Buildings & Facilities				
Yard Office and Crew Facility	15,000.00	SF	$100.00	$1,500,000
Yard Air	1.00	LS	$1,000,000.00	$1,000,000
Yard Lighting	1.00	LS	$3,000,000.00	$3,000,000
Site Utilities and Fire Protection	1.00	LS	$10,000,000.00	$10,000,000
Drainage				
Yard Site Estimate	1.00	LS	$20,000,000.00	$20,000,000
Track - 136# CWR New - Wood Ties & Ballast				
Install Main/Running Track	7.50	TM	$900,000.00	$6,750,000
Install Lead/Yard Track	60.27	TM	$725,000.00	$43,695,750
No. 11, RBM Turnout - Manual	80.00	EA	$175,000.00	$14,000,000
No. 11, RBM Turnout - Power	70.00	EA	$235,000.00	$16,450,000
No. 20, RBM Turnout - Manual	0.00	EA	$240,000.00	$0
No. 20, RBM Turnout - Power	4.00	EA	$305,000.00	$1,220,000
Remove Track	0.00	TF	$10.00	$0
Remove Turnout	0.00	EA	$16,000.00	$0
Signal and Control				
Mainline Signal Control Points	2.00	EA	$1,750,000.00	$3,500,000
Communications and Signals - General	1.00	LS	$10,000,000.00	$10,000,000
Subtotal				**$173,478,250**
ROW Acquisition	331.00	Acres	$150,000.00	$49,650,000
Relocation Expenses	0.00	EA	$1,250,000.00	$0
Subtotal				**$49,650,000**
Design, Environmental & Contingency		% of Total	20.00%	$44,625,650
Subtotal				**$44,625,650**
TOTAL				**$267,753,900**

Table 7.11: Indio Exchange Point Yard Capital Cost Estimate

Locomotive Exchange Point - Indio				
Preliminary Order of Magnitude Estimate - July 2015				
Description	**Quantity**	**Unit**	**Cost/ Unit**	**TOTAL**
Sitework				
Mobilization	1.00	LS	$1,500,000.00	$1,500,000
Clearing and Grubbing	298.00	AC	$2,500.00	$745,000
Embankment	2,400,000.00	CY	$5.00	$12,000,000
Excavation	1,500,000.00	CY	$4.00	$6,000,000
Subballast	280,000.00	CY	$35.00	$9,800,000
Perimeter Fence	30,200.00	LF	$30.00	$906,000
Paved Yard Roads (24') and Parking - HMAC	145,000.00	SY	$45.00	$6,525,000
Buildings & Facilities				
Yard Office and Crew Facility	15,000.00	SF	$100.00	$1,500,000
Yard Air	1.00	LS	$850,000.00	$850,000
Yard Lighting	1.00	LS	$2,550,000.00	$2,550,000
Site Utilities and Fire Protection	1.00	LS	$9,000,000.00	$9,000,000
Drainage				
Yard Site Estimate	1.00	LS	$17,000,000.00	$17,000,000
Track - 136# CWR New - Wood Ties & Ballast				
Install Main/Running Track	7.50	TM	$900,000.00	$6,750,000
Install Lead/Yard Track	45.44	TM	$725,000.00	$32,944,000
No. 11, RBM Turnout - Manual	60.00	EA	$175,000.00	$10,500,000
No. 11, RBM Turnout - Power	54.00	EA	$235,000.00	$12,690,000
No. 20, RBM Turnout - Manual	0.00	EA	$240,000.00	$0
No. 20, RBM Turnout - Power	4.00	EA	$305,000.00	$1,220,000
Remove Track	0.00	TF	$10.00	$0
Remove Turnout	0.00	EA	$16,000.00	$0
Signal and Control				
Mainline Signal Control Points	2.00	EA	$1,750,000.00	$3,500,000
Communications and Signals - General	1.00	LS	$8,500,000.00	$8,500,000
Subtotal				**$144,480,000**
ROW Acquisition	298.00	Acres	$150,000.00	$44,700,000
Relocation Expenses	0.00	EA	$1,250,000.00	$0
Subtotal				**$44,700,000**
Design, Environmental & Contingency		% of Total	20.00%	$37,836,000
Subtotal				**$37,836,000**
TOTAL				**$227,016,000**

Table 7.12: Oceanside Exchange Point Yard Capital Cost Estimate

Locomotive Exchange Point - Oceanside Preliminary Order of Magnitude Estimate - July 2015				
Description	**Quantity**	**Unit**	**Cost/ Unit**	**TOTAL**
Sitework				
Mobilization	1.00	LS	$1,500,000.00	$1,500,000
Clearing and Grubbing	51.00	AC	$2,500.00	$127,500
Embankment	410,000.00	CY	$5.00	$2,050,000
Excavation	250,000.00	CY	$4.00	$1,000,000
Subballast	27,000.00	CY	$35.00	$945,000
Perimeter Fence	24,800.00	LF	$30.00	$744,000
Paved Yard Roads (24') and Parking - HMAC	67,000.00	SY	$45.00	$3,015,000
Buildings & Facilities				
Yard Office and Crew Facility	5,000.00	SF	$100.00	$500,000
Yard Air	1.00	LS	$540,000.00	$540,000
Yard Lighting	1.00	LS	$1,500,000.00	$1,500,000
Site Utilities and Fire Protection	1.00	LS	$2,500,000.00	$2,500,000
Drainage				
Yard Site Estimate	1.00	LS	$7,000,000.00	$7,000,000
Track - 136# CWR New - Wood Ties & Ballast				
Install Main/Running Track	0.00	TM	$900,000.00	$0
Install Lead/Yard Track	5.02	TM	$725,000.00	$3,639,500
No. 11, RBM Turnout - Manual	6.00	EA	$175,000.00	$1,050,000
No. 11, RBM Turnout - Power	6.00	EA	$235,000.00	$1,410,000
No. 20, RBM Turnout - Manual	0.00	EA	$240,000.00	$0
No. 20, RBM Turnout - Power	0.00	EA	$305,000.00	$0
Remove Track	0.00	TF	$10.00	$0
Remove Turnout	0.00	EA	$16,000.00	$0
Signal and Control				
Mainline Signal Control Points	2.00	EA	$1,750,000.00	$3,500,000
Communications and Signals - General	1.00	LS	$2,000,000.00	$2,000,000
Subtotal				**$33,021,000**
ROW Acquisition	51.00	Acres	$150,000.00	$7,650,000
Relocation Expenses	0.00	EA	$1,250,000.00	$0
Subtotal				**$7,650,000**
Design, Environmental & Contingency		% of Total	20.00%	$8,134,200
Subtotal				**$8,134,200**
TOTAL				**$48,805,200**

7.5 Exchange Point Servicing Infrastructure Capital Cost

New technology locomotives are most conveniently fueled, serviced and inspected at the locomotive exchange facilities. In addition, once the exchange point is established, conventional diesel-electric locomotives are assumed to not operate into the basin to reach existing diesel fueling and servicing infrastructure. Thus each exchange point must be equipped to service both new technology and conventional diesel-electric locomotives.

The capital cost of locomotive servicing and fueling infrastructure can be estimated as $200,000 per locomotive dwelling in the peak hour. An additional allowance of $500,000 per locomotive dwelling in the peak hour is made to account for complexity of cryogenic LNG refueling infrastructure. An additional allowance of $800,000 per locomotive dwelling in the peak hour is made to account for the expense of battery tender charging infrastructure. Since the battery tenders only have enough storage capacity for a one-way trip, the same total battery charging infrastructure investment must be made at the various origin-destination terminals within the South Coast basin (Table 7.12).

Table 7.13: Servicing Infrastructure Capital Cost ($ million)

Location	General	LNG	Battery Charging
Oxnard	0.8	2.0	3.2
Palmdale	4.0	10.0	16.0
Yermo	2.8	7.0	11.2
Barstow	18.0	45.0	72.0
Indio	12.0	30.0	48.0
Oceanside	1.6	4.0	6.4
At Terminals	--	--	156.8
Total	39.2	98.0	313.6

7.6 Exchange Point Operating Cost

To operate exchange points, additional personnel are required to serve as inspectors, hostlers, and “utility” ground crew to help throw turnouts and position locomotives. It is estimated that three crew members are required for each train dwelling during the peak hour, for total of 87 between the six exchange points. This staffing level will be maintained for three shifts at a railway cost of $79.80 per hour (Lovett, 2015). This corresponds to an annual operating expense of $61 million.

7.7 Summary

Based on full-scale field trials, depending on the locomotive configuration, locomotive exchanges are likely to take between 60 and 222 minutes at the locomotive exchange points. The number of tracks at each exchange point is determined from the anticipated dwell time and peak train flow rate. The peak train flow rate is the average train flow rate multiplied by a factor of 2.5.

Construction of six appropriately-sized exchange facilities for the South Coast basin incurs $824 million in capital construction cost, including all sitework, track, support facilities and right-of-way. Depending on the locomotive technology, an additional $39 to $353 million in capital cost is required to establish locomotive and tender servicing and fueling facilities, Crews to operate the exchange points correspond to an annual expense of $61 million.

8 Exchange Point Delay Cost and Modal Shift

As described in Section 6.1, the locomotive exchange process disrupts the natural flow of rail traffic and potentially introduces additional train delay. Train delay has direct and indirect costs to the railway through reduced resource utilization. Train delay also limits the ability of the railways to compete with trucks for certain types of freight that are particularly time-sensitive. Excessive train delay may cause shippers to shift freight to the highway transportation mode with railway revenue and emissions implications.

8.1 Methodology

There are two types of train delay: primary delay and secondary delay (Martland, 2008). Primary delays are those that directly result from the root cause of traffic disruption. Secondary delays are additional delay incurred because of the primary delay to the directly impacted train. For example, when a train stops due to a warning from a wayside defect detector, the time lost by that train is the primary delay. Later, if this delay causes the train to miss a planned meeting point and experience additional delay waiting for another train, the delay experienced by the first train is an example of a secondary delay. A train following the first train that must also stop when the first train is stopped by the wayside detector warning also experiences secondary delay.

8.1.1 Primary Exchange Delays

At the locomotive exchange points, primary train delays correspond to the baseline exchange times outlined in Section 7. These delays include the direct required to execute the locomotive exchange.

8.1.2 Acceleration/Braking Delays

Secondary delays are time lost accelerating and decelerating to/from the exchange point and time spent waiting for a slot in the exchange point under congested conditions. Trains held outside the exchange point can create cascading train delays that further deteriorate the level of service on the route segment.

Bunching of trains can exacerbate braking delay at the locomotive exchange point. Based on the train length and required clearance time, there must be 12 minutes of headway between trains entering the yard at 10 mph. However, the mainline signal system can allow trains running at 60 mph to be separated by 5 miles, corresponding to a 5-minute headway. As the first train enters the exchange point at 10 mph, the second train must slow down and experience 7 minutes of delay before it can enter the yard. If three trains are bunched, the third train experiences 14 minutes of delay. To study this pattern in a more rigorous manner, queuing models were developed of various bottlenecks in the locomotive exchange process.

8.1.3 Lead Track Queuing Delay- M/D/1 Model

When a train is preparing to enter the locomotive exchange facility from the mainline, the lead track is the first bottleneck it encounters and represents the first potential for queuing. An M/D/1 model assumes a random arrival distribution, deterministic service times, and one service channel. Although the facility is sized according to an assumed peak train flow, the random arrival distribution is assumed for determining the average queuing time for both the lead track and the exchange facility. The service times are designated as deterministic because the moves occupying the lead track are relatively consistent. Following the nomenclature from “Principles of Highway Engineering and Traffic Analysis” by Mannering et al, the average queue time under the given parameters can be calculated using Equations (1)-(3). (Mannering et al, 2009)

$$\rho = \frac{\lambda}{\mu}. \quad (1)$$

$$\bar{Q} = \frac{\rho}{2(1-\rho)}. \quad (2)$$

.

$$t_l = \frac{\rho + \bar{Q}}{\lambda} - \frac{1}{\mu}. \quad (3)$$

where:

ρ = traffic intensity

λ = average arrival rate in trains per unit time

μ = average departure (processing) rate in trains per unit time

$\bar{Q}$ = average length of queue (in no. of trains)

t_l = average waiting time in the lead queue, in unit time per train

The average arrival rate (λ) is calculated by taking the daily flow rate of the impacted rail line and dividing it by 24. The average departure rate (μ) is the inverse of the processing time in hours. In other terms, for a locomotive configuration requiring 2 hours to be processed, the departure rate is 0.5 trains per hour.

Each incoming train effectively occupies each lead twice during its inbound and outbound moves: once when it is entering or leaving the yard and physically occupying the track and again while its locomotives are being moved to and from the locomotive servicing facility. This means that the average arrival rate for the model is two times the flow rate through the exchange facility and that the total lead delay is double the calculated average waiting time.

8.1.4 Exchange Facility Queuing Delay- M/M/N Model

Even if the lead is clear, there is still a chance that a train will need to queue while waiting for an exchange track to clear within the exchange facility. An M/M/N (aka M/M/c) queue is a modification of a classical queue assuming that trains arrive according to a rate with Poisson distribution, the processing times are exponentially distributed, and there are two or more servers (exchange track) operating independently of each other (Sztrik, 2012). Unlike the lead processing time, the exchange facility processing times are considered to be exponentially distributed. This is because the processing times for the exchange are the sum of a series of individual sub-events and deviation from the mean processing time has the potential to significantly impact results.

The assumption of independent parallel processes is simplifying in that there is potential interaction between the parallel exchange processes on the inbound and outbound leads and during the moves between each process. This assumption also infers that there are sufficient crews to operate each pair of exchange tracks independently which may not be the case due to the high cost of labor in the industry. The final assumption is that the inbound buffer, i.e. the mainline track, is of infinite size (Sztrik, 2012). While this assumption is valid for the given application, trains queuing on the mainline incur additional delays on any run-through traffic as well as on trains flowing through the facility against the direction of the queue. Equations 4-5 provide the average queuing time for the given parameters (Mannering, 2009).

$$P_0 = \left[\sum_{n_c=0}^{N-1} \frac{\rho^{n_c}}{n_c!} + \frac{\rho^N}{N!\left(1 - \frac{\rho}{N}\right)}\right]^{-1}. \quad (4)$$

$$\bar{Q} = \frac{P_0 \rho^{N+1}}{N!\,N} \left[\frac{1}{\left(1 - \frac{\rho}{N}\right)^2}\right]. \quad (5)$$

$$t_e = \frac{\rho + \bar{Q}}{\lambda} - \frac{1}{\mu}. \quad (6)$$

where:

P_0 = probability of having no trains in the exchange point

N = number of service channels (pairs of exchange tracks)

n_c = departure channel number

t_e = average waiting time in the exchange facility queue, in unit time per train

(other variables as for Equations 1-3)

It is evident from equations (4) and (5), if ρ/N=1 (i.e. the number of tracks requires 100 percent utilization to accommodate the average train flow rate) the equation is unsolvable and infinite queuing delay is experienced. In order for the solutions to be valid, ρ/N must be less than 1 for all train flows and facility sizes.

To calculate the total queuing time, the lead and exchange facility queue time are assumed to be additive for the purposes of this study. The probabilities of one or the other being full and causing further delay are not dependent on one another and thus each can be considered independent. The final delay for a given train flow, locomotive configuration, and facility size is the sum of the inbound lead occupation time, inbound lead queue delay, locomotive exchange time, exchange facility delay, outbound lead occupation time and outbound queue delay.

8.1.5 Direct Cost of Train Delay

U of I research has estimated the cost of train delay between $250 and $1,000 per train-hour depending on the commodity being handled (Schafer, 2008; Dingler, 2010; Lovett, 2014; Lovett 2015). Only portions of this delay are experienced at the exchange point, including railcars, crew, locomotive fuel and locomotive operating costs. Changes in locomotive ownership expense due to lower equipment utilization and increased fleet size are implicitly included in the fleet size analysis in Section 6.

The train delay cost rates (Table 8.1) quantify inefficiencies that arise when trains are delayed:

- Crew cost is extra labor time spent executing the locomotive exchange and is calculated per train-hour.
- Locomotive diesel fuel is the cost of extra diesel fuel consumed while idling conventional diesel-electric motive power during the locomotive exchange process. The cost of fuel is calculated per locomotive-hour and is dependent on the cost of diesel fuel.
- Locomotive operating cost reflects the hourly ownership cost of each locomotive. This cost is a proxy for the opportunity cost of the locomotive being unavailable for other productive work earning revenue during the exchange process.
- Railcar costs are the direct cost of extra car-hire (rent) required because train delay increases the overall car cycle time. Railcars costs also include the opportunity cost incurred while delayed railcars are delayed at the exchange point instead of earning revenue from another load.

Table 8.1: Components of Railroad Delay Costs (Lovett, 2015)

Item	Rate ($)
Crew (per train-hour)	79.53
Locomotive Diesel Fuel (per locomotive-hour)	185.00
Locomotive Operating (per locomotive-hour)	66.73
Bulk railcars (per railcar-hour)	0.58
Manifest railcars (per railcar-hour)	0.84
Intermodal railcars (per railcar-hour)	1.00

8.1.6 Modal Assignment and Shift of Traffic to Competing Modes

Shippers of high-value commodities are driven to select the transportation option that provides the best transit time and most consistent level of service while meeting their economic needs. Train delay increases transit time and the cost of railway transportation. Train delay also introduces variability, decreasing the consistency of the level of service provided by the railways. When oil prices are high, shippers may tolerate more delays to take advantage of the energy efficiency of railway transportation. However, as oil prices drop and fuel comprises a smaller share of transportation operating costs, shippers are less likely to tolerate increased train transit time and may shift their freight to the highway truck mode.

To capture this shipper behavior and assess the impact of train delays at locomotive exchange points, this study determines the modal split between truck and rail for freight shipments with the model developed by Hwang and Ouyang (2014). The model is a binomial logit market share model based on the inputs of oil price, freight commodity value, and truck and rail shipment distance/time. The model calculates a predicted freight rail market share for nine individual commodity groups (Table 4.7).

In order to evaluate the impact of train delay on freight rail market share for a given commodity, the predicted rail market share of a base case with actual rail and truck shipment distances is compared to a case adjusted for train delay. To account for train delay in the model formulation, the truck shipment distance is proportionately shortened relative to the original travel distance such that the truck arrives at the destination earlier by a time equal to the total train delay time (7). An average highway truck speed is required to complete the calculation.

$$D^* = \left(\frac{\frac{D}{V_T} - T_E}{D/V_T} \right) D. \tag{7}$$

where:

D^* = modified truck distance

D = original shipment distance

V_T = average truck velocity

T_E = exchange point delay

When combined with the above transformation, the overall model outputs the expected change in rail market share for each train run that experiences train delay at the exchange point. Since the model is commodity-specific, it must be run multiple times for each train to calculate the expected change in market share for each commodity being handled by the train. Assigning train tons to each commodity group from the analysis of waybill data allows the model to make different mode choice decisions for different combinations of shipment values and priorities, such as intermodal traffic and manifest carload traffic. By performing the calculation at the commodity level, lost revenue can be calculated using the reduced market share and commodity specific revenue rates per ton-mile.

A limitation of this model and this study is that it does not consider specific business penalties relating to train delay and level of service. Such clauses are negotiated between shippers and the railroads as private contracts. Thus it is not known if specific shipments may have tighter delay tolerance written into their contracts than that predicted by the modal split model.

8.2 Cost of Train Delay at Exchange Points

Train and locomotive hours of delay are calculated based on the exchange time and power requirements for each train and the properties of the exchange point yards. For the exchange process, it is assumed that each locomotive technology requires the same amount of time to complete the locomotive exchange. To reflect the different amount of locomotive exchange delay associated with each train configuration, each type of train (premium intermodal, intermodal, auto, manifest, and bulk) is assigned a locomotive configuration based on the typical properties of that train type (Table 8.2). The presented delay values include the primary delay and secondary queuing delay as described in the previous section. The queueing delay is calculated with the lead track and exchange facility queuing models with the train arrival rates (Table 7.3) and number of tracks specified for each exchange point (Table 7.5). The locomotive configuration and exchange time for a particular train type is used for all trains of that type under study. This study assigns train configurations with the lowest exchange delay time to the most time-sensitive traffic: premium intermodal and auto trains.

Table 8.2: Locomotive Configurations and Exchange Delay Times by Train Type

Train Type	Locomotive Configuration (Front-Middle-Rear)	Exchange Delay Time (hours)
Premium Intermodal	X-0-0	1.59
Intermodal	X-0-X	2.61
Auto	X-0-0	1.59
Manifest	X-0-X	2.61
Unit	X-X-X	4.29

Given the delay times above, the annual number of trains on each route and number of locomotives and railcars operating on each train, the annual total train, locomotive and railcar delay is calculated (Table 8.3-8.4). Delays for BNSF traffic to San Diego are included in the BNSF Cajon Subdivision figures. Manifest traffic on the BNSF Cajon Subdivision terminating at the existing Barstow Yard would not accumulate delay at the exchange point.

Table 8.3: Annual Train and Locomotive Delay at Exchange Points

Route	Train Delay (train-hours)			Locomotive Delay (locomotive-hours)
	Intermodal	Manifest	Unit	
Union Pacific Santa Barbara Subdivision	--	--	1,566	4,698
Union Pacific /Metrolink Valley Subdivision	3,341	--	--	5,040
Union Pacific Mojave Subdivision	--	5,716	1,253	15,190
BNSF Cajon Subdivision	53,510	--	626	217,148
Union Pacific Cima Subdivision (via Cajon)	3,778	3,811	1,879	32,324
Union Pacific Yuma Subdivision	19,962	9,527	--	100,270
Total	80,591	19,054	5,324	353,062

Table 8.4: Annual Railcar Delay at Exchange Points

Route	Railcar Delay (car-hours)		
	Intermodal	Manifest	Unit
Union Pacific Santa Barbara Subdivision	--	--	68,897
Union Pacific /Metrolink Valley Subdivision	61,734	--	--
Union Pacific Mojave Subdivision	--	162,903	137,795
BNSF Cajon Subdivision	5,773,140	--	68,897
Union Pacific Cima Subdivision (via Cajon)	259,065	120,987	206,692
Union Pacific Yuma Subdivision	2,514,181	122,130	--
Total	8,608,120	406,019	551,179

With the train delay cost rates in Table 8.1, the annual direct cost of train delay is calculated for train operation through the South Coast basin locomotive exchange points (Table 8.5). The exchange points introduce $112 million in annual train delay costs.

Table 8.5: Annual Direct Cost of Train Delay ($ millions)

Route	Train Delay Cost
Union Pacific Santa Barbara Subdivision	1.4
Union Pacific /Metrolink Valley Subdivision	1.6
Union Pacific Mojave Subdivision	4.6
BNSF Cajon Subdivision	64.8
Union Pacific Cima Subdivision (via Cajon)	9.4
Union Pacific Yuma Subdivision	30.2
Total	112.0

8.3 Mode Shift and Lost Revenue

The freight mode split model described in Section 8.1.6 requires inputs of truck and rail distance, commodity value per ton, and the West Texas Intermediate (WTI) crude oil price. The rail and corresponding highway truck distance for each train symbol movement are estimated using PC*Miler and Google maps software, respectively, between origin and destination terminal. The commodity values per ton are derived from the STB waybill sample data for each shipment type (manifest, intermodal, bulk, and auto) and commodity group. The WTI crude oil price was set to the 2014 average of $51.75/barrel.

To calculate mode shift for each train symbol movement, a base case without train delay is compared to a delayed case. To include train delay in the mode split model, the truck distance is decreased based on the length of the train delay and truck travel speed. The delay for each train symbol movement depends on train type and typical locomotive configurations (Table 8.2). As with the direct delay costs, it is assumed that each locomotive technology requires the same amount of time to exchange locomotives. Thus traffic losses are the same for each alternative technology. Annual mode shift volume is calculated for every train symbol shipment transiting the South Coast basin and aggregated for each route.

When subject to exchange point delay, approximately 12.5 million tons of competitive and time sensitive annual freight rail traffic shifts to the highway mode (Table 8.6). This amount of freight shifting to truck corresponds to 12.5 percent of the 99.9 million tons of rail freight originated or terminated in the South Coast basin during 2011 (Table 4.8). Unit train commodities were found to be insensitive to the levels of delay experienced at the exchange points for the shipment distances involved.

The annual rail traffic volume loss in tons is converted into ton-miles by multiplying the lost tons for each train symbol run by its particular shipment distance. To monetize the lost rail traffic, estimates of railroad revenue per ton-mile for each commodity group derived from the STB waybill data (Table 8.7) are multiplied by the lost ton-miles to quantify potential lost revenue.

Table 8.6: Annual Freight Shift from Rail to Truck (tons)

Route	Intermodal	Manifest	Unit
Union Pacific Santa Barbara Subdivision	--	--	--
Union Pacific /Metrolink Valley Subdivision	83,592	--	--
Union Pacific Mojave Subdivision	--	479,390	--
BNSF Cajon Subdivision	8,039,114	--	--
Union Pacific Cima Subdivision (via Cajon)	401,530	203,372	--
Union Pacific Yuma Subdivision	3,227,101	201,124	--
Total	11,751,336	883,886	--

Table 8.7: Railroad Revenue ($) per Ton-Mile by Commodity Group

Commodity Group	1	2	3	4	5	6	7	8	9
Manifest	.031	.033	.036	.044	.040	.043	.046	.084	.048
Intermodal	.022	.034	.033	.032	.046	.034	.041	.053	.045

Due to freight mode shift to truck associated with the delay at the locomotive exchange points, it is estimated that the railroads have the potential lose approximately $1.1 billion in revenue from intermodal and manifest traffic each year (Table 8.8). This magnitude of revenue loss represents approximately 1.6 percent of all US Class 1 railroad revenue from 2012 (AAR, 2012).

Table 8.8: Annual Lost Railroad Revenue Due to Modal Shift to Truck ($ million)

Route	Intermodal	Manifest	Unit	Total
Union Pacific Santa Barbara Subdivision	--	--	--	--
Union Pacific /Metrolink Valley Subdivision	4.0	--	--	4.0
Union Pacific Mojave Subdivision	--	9.8	--	9.8
BNSF Cajon Subdivision	741.3	--	--	741.3
Union Pacific Cima Subdivision (via Cajon)	41.5	9.2	--	50.7
Union Pacific Yuma Subdivision	287.0	7.2	--	294.2
Total	1,073.8	26.2	--	1,100.0

8.4 Emissions Considerations of Mode Shift

For the mode split calculated in the previous section, 24.3 billion ton-miles of freight are shifted from rail to truck. Of this total, 2.6 billion ton-miles are shifted from rail to trucks within the South Coast air basin. The majority of this traffic is intermodal freight that, according to the energy inventory prepared in Section 4, can be transported by rail with an average efficiency of 250 ton-miles per gallon of diesel. The average efficiency of a highway semi-trailer truck is only 100 ton-miles per gallon of diesel (ICF, 2009), approximately 60-percent less fuel efficient. Diesel fuel consumption increases when freight is shifted from the rail to truck mode in the South Coast basin.

The shift of freight from rail to truck causes the corresponding mainline line-haul freight rail emissions to be replaced by heavy-duty truck emissions within the basin. Average in-use emissions factors for diesel-powered highway semi-trailer trucks (Class VIIIa trucks) are expressed per truck-mile (EPA, 2008). For a semi-trailer truck with a payload of 22.5 tons, the 2.6 billion ton-miles of freight shifted to truck in the South Coast is equivalent to 116 million truck-miles.

Using the published EPA emissions factors, the annual emissions from 116 million truck-miles truck miles can be computed and compared to equivalent freight movement by rail with Tier 2 and Tier 4 diesel-electric locomotives and the various alternative locomotive technologies (Table 8.9). Since the majority of the freight shifted from rail is transported over long distances, the EPA average in-use emissions factors for Class VIIIa trucks are used in this calculation to be representative of the interstate semi-trailer truck fleet. Although shorter-haul movements are more likely to involve California-based trucks that are subject to stricter emissions standards, this detail is not included in the analysis of truck emissions.

Table 8.9: Annual Rail vs Highway Truck Emissions for Freight Shifted from Rail (lbs)

Mode	CO_2	PM	HC	NOx	CO
Tier 2 Diesel Locomotive	234,100,000	85,800	124,000	2,361,000	610,400
Tier 4 Diesel Locomotive	234,100,000	7,154	19,100	476,900	610,400
Tier 4 Diesel w/After-T	234,100,000	1,790	19,100	119,200	610,400
Diesel-LNG	217,400,000	7,760	20,700	517,300	662,100
Battery Tender w/ Regen	0	0	0	0	0
SOFC-GT w/ LNG	100,700,000	3,775	10,100	251,600	322,100
Electrification	0	0	0	0	0
LSM	0	0	0	0	0
Diesel Semi-Trailer Truck (Class VIIIa)	585,200,000	54,800	117,400	2,341,500	610,100
Net Increase with Shift to Truck from Tier 2 Baseline	351,100,000	-31,000	-6,600	-19,200	-300
Net Increase with Shift to Truck from Tier 4 Baseline	351,100,000	47,600	98,400	1,864,600	-300

For Tier 4 diesel-electrics and all of the alternative locomotive technologies, with the exception of CO, emissions are increased in all categories, negating some of the benefit of a switch to lower-emission locomotive technologies. Only when compared to Tier 2 locomotives does a shift to truck exhibit improvement in the criteria pollutants (at the expense of increased CO_2 emissions).

To illustrate the impact of mode shift to truck on the different locomotive technology deployment scenarios, the expected annual line-haul mainline freight locomotive emissions within the South Coast air basin were recalculated. In the new calculation, the portion of the rail emissions associated with freight shifted to the truck mode was replaced with the corresponding truck emissions for movement of the shifted freight (Table 8.10). Both the original Tier 2 and Tier 4 diesel emissions before the freight mode shift are included in Table 8.10 to serve as a baseline for emission reductions (Table 8.11 and Table 8.12).

Table 8.10: Combined Annual South Coast Basin Alternative Locomotive Emissions and Truck Emissions for Rail Shipments Shifted to the Highway Mode (pounds)

Technology	CO_2	PM	HC	NOx	CO
Tier 2 Diesel (Baseline)*	743,970,000	272,900	394,200	7,502,000	1,940,000
Tier 4 Diesel (Baseline)*	743,970,000	22,700	60,600	1,514,000	1,940,000
Tier 4 Diesel w/After-T	1,095,100,000	58,700	159,000	2,601,000	1,940,000
Diesel-LNG	1,058,700,000	71,700	162,500	3,468,000	2,052,000
Battery Tender w/ Regen	585,200,000	54,800	117,400	2,341,500	610,000
SOFC-GT w/ LNG	804,540,000	63,000	139,400	2,890,000	1,312,000
Electrification	585,200,000	54,800	117,400	2,341,500	610,000
LSM	585,200,000	54,800	117,400	2,341,500	610,000

*Baseline before mode shift

Table 8.11: South Coast Alternative Locomotive Emissions and Truck Emissions for Rail Shipments Shifted to the Highway Mode (% Reduction from Tier 2 Baseline)

Technology	CO_2	PM	HC	NOx	CO
Tier 2 Diesel (Baseline)	--	--	--	--	--
Tier 4 Diesel w/After-T	-47.2	78.5	59.7	65.3	0.0
Diesel-LNG	-42.3	73.7	58.8	53.8	-5.8
Battery Tender w/ Regen	21.3	79.9	70.2	68.8	68.5
SOFC-GT w/ LNG	-8.1	76.9	64.6	61.5	32.4
Electrification	21.3	79.9	70.2	68.8	68.5
LSM	21.3	79.9	70.2	68.8	68.5

Table 8.12: South Coast Alternative Locomotive Emissions and Truck Emissions for Rail Shipments Shifted to the Highway Mode (% Reduction from Tier 4 Baseline)

Technology	CO_2	PM	HC	NOx	CO
Tier 4 Diesel (Baseline)	--	--	--	--	--
Tier 4 Diesel w/After-T	-47.2	-158.1	-162.3	-71.6	0.0
Diesel-LNG	-42.3	-215.3	-168.1	-128.8	-5.8
Battery Tender w/ Regen	21.3	-140.9	-93.7	-54.5	68.5
SOFC-GT w/ LNG	-8.1	-177.1	-129.9	-90.7	32.4
Electrification	21.3	-140.9	-93.7	-54.5	68.5
LSM	21.3	-140.9	-93.7	-54.5	68.5

When adjusted to include truck emissions induced by mode shift, the emissions benefits of all locomotive technologies compared to the Tier 2 baseline (Figure 8-1) decrease relative to the pre-mode shift values (Figure 5-1). Because they provide little CO_2 benefit compared to the Tier 2 baseline, Tier 4 diesel with after-treatment and diesel-LNG actually experience substantially increased CO_2 emissions when induced truck emissions are included in the calculation. The SOFC locomotive exhibits a similar result but only experiences an 8-percent increase in CO_2 due to its baseline efficiency. Interestingly, because of the induced truck emissions, the three electric zero-emission technologies only result in 21-percent reduction in CO_2 emissions relative to the baseline condition.

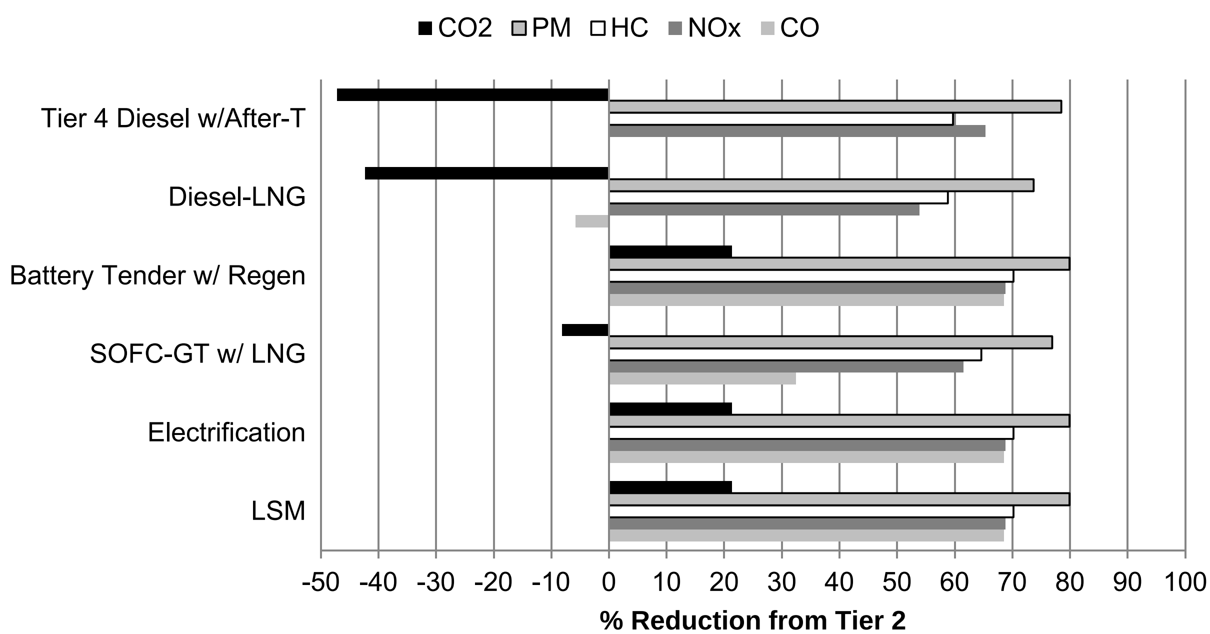

Figure 8-1, Potential reduction in South Coast line-haul locomotive emissions from Tier 2 baseline after mode shift to truck

With the exception of CO for diesel-LNG locomotives, the other criteria pollutants still show net decreases relative to the Tier 2 baseline even after induced truck emissions are included in the analysis. Although PM, HC and NOx still exhibit substantial reductions, benefits that were at or near 100-percent reduction are now only in the range of 60 to 80-percent below Tier 2 levels. At these levels, the electrified zero-emission locomotive technologies with exchange points are actually outperformed by current Tier 4 diesel-electric or diesel-LNG locomotives without mode shift due to exchange points (Figure 8-2). Because of the truck emissions from mode shift due to exchange points, for certain pollutants, an electric zero-emissions technology in a captive fleet may have worse emissions performance relative to the Tier 2 baseline than a more conventional locomotive technology consuming diesel or LNG fuel in a fleet-wide deployment.

Figure 8-2, Potential reduction in South Coast NOx emissions from Tier 2 baseline with and without mode shift to truck due to exchange points

When a similar adjustment is made for truck emissions relative to the Tier 4 baseline, the emissions benefits of all locomotive technologies from the Tier 4 baseline (Figure 8-3) decrease substantially relative to the pre-mode shift values (Figure 5-2). The only pollutants showing a positive reduction from Tier 4 after inclusion of truck emissions are CO_2 for the three electric-propulsion technologies and CO for the three electric technologies and the SOFC locomotive. Because of the induced truck emissions, the three electric zero-emission technologies only result in 21-percent reduction in CO_2 emissions relative to the baseline condition. Since the shift of some freight to truck eliminates almost all potential emission reductions from Tier 4 levels, the electrified zero-emission locomotive technologies with exchange points are actually outperformed by current Tier 4 diesel-electric or diesel-LNG locomotives without mode shift due to exchange points (Figure 8-4).

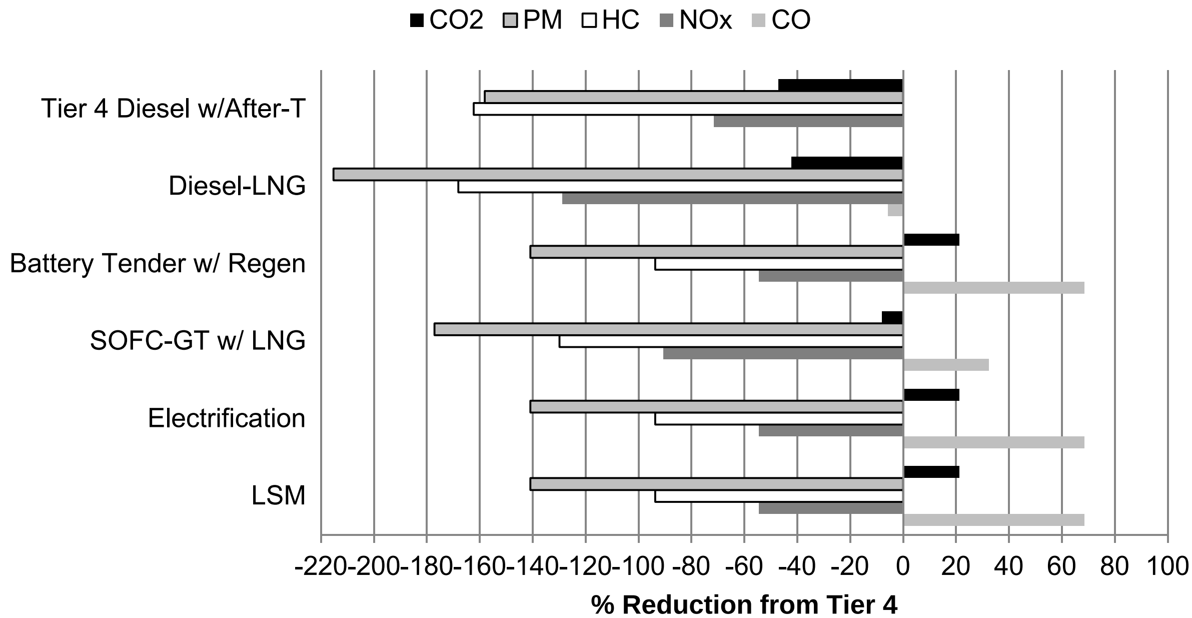

Figure 8-3, Potential reduction in South Coast line-haul locomotive emissions from Tier 4 baseline after mode shift to truck

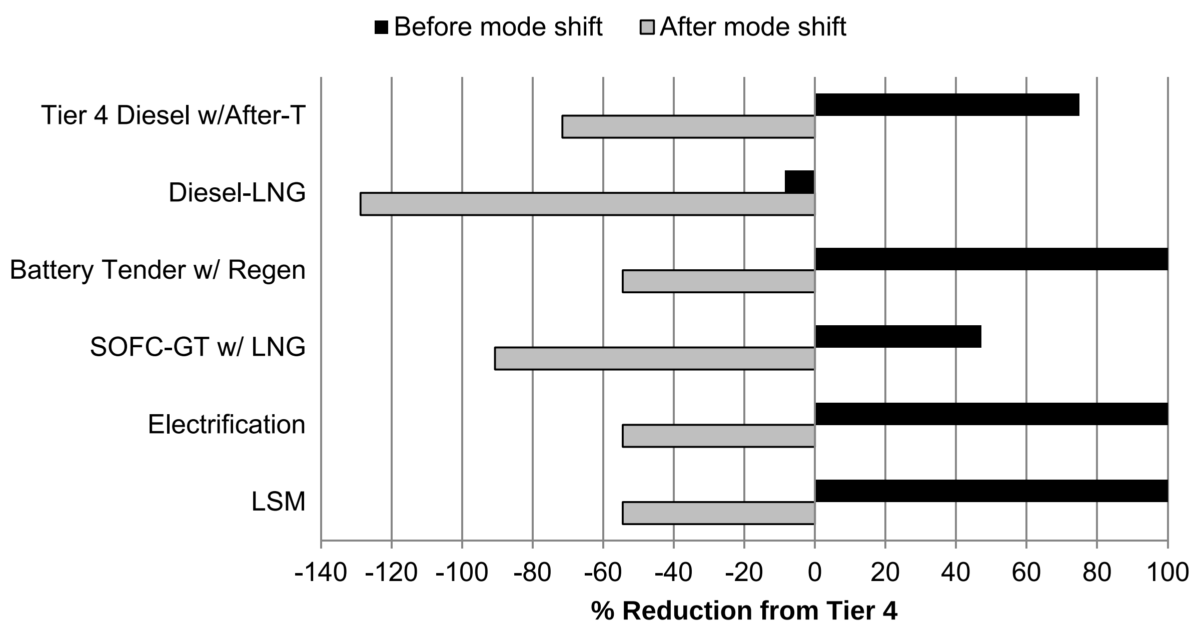

Figure 8-4, Potential reduction in South Coast NOx emissions from Tier 4 baseline with and without mode shift to truck due to exchange points

The emissions results relative to both Tier 2 and Tier 4 baselines suggest that mode shift due to exchange point delays is not only detrimental to railroad revenues but also to the emissions benefits of new locomotive technology when deployed in a captive fleet within the South Coast.

8.5 Summary

Trains operating through locomotive exchange points are anticipated to experience between 1.59 and 4.29 hours of delay depending on the train type. The annual direct cost of train delay encountered at the South Coast basin locomotive exchange points is $112 million per year. This cost accrues from inefficiencies in crew, railcar and locomotive utilization created by delays at the exchange point.

A mode shift model was used to evaluate the potential for time-sensitive freight in the South Coast to shift to trucks when subject to delay at the exchange points. According to the model, each year, approximately 12.5 million tons of freight would move on trucks that formerly moved on rail. Due to this freight mode shift to truck associated with the delay at the locomotive exchange points, it is estimated that the railroads have the potential lose approximately $1.1 billion in revenue from intermodal and manifest traffic each year.

The shift of freight from rail to truck reduces the emissions benefits of the alternative locomotive technologies. Technologies that showed emissions reductions before mode shift may show increases in emissions when the induced truck emissions are included in the calculations.

9 Benefits of Improved Efficiency and Alternative Sources on Energy Supply Costs

This section determines the potential efficiency and energy supply cost benefits of each alternative locomotive technology on the local energy consumption of line-haul mainline freight rail operations within the South Coast basin. The first section describes the process of modifying the train energy inventory for the different locomotive deployment scenarios and translating the energy demand into fuel and electricity consumed. The second section reviews cost factors for liquid fuel and electricity. The third section combines consumption with the cost factors to evaluate reduction in energy costs relative to baseline conditions.

9.1 Energy and Fuel Consumption of Alternative Technologies

The energy consumption for emissions benefits was limited to the specific portions of each route between terminals in the South Coast and the air basin boundary. For the purposes of energy supply costs, railroads continue to receive potential fuel cost savings for operation of new technology locomotives on the portion of the route between the air basin boundary and the locomotive exchange point. Thus the energy inventory calculated in Section 5.1 must be adjusted to consider the entire route out to the exchange point. The incremental energy consumption of rail operations between the air basin boundary and locomotive exchange point (Table 9.1) is calculated with similar assumptions as documented in Section 5.1.

Table 9.1: Annual Incremental Energy/Fuel Consumption to Exchange Points

	Energy (TJ)			Electricity	Diesel	LNG	
Technology	At Wheels	Traction	Fuel/ Electricity	MWh	Gallons	Gallons	Diesel-Gallon-Equivalent
Tier 2 Diesel-electric (baseline)	1,831	2,154	5,523	--	38,645,000	--	--
Tier 4 Diesel-electric (baseline)	1,831	2,154	5,523	--	38,645,000	--	--
Tier 4 Diesel-electric with After-treatment	1,831	2,154	5,523	--	38,645,000	--	--
Diesel-Liquefied Natural Gas (LNG)	1,972	2,320	6,629	--	9,276,000	60,817,000	36,200,000
Battery Tender w/ Regeneration	1,988	2,339	5,997	--	41,959,000	--	--
SOFC-Gas Turbine with LNG	1,972	2,320	3,314	--	--	38,010,000	22,625,000
Electrification	1,831	2,154	2,393	664,900	--	--	--
Linear Synchronous Motor (LSM)	1,831	2,154	2,393	664,900	--	--	--

A key difference between the calculation of Table 9.1 and Table 5.1 is the treatment of the battery tender scenario. To avoid an impractical number of battery tenders, outside of the air basin, the battery tender scenario makes use of dual-mode capability to operate in diesel mode to the exchange points. Thus in calculating the incremental fuel and energy consumption, the battery tender scenario is treated as a conventional diesel-electric locomotive. Due to the weight of the battery tenders (and lack of regeneration capability), the battery tender scenario consumes the most traction energy and more diesel gallons than the conventional diesel-electric locomotive.

To determine the cost of rail operations for the entire trip to the exchange point, the values in Table 5.1 and Table 9.1 are combined (Table 9.2).

Table 9.2: Annual Locomotive Energy/Fuel Consumption to Exchange Points

	Electricity	Diesel	LNG	
Technology	MWh	Gallons	Gallons	Diesel-Gallon-Equivalent
Tier 2 Diesel-electric (baseline)	--	71,697,000	--	--
Tier 4 Diesel-electric (baseline)	--	71,697,000	--	--
Tier 4 Diesel-electric with After-treatment	--	71,697,000	--	--
Diesel-Liquefied Natural Gas (LNG)	--	17,220,000	112,906,000	67,206,000
Battery Tender w/ Regeneration	593,100	41,959,000	--	--
SOFC-Gas Turbine with LNG	--	--	70,566,000	42,004,000
Electrification	1,233,000	--	--	--
Linear Synchronous Motor (LSM)	1,233,000	--	--	--

9.2 Energy Cost Factors

As described in Section 2, the following factors are used in the calculation of annual line-haul freight railway fuel and energy costs in the South Coast basin:

- The railway cost of diesel fuel is $3.12 per gallon of diesel (AAR, 2014).
- As described in Section 2, the cost of LNG is $2.54 per diesel-gallon-equivalent of LNG.
- The commercial cost of electricity in California is $87.60 per MWh.

9.3 Annual Energy Supply Cost Benefits in South Coast Basin

The alternative locomotive fuel consumption and cost factors are combined to calculate the expected energy supply cost of line-haul mainline freight locomotive operations between terminals within the South Coast air basin and the locomotive exchange points (Table 9.3). The Tier 2 diesel fuel cost is presented to estimate energy supply expense before the delivery of Tier 4 locomotives in 2015 and serve as one baseline for cost reductions (Table 9.4). The Tier 4 diesel fuel cost is presented to estimate baseline energy expense at a future date once the current mainline fleet has been renewed with new Tier 4 diesel-electric locomotives. This Tier 4 scenario serves as a second baseline for emissions reductions relative to "future" levels in 2030. The diesel-LNG locomotive increases fuel cost due to decreased fuel efficiency and the small difference in the price of diesel and LNG. The efficiency of the SOFC-gas turbine with LNG provides the lowest energy supply cost of the liquid fuels, saving $117 million per year. The cost of this operation is nearly comparable to electrification and the LSM.

Table 9.3: Annual Locomotive Energy/Fuel Cost to Exchange Points ($ million)

	Electricity	Diesel	LNG	
Technology	MWh	Gallons	Diesel-Gallon-Equivalent	Total
Tier 2 Diesel-electric (baseline)	--	223.7	--	223.7
Tier 4 Diesel-electric (baseline)	--	223.7	--	223.7
Tier 4 Diesel-electric with After-treatment	--	223.7	--	223.7
Diesel-Liquefied Natural Gas (LNG)	--	53.7	170.7	224.4
Battery Tender w/ Regeneration	52.0	130.9	--	182.9
SOFC-Gas Turbine with LNG	--	--	106.7	106.7
Electrification	108.1	--	--	108.1
Linear Synchronous Motor (LSM)	108.1	--	--	108.1

Table 9.4: Change in Annual Locomotive Energy/Fuel Cost to Exchange Points

Technology	Total ($ million)	Reduction from Tier 2 ($ million)	Reduction from Tier 2 (%)	Reduction from Tier 4 ($ million)	Reduction from Tier 4 (%)
Tier 2 Diesel-electric (baseline)	223.7	--	--	--	--
Tier 4 Diesel-electric (baseline)	223.7	--	--	--	--
Tier 4 Diesel-electric with After-treatment	223.7	0.0	0.0	0.0	0.0
Diesel-Liquefied Natural Gas (LNG)	224.4	-0.7	-0.3	-0.7	-0.3
Battery Tender w/ Regeneration	182.9	40.8	18.2	40.8	18.2
SOFC-Gas Turbine with LNG	106.7	117.0	52.3	117.0	52.3
Electrification	108.1	115.6	51.7	115.6	51.7
Linear Synchronous Motor (LSM)	108.1	115.6	51.7	115.6	51.7

Unlike electrification and LSM, the limited range of the battery tender locomotive requires it to operate in diesel mode between the air basin boundary and the locomotive exchange point. The diesel fuel consumed during this portion of the trip increases annual energy costs relative to the other electric locomotive technologies. While electrification and LSM reduce energy costs by 52 percent or $116 million per year, the battery tender only exhibits an 18-percent reduction or $41 million per year (Figure 9-1).

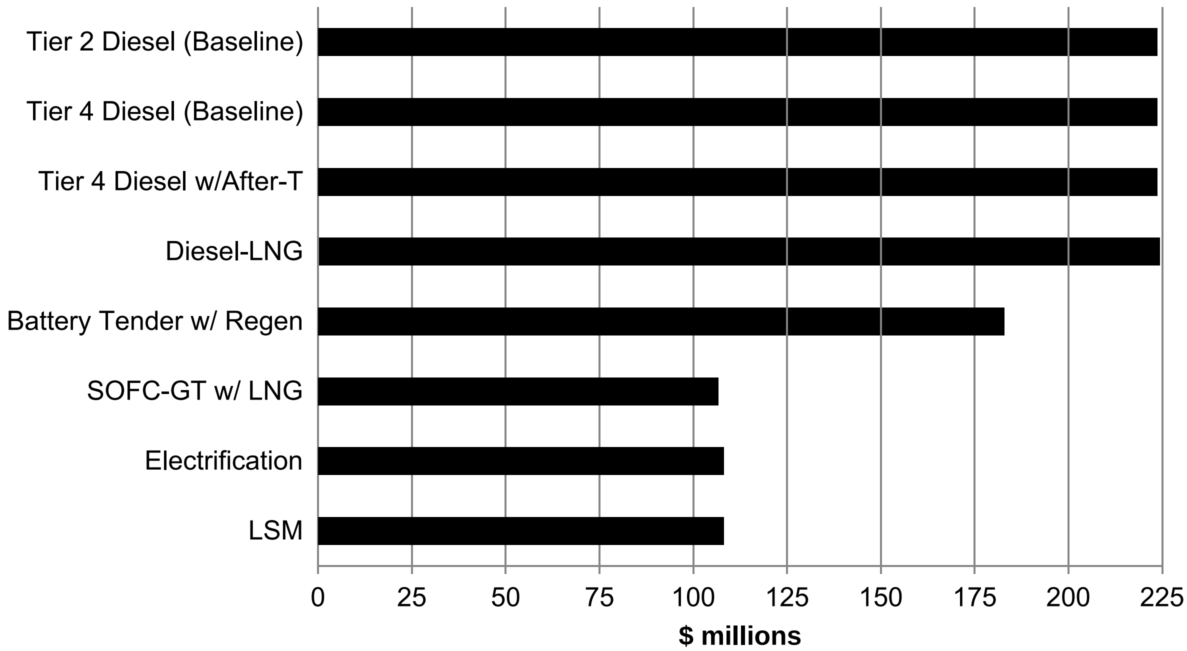

Figure 9-1, Annual locomotive energy/fuel cost to South Coast exchange points

10 Other Considerations

This section describes other economic and operational considerations of employing alternative technology locomotives as a captive fleet within the South Coast basin that either do not fit into the main economic analysis conducted under this study, mainly impact non-railroad costs or are difficult to quantify within the scope of this study. These considerations are documented here to provide a more complete picture of the challenges of establishing a dedicated line-haul locomotive fleet within the South Coast.

10.1 Employment and Relocation of Servicing Personnel

Current railroad operations rely on line-haul diesel-electric locomotives to be fueled, serviced and inspected at various locations within the South Coast basin. The line-haul locomotive servicing facilities within the South Coast employ specially-trained railroad employees to execute tasks essential to the safe and efficient operation of line-haul freight trains.

Under the deployment scenario of a captive South Coast basin fleet with locomotive exchange points, conventional diesel-electric line-haul freight locomotives will no longer operate into the basin. It is assumed that all servicing and inspection activities associated with conventional line-haul diesel-electric locomotives will move to newly constructed facilities at the locomotive exchange points. Although conventional diesel-electric locomotives still operating in local and switching service within the basin will provide some demand for servicing at existing facilities within the basin, the number of employees required at these facilities will be reduced. At the same time, employment demand will be created at the new exchange point facilities on the remote edges of the South Coast basin. It is possible that, given land availability and other constraints, the new locomotive shops supporting new technology locomotives in the South Coast will be constructed at the exchange points and not near existing yards and servicing facilities within the basin. Provided labor agreements allow them to move to the new facilities, servicing and craft labor employees may need to relocate over 100 miles to their new work location. Besides the direct impact on the railroad employees, the shift of jobs will impact local economies in the vicinity of the existing servicing facilities.

While an important consideration within the South Coast, there is a far larger potential impact in a state-wide deployment scenario. The UP locomotive shop at Davis Yard in Roseville, California is a major facility that maintains diesel-electric locomotives that operate both within and outside California. Eliminating the ability for line-haul diesel-electrics to access this shop may substantially alter its role in the UP system and increase the number of locomotives maintained at other shops on the network (with corresponding shifts in employment). However, under such a scenario, the shop would become a potential location for maintaining the new technology locomotives.

10.2 Shift of Diesel Fuel Supply

Related to the discussion of the previous section, under the captive South Coast basin fleet deployment scenario developed in this study, fueling of conventional diesel-electric line-haul freight locomotives will be moved to the exchange points since conventional line-haul diesels will no longer operate into the basin.

According to ARB data, each year approximately 250 million gallons of diesel fuel are dispensed for railroad applications in California. Approximately two-thirds of this volume, or 160 million gallons, is dispensed within the South Coast basin. Approximately 15 percent of this fuel is used for local and switching service and will remain in the basin after conversion to new line-haul locomotive technology. The remaining 136 million gallons of diesel fuel will shift to be dispensed at the locomotive exchange points each year. The actual volume of diesel dispensed may vary between locomotive technology scenarios as different energy sources (LNG and electricity) replace the demand for diesel within the South Coast.

Besides the fuel supply and storage infrastructure that must be established to supply this diesel fuel at the exchange points (in addition to alternative fuel infrastructure) the change in fueling location may also shift related economic activity. Different fuel suppliers in different jurisdictions will be required to replace those formerly used by the railroads within the South Coast basin. Decreased demand for diesel fuel within the South Coast will reduce related employment, economic activity and tax receipts.

As with the previous consideration, while important for local jurisdictions within the South Coast, there is a larger potential impact of a state-wide deployment scenario. Under the state-wide deployment scenario, the majority of line-haul freight diesel fueling activity would move to neighboring states. Taxes and economic activity related to line-haul locomotive diesel fueling operations would leave the State of California.

10.3 Run-Through Foreign-Line Locomotives

As described in Section 3.3.1, the North American railroads have worked to establish an interoperable fleet of line-haul freight locomotives. Interoperability allows railroads to offer joint “run-through” service where the locomotives from one railroad can continue on to power the same train on a different railroad without the need to stop the train for a lengthy locomotive exchange where the two railroads meet. With respect to rail operations in the South Coast basin, both BNSF and UP offer joint intermodal service between terminals in the basin and eastern destinations on CSX and Norfolk Southern (NS) such as Atlanta or New York. To avoid mid-route locomotive changes and share in the cost of operating the run-through service, these trains often operate with a mixture of locomotives from NS or CSX.

It is unlikely that CSX or NS would invest in new technology locomotives that could enter or remain captive to the South Coast basin. Under the captive fleet deployment scenario explored in this study, conventional CSX and NS run-through diesel-electric locomotives would no longer be able to operate to final destinations within the South Coast basin. The CSX and NS locomotives would be turned back at the locomotive exchange points, decreasing their overall utilization as they wait for their return run-through train to unload, load and exit the basin. Stopping the CSX and NS locomotives short also changes the balance of horsepower-hours accumulated by the locomotives of each railroad participating in the run-through service. By exclusively operating their locomotives within the basin, BNSF and UP would assume a larger share of the horsepower-hours associated with each run-through train. To balance this increase in motive power demand, CSX and NS would need to assign additional locomotives for service on BNSF and UP outside the basin. Depending on motive power availability, this may create locomotive assignment and utilization issues for CSX and NS.

10.4 Pooled California Fleet

On rail corridors with smaller train counts, the locomotive exchange process becomes inefficient. With fewer inbound and outbound trains, both conventional and new technology locomotives can be subject to lengthy dwells until a train in the appropriate direction passes through the exchange point. Increased locomotive dwell decreases utilization and drives up railroad operating costs.

This situation is compounded on routes where both BNSF and UP operate through an exchange point via trackage rights. At the shared exchange point, each railroad will desire to use their own locomotives for their own trains even if more efficient locomotive connections could be made to trains operated by the other railroad. For example, in this study, UP operates nine trains per day over the BNSF Cajon Subdivision through Barstow to Yermo. This study assumes that UP operates their own exchange point at Yermo for their nine trains while BNSF operates a separate exchange point at Barstow for their 67 trains per day. Given the disparity in traffic volumes between the two exchange points, there is likely to be times when UP will have new technology locomotives on extended dwell at Yermo (incurring cost and wasting resources) while BNSF is running short of new technology locomotives at Barstow and potentially delaying inbound trains (again incurring cost and wasting resources).

In this case, the operations of both parties may potentially be improved by operating a joint exchange point and making the new technology locomotives captive to the South Coast a pooled fleet that can be used by either railroad. By eliminating time spent by a UP locomotive dwelling for a UP train while BNSF trains pass (or the opposite), the pooled fleet can facilitate more efficient locomotive connections. Increased utilization decreases the required size of the captive South Coast basin fleet and the corresponding capital cost of implementing new reduced-emissions locomotive technology.

10.5 Network Configuration and Operating Plan

A railroad operating plan carefully manages and coordinates the crew, locomotive, fuel and railcar resources required to safely and efficiently move freight by rail. The captive South Coast basin fleet scenario with locomotive exchange points explored in this study will alter several of the parameters that go into developing the railroad operating plan. Delay at the locomotive exchange points will extend transit times over the links leading to and from the South Coast. This has several implications for railroad operations planning:

- Where the locomotive exchange facility does not fall at a current crew change point, train crews may not be able to perform the locomotive exchange and then continue on to complete their assigned crew district. If a crew cannot reach its destination terminal within 12 hours, the train must be stopped until a replacement crew arrives, negatively impacting operations. To avoid this possibility, the limits of crew districts may need to be changed. This has a ripple effect across the network as one district is shortened another becomes longer. Changes to crew districts may also require renegotiating labor agreements with operating crews.
- Increased transit time will delay arrival of railcars and freight at the next terminal. Changes to terminal arrival times alter the probability that railcars and freight will make desired connections to other trains. Missed connections result in increased terminal dwell, increasing the number of railcars waiting in the terminal and making terminal operations more difficult. Changing the inbound arrival pattern can also impact the efficiency of the terminal process and resources required to keep the terminal fluid. Degraded terminal performance can create secondary delays to other trains and freight on the network, incurring cost and increasing the possibility of additional mode shift to truck.
- Connections between locomotives and other trains at terminals both inside and outside the basin will be impacted by increased transit times. This has the potential to further increase the required locomotive fleet beyond that described earlier in this report.

Under these circumstances, both BNSF and UP are certain to develop new operating plans for trains transiting the South Coast. Traffic on certain routes may increase or decrease with associated impacts on the public, freight shippers and industrial development.

An example of one operating impact that may result in changes to the operating plan is classification of certain shipments at the UP West Colton yard facility. Since West Colton is inside the basin, shipments originating from and destined to points outside the basin must cross the basin boundary twice. For example, traffic originating in Northern California and bound for Texas may enter the basin via locomotive exchange at Palmdale, be classified at West Colton and then exit the basin via locomotive exchange at Indio. Experiencing two locomotive exchange delays may result in an unacceptable level of service for this shipment. To avoid losing the traffic, UP may need to explore different routing options that utilize different corridors to avoid the South Coast basin. If none of these options prove feasible due to transit time or capacity issues, UP will likely lose additional traffic.

10.6 Operational Flexibility and Recovery

A final item to consider is the impact of the locomotive exchange process and dedicated South Coast locomotive fleet on operational flexibility and recovery from disruptions.

In sizing the locomotive exchange points according to short-peak train flows, the facilities become another potential capacity constraint on the rail network. Following a disruption or planned line outage for track maintenance, rail corridors are often operated near maximum capacity until the backlog of rail traffic can be processed and cleared through the network. One recovery strategy is to “fleet” trains across a corridor by operating multiple trains in the same direction in rapid succession. When a fleet of trains is operated through a locomotive exchange point that requires an even directional balance of inbound and outbound trains to operate effectively, the multiple trains travelling in the same direction can quickly deplete the available supply of locomotives. With no locomotives available, trains will begin to dwell and the exchange point will become another source of congestion on an already strained network. With a fixed capacity for completing the exchange process subject to the availability of locomotive resources, the locomotive exchange point becomes a natural bottleneck that can prolong network recovery time.

The fixed capacity of the locomotive exchange point also becomes another limiting factor when railroads examine the possibility of rerouting trains around a disruption or planned maintenance. Shifting too many trains to a route with an inadequately-sized exchange point will quickly result in congestion and degraded service.

Finally, when congestion occurs on the rail network, it often manifests as increased locomotive demand at a particular terminal. To avoid complete failure of the terminal, additional locomotive resources are transferred to the impacted terminal to help move freight away from the congested area. A dedicated fleet of new technology locomotives within the South Coast cannot be reassigned outside the basin to alleviate locomotive shortages and congestion on the network. This lack of flexibility in locomotive assignments takes away one tool the railroad operating departments can use to avoid further deterioration of service. In this manner, the dedicated locomotive fleet can make the railway operation less resilient to disruptions, increasing the risk of poor levels of service.

11 Summary of Technology Deployment Scenarios

This section collects the capital and annual costs and benefits determined through the analyses of the preceding sections to provide an overall measure of the economic impact of each alternative locomotive technology scenario.

11.1 Total Annual Non-Capital Cost

The change in total annual cost of each alternative locomotive technology scenario relative to the baseline includes all non-capital items from the analyses in the preceding sections (Table 11.1). The annual cost items include:

- Incremental maintenance expense of new technology locomotives within the South Coast basin, ranging from a decrease of $14.6 million per year to an increase of $64 million per year depending on the locomotive technology and if comparing to a Tier 2 or Tier 4 baseline.
- Maintenance of overhead catenary traction power distribution infrastructure within the South Coast at $18.9 million per year.
- The $61 million annual operating cost of personnel at the locomotive exchange points.
- An operating cost increase of $112 million per year due to train delay encountered at the locomotive exchange points and resulting inefficiencies in crew, railcar and locomotive utilization.
- The $1.1 billion in annual revenue loss due to freight shifting to truck as a result of delays at locomotive exchange points

Table 11.1: Summary of Annual Non-Capital Costs ($ million)

Annual Cost	Tier 4	LNG	Battery	SOFC	Elec	LSM
Catenary Maintenance	--	--	--	--	18.9	unknown
Exchange Point Operating	61	61	61	61	61	61
Train Delay	112	112	112	112	112	112
Revenue Loss	1,100	1,100	1,100	1,100	1,100	1,100
Fuel Savings	0	0.7	-40.8	-117.0	-115.6	-115.6
Subtotal	1,273.0	1,273.7	1,232.2	1,156.0	1,176.3	unknown
Incremental Locomotive Maint. from Tier 2	6.4	12.8	19.3	64.2	-12.8	unknown
Total (relative to Tier 2)	1,279.4	1,286.5	1,251.5	1,220.2	1,163.5	unknown
Incremental Locomotive Maint. from Tier 4	4.6	11.0	17.5	62.4	-14.6	unknown
Total (relative to Tier 4)	1,277.6	1,284.7	1,249.7	1,218.4	1,161.7	unknown

- A credit for any fuel/energy cost savings relative to the baseline case, ranging from no change to a decrease of $117 million per year depending on the locomotive technology.

Note that the items in Table 11.1 reflect cost increases or decreases over the baseline condition and not absolute operating costs. For example, the cost figures only capture the incremental cost of line-haul freight crews due to train delay at the exchange point and not the base cost of these train crews. Since the same trains are operated over the same routes, this base cost would be the same for all locomotive technology scenarios and can be excluded from the comparison between technologies.

Since there is not enough information available to provide reasonable estimates for several items related to the LSM technology, the total annual cost of LSM is unknown at this time.

For the five technologies where totals can be calculated, the change in total annual non-capital cost ranges from approximately $1.16 to $1.29 billion per year regardless of comparison to Tier 2 or Tier 4 baseline conditions. The calculation of annual cost is dominated by the revenue lost through freight mode shift to truck due to exchange point delay. The $1.1 billion in annual revenue loss comprises the majority of the change in annual cost regardless of locomotive technology and Tier 2 or Tier 4 baseline.

Potential annual benefits from reduced fuel and energy costs are not large enough to offset increases in other annual non-capital cost items. Tier 4 diesel-electric with after-treatment and diesel-LNG offer no fuel savings to offset other increases in annual cost. Fuel savings for battery tender locomotives, SOFC locomotives with LNG and electrification are, respectively, $41 million, $117 million and $116 million per year. These fuel savings are all an order of magnitude less than the revenue loss.

If the lost revenue is removed from consideration (i.e. the predicted shift of freight to trucks does not occur), each alternative locomotive technology deployment scenario still exhibits an increase in annual non-capital costs. For the three technologies that provide annual fuel savings, when revenue loss is not considered, battery tender locomotives increase costs by $150 million per year, SOFC locomotives with LNG by $120 million per year and electrification by $62 million per year. For both the Tier 2 and Tier 4 baseline, from the perspective of annual railroad operating and maintenance cost, even without freight mode shift to truck, none of the alternative locomotive technology scenarios yield an economic benefit.

11.2 Total Capital Cost

The capital cost of each alternative locomotive technology scenario includes all capital items from the analyses in the preceding sections (Table 11.2). The capital cost items include:

- Purchase cost of new locomotives and tenders, and cost of modifications to conventional locomotives, for the captive new technology locomotive fleet within the South Coast ranging from $1.7 to $19 billion depending on the locomotive technology.
- Installed cost of the overhead catenary traction power distribution system for electrification ($31.5 billion) and LSM infrastructure ($12.6 billion).
- Construction cost of new locomotive shop facilities for new technology locomotives within the South Coast, ranging from $109 to $285 million depending on the locomotive technology.
- The $824 million construction cost of the locomotive exchange facilities, including all sitework, track, support facilities and right-of-way.

- The construction cost of locomotive and tender servicing and fueling facilities, ranging from $39 to $353 million depending on the locomotive technology.

The overall capital cost of each alternative locomotive technology is shown as the "Subtotal Capital Cost" in Table 11.2. Since there is not enough information available to provide reasonable estimates for several items related to the LSM technology, the total capital cost of LSM is unknown at this time.

The five technologies with complete cost data exhibit a wide range of total capital cost. Electrification has the highest capital cost at $35.5 billion, with construction of the overhead catenary traction power system contributing 89 percent of the capital cost. The second most capital-intensive technology is the battery tender locomotive with a capital cost of $20.5 billion. The capital cost of the battery tender technology is dominated by the cost of locomotives and tenders that, at $19.2 billion, represents 94 percent of the capital cost.

Table 11.2: Summary of Capital and Present Value Costs ($ million)

Capital Cost	Tier 4	LNG	Battery	SOFC	Elec	LSM
Locomotive and Tenders	1,995	1,680	19,181	3,214	2,850	unknown
Overhead Catenary/LSM	--	--	--	--	31,500	12,600
Locomotive Shop	199	132	109	285	285	unknown
Exchange Facilities	824	824	824	824	824	824
Servicing Facilities	39	137	353	137	39	39
Subtotal Capital Cost	3,057	2,773	20,467	4,460	35,498	unknown
Present Value of Annual Non-Capital Costs Relative to Tier 2 (from Table 11.1)	9,731	9,785	9,519	9,281	8,850	unknown
Total Present Value Cost (relative to Tier 2)	12,788	12,558	29,986	13,741	44,348	unknown
Present Value of Annual Non-Capital Costs Relative to Tier 4 (from Table 11.1)	9,718	9,772	9,505	9,267	8,836	unknown
Total Present Value Cost (relative to Tier 4)	12,775	12,545	29,973	13,727	44,334	unknown

Compared to the electric options, the three liquid-fuel locomotive technologies exhibit an order of magnitude lower capital costs, ranging from $2.8 to $4.5 billion. The differences in costs between these three technologies is primarily driven by the relative unit cost of each locomotive and required tender. For these three technologies, the cost of the exchange facilities ($824 million) represents between 18 and 30 percent of the capital cost of that alternative.

11.3 Total Present Value Cost

To provide an overall measure of the economic impact of each alternative locomotive technology scenario the annual costs from Table 11.1 are combined with the capital costs from Table 11.2 in a present value calculation over the 15-year initial mainline service life of a line-haul freight locomotive.

Although it is likely that the various technologies would be phased in over time and thus the capital cost would also be incurred over time, this portion of the study makes the simplifying assumption that all capital costs are incurred in the first year of the present value calculation.

The annual non-capital costs are transformed to present value by assuming they are incurred over 15 years with a discount rate of 10 percent. Once discounted to present value (Table 11.2), they can be added to the total capital costs to determine the total present value cost of each alternative locomotive technology scenario (Figure 11-1). A present value cannot be computed for LSM because of lack of information. Total costs relative to the Tier 2 baseline and Tier 4 baseline are both presented in Table 11.2. However, since the difference in annual incremental locomotive maintenance expenses between the Tier 2 and Tier 4 baseline is relatively small compared to other cost factors, there are only minor differences between the two sets of total present value costs.

Since the present value of annual non-capital costs is of similar magnitude for the five technologies with complete cost data, the total present value cost follows the same trends as the total capital cost. Electrification has the highest present value cost at $44.3 billion. Due to the cost of battery tenders, the battery tender locomotives have the second-highest present value cost at $30.0 billion.

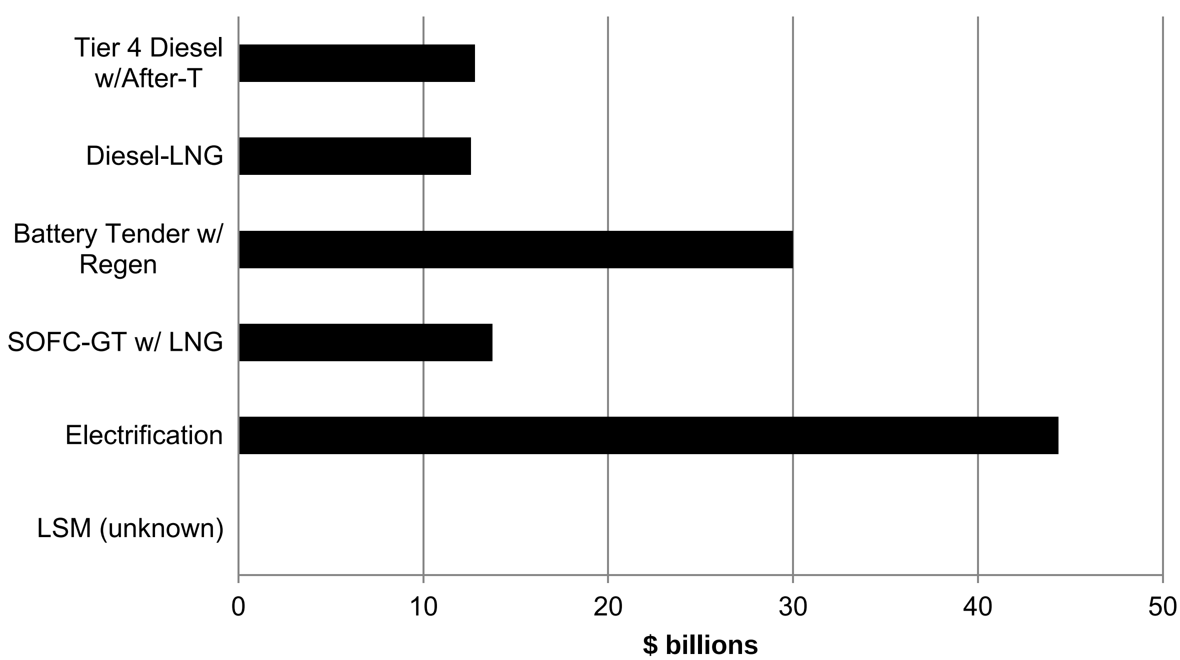

Figure 11-1, Total of capital and present value costs

Interestingly, the three liquid fuel locomotive technologies exhibit a trade-off between total capital and present value of annual non-capital costs. Between the three liquid fuel locomotive technologies, SOFC locomotives have the highest capital cost but lowest annual cost, diesel-LNG has the lowest capital cost but highest annual cost, and Tier 4 with after-treatment falls in the middle for both capital and annual cost. This finding results in the range of total present value cost ($12.5 to $13.7 billion) being narrower when compared to the range of liquid fuel capital costs described in the previous section.

11.4 Emissions Benefits per Unit Cost

The previous sections directly compare the costs of the alternative locomotive technology scenarios without considering differences in their relative emissions benefits. The locomotive technologies that employ electricity as an energy source tend to have both higher net present value costs but also greater emissions benefits. However, it is not immediately apparent if the magnitude of the increased emissions benefits is proportional to the increased present value cost relative to other locomotive technologies. A proxy benefit/cost calculation can help determine if certain locomotive technologies are more economically efficient at reducing the emissions of line-haul freight rail in the South Coast.

The performance metric selected for this study is "percent emissions reduction per billion dollars of investment". The percent emissions reduction value for each locomotive technology is relative to the Tier 2 baseline and Tier 4 baseline as calculated in Section 5.3 (before mode shift) and Section 8.4 (after mode shift). These percent reduction values are divided by the total present value cost from Section 11.3 to provide a measure of the performance of each technology before mode shift and after mode shift to truck.

When mode shift is not considered (Table 11.3), the SOFC-gas turbine locomotive with LNG fuel offers the greatest percent reduction in emissions from Tier 2 per billion dollars of present value cost. Although electrification and battery tenders provide emissions reductions of 100 percent before mode shift, their high capital cost reduces the relative economic effectiveness of these technologies. Compared to SOFC locomotives, battery tenders yield half the percent emissions reduction per billion dollars invested and electrification only yields one-third the percent emissions reduction per billion dollars invested. The other two liquid fuel locomotive technologies provide performance similar to SOFC for PM, HC and NOx. However, the Tier 4 diesel with after-treatment and diesel-LNG offer the poorest performance for CO_2 and CO.

Table 11.3: South Coast Percent Reduction in Locomotive Emissions from Tier 2 Baseline per Billion Dollars of Total Present Value Cost (No Mode Shift)

Technology	CO_2	PM	HC	NOx	CO
Tier 4 Diesel w/After-T	0.0	7.6	6.6	7.4	0.0
Diesel-LNG	0.6	7.2	6.6	6.2	-0.7
Battery Tender w/ Regen	3.3	3.3	3.3	3.3	3.3
SOFC-GT w/ LNG	4.1	6.9	6.7	6.5	3.4
Electrification	2.2	2.2	2.2	2.2	2.2
LSM	N/A	N/A	N/A	N/A	N/A

When mode shift is considered (Table 11.4), the results are mixed with no one locomotive technology having a clear advantage over the others. The SOFC locomotive has poor performance for CO_2 but is among the best for the other four pollutants. While electrification and battery tenders are the only options that reduce CO_2 emissions, their high capital cost leads to poor economic effectiveness at reducing the other four pollutants.

Table 11.4: South Coast Percent Reduction in Locomotive Emissions from Tier 2 Baseline per Billion Dollars of Total Present Value Cost (After Mode Shift)

Technology	CO_2	PM	HC	NOx	CO
Tier 4 Diesel w/After-T	-3.7	6.1	4.7	5.1	0.0
Diesel-LNG	-3.4	5.9	4.7	4.3	-0.5
Battery Tender w/ Regen	0.7	2.7	2.3	2.3	2.3
SOFC-GT w/ LNG	-0.6	5.6	4.7	4.5	2.3
Electrification	0.5	1.8	1.6	1.6	1.5
LSM	N/A	N/A	N/A	N/A	N/A

The changes in relative economic effectiveness at reducing CO_2 (Figure 11-2) and NOx (Figure 11-3) emissions between the cases with and without mode shift to truck, emphasize the importance of considering delay at the locomotive exchange points in the analysis.

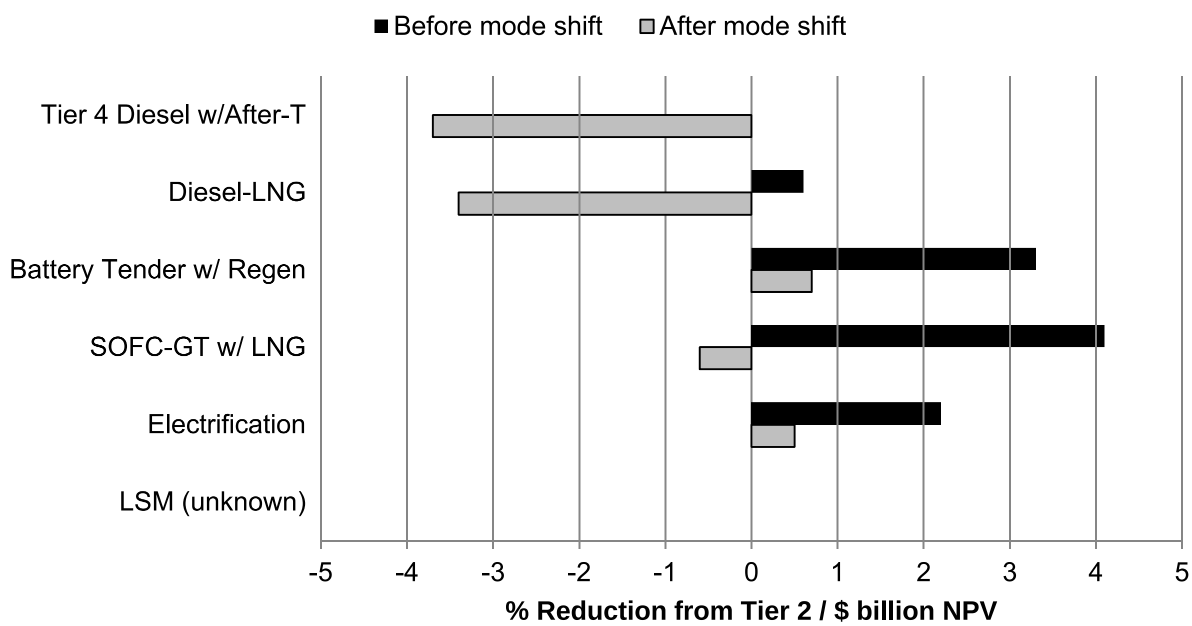

Figure 11-2, Percent reduction in South Coast CO_2 emissions from Tier 2 baseline per billion in total present value cost with and without mode shift

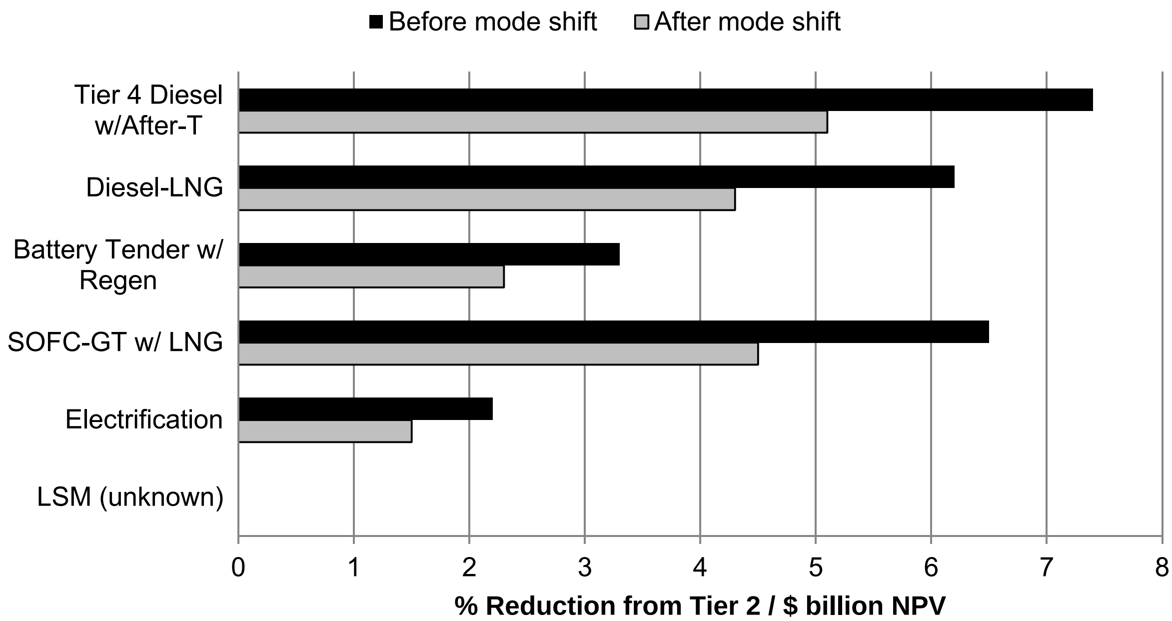

Figure 11-3, Percent reduction in South Coast NOx emissions from Tier 2 baseline per billion in total present value cost with and without mode shift

In examining the technologies relative to the Tier 4 baseline, when mode shift is not considered (Table 11.5), the SOFC-gas turbine locomotive with LNG fuel again offers the greatest percent reduction in emissions from Tier 4 per billion dollars of present value cost. Although electrification and battery tenders provide emissions reductions of 100 percent before mode shift, their high capital cost reduces the relative economic effectiveness of these technologies. However, the battery tender locomotive offers nearly the same emissions return on investment as the locomotives relative to Tier 4. The other two liquid fuel locomotive technologies provide mixed performance. This is largely due to uncertainty in the ability of these technologies to reduce emissions below Tier 4 levels.

Table 11.5: South Coast Percent Reduction in Locomotive Emissions from Tier 4 Baseline per Billion Dollars of Total Present Value Cost (No Mode Shift)

Technology	CO_2	PM	HC	NOx	CO
Tier 4 Diesel w/After-T	0.0	5.9	0.0	5.9	0.0
Diesel-LNG	0.6	-0.7	-0.7	-0.7	-0.7
Battery Tender w/ Regen	3.3	3.3	3.3	3.3	3.3
SOFC-GT w/ LNG	4.1	3.4	3.4	3.4	3.4
Electrification	2.2	2.2	2.2	2.2	2.2
LSM	N/A	N/A	N/A	N/A	N/A

When mode shift is considered relative to the Tier 4 baseline (Table 11.6), the results are overwhelmingly negative. The truck emissions induced by freight mode shift away from rail more than offset any emissions benefits of the alternative locomotive technologies relative to Tier 4 baseline levels. Only CO_2 emissions for the electric-powered technologies and CO emissions show some positive reductions relative to the Tier 4 baseline.

Table 11.6: South Coast Percent Reduction in Locomotive Emissions from Tier 4 Baseline per Billion Dollars of Total Present Value Cost (After Mode Shift)

Technology	CO_2	PM	HC	NOx	CO
Tier 4 Diesel w/After-T	-3.7	-12.4	-12.7	-5.6	0.0
Diesel-LNG	-3.4	-17.2	-13.3	-10.3	-0.5
Battery Tender w/ Regen	0.7	-4.7	-3.1	-1.8	2.3
SOFC-GT w/ LNG	-0.6	-12.9	-9.5	-6.6	2.4
Electrification	0.5	-3.2	-2.1	-1.2	1.5
LSM	N/A	N/A	N/A	N/A	N/A

The changes in relative economic effectiveness at reducing CO_2 (Figure 11-4) and NOx (Figure 11-5) emissions below Tier 4 levels between the cases with and without mode shift to truck, further reinforces the importance of considering delay at the locomotive exchange points in the analysis.

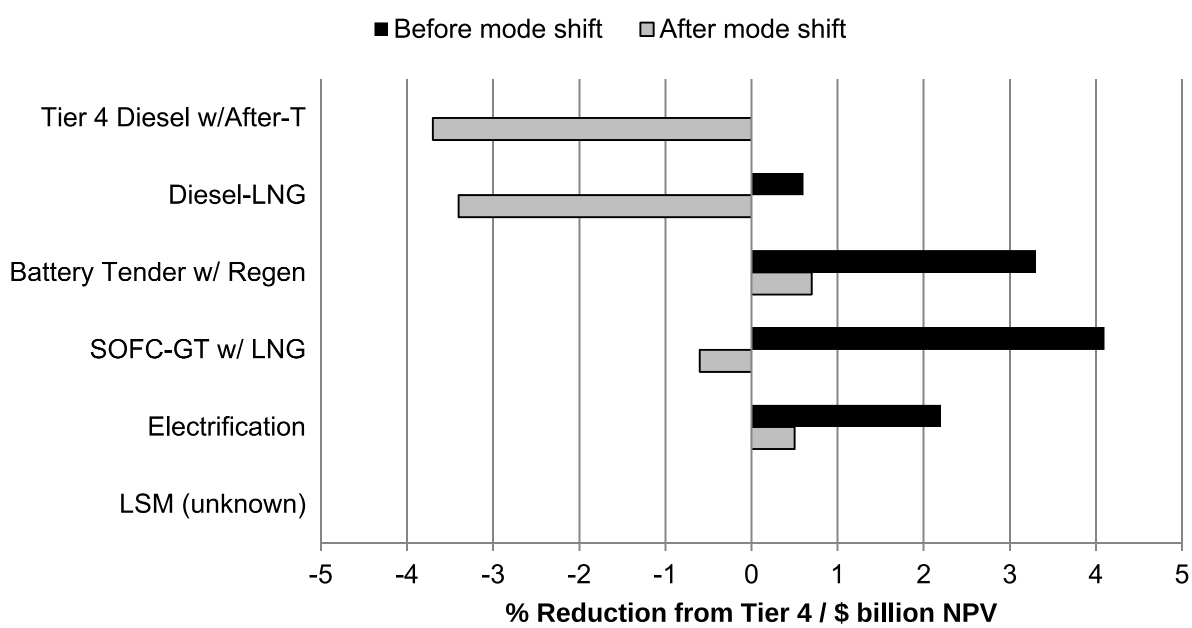

Figure 11-4, Percent reduction in South Coast CO_2 emissions from Tier 4 baseline per billion in total present value cost with and without mode shift

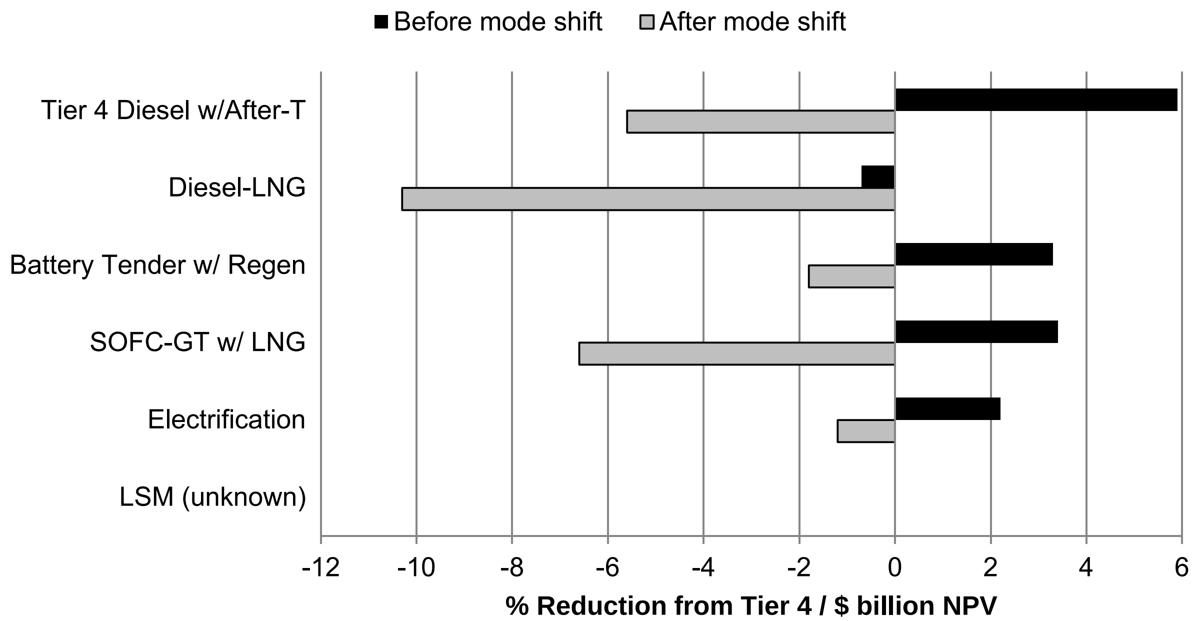

Figure 11-5, Percent reduction in South Coast NOx emissions from Tier 4 baseline per billion in total present value cost with and without mode shift

11.5 Summary of Alternative Locomotive Technology Scenarios

The following sections summarize the cost and economic performance of each alternative locomotive technology deployment scenario.

11.5.1 Tier 4 Diesel-Electric with After-Treatment

The annual non-capital cost of Tier 4 diesel-electric locomotives with after-treatment is approximately $1.3 billion per year. The majority of this cost is attributed to $1.1 billion in lost revenue due to mode shift to truck associated with train delay at the exchange points. There are no annual fuel savings to offset increased costs. Thus annual costs to the railroads are expected to increase with this technology.

The capital cost of Tier 4 diesel-electric locomotives with after-treatment is approximately $3.0 billion. Approximately two-thirds of this capital cost is new locomotives while the remaining third is largely the cost of the locomotive exchange point facilities and new locomotive shops.

The present value cost of this technology is $12.8 billion. In terms of relative economic efficiency of achieving emissions reductions, Tier 4 diesel-electric locomotives with after-treatment compare favorably with the other technologies for PM, HC and NOx but are poor for CO_2 and CO.

11.5.2 Liquefied Natural Gas

The annual non-capital cost of diesel-LNG locomotives is approximately $1.3 billion per year. The majority of this cost is attributed to $1.1 billion in lost revenue due to mode shift to truck associated with train delay at the exchange points. There are no annual fuel savings to offset increased costs; fuel costs will actually increase by $700,000 per year. Thus annual costs to the railroads are expected to increase with this technology.

The capital cost of diesel-LNG locomotives is approximately $2.8 billion. Approximately two-thirds of this capital cost is new locomotives and tenders while the remaining third is largely the cost of the locomotive exchange point facilities and new locomotive shops.

The present value cost of this technology is $12.6 billion. In terms of relative economic efficiency of achieving emissions reductions, diesel-LNG locomotives compare favorably with the other technologies for PM, HC and NOx but are poor for CO_2 and CO.

11.5.3 Battery Tenders

The annual non-capital cost of battery tender locomotives is approximately $1.2 billion per year. The majority of this cost is attributed to $1.1 billion in lost revenue due to mode shift to truck associated with train delay at the exchange points. The $40.8 million in annual fuel savings is not sufficient to offset other cost increases. Thus annual costs to the railroads are expected to increase with this technology.

The capital cost of battery tender locomotives is approximately $20.5 billion. Approximately 94 percent of this capital cost is new locomotives and tenders. Due to the large number of battery tenders that need to be charged, this technology has the highest servicing facility cost.

The present value cost of this technology is $30.0 billion. In terms of relative economic efficiency of achieving emissions reductions, battery tender locomotives compare favorably with the other technologies for CO_2 and CO but are not as effective for reducing PM, HC and NOx per unit of total investment.

11.5.4 Solid-Oxide Fuel Cell

The annual non-capital cost of SOFC locomotives is approximately $1.2 billion per year. The majority of this cost is attributed to $1.1 billion in lost revenue due to mode shift to truck associated with train delay at the exchange points. The $117 million in annual fuel savings is not sufficient to offset other cost increases. Thus annual costs to the railroads are expected to increase with this technology.

The capital cost of SOFC locomotives is approximately $4.5 billion. Approximately two-thirds of this capital cost is new locomotives and tenders while the remaining third is largely the cost of the locomotive exchange point facilities and new locomotive shops.

The present value cost of this technology is $13.7 billion. In terms of relative economic efficiency of achieving emissions reductions, SOFC locomotives compare favorably with the other technologies for all pollutants. However, due to freight mode shift to truck, SOFC locomotives can exhibit poor CO_2 performance per unit of total investment.

11.5.5 Electrification

The annual non-capital cost of electrification is approximately $1.2 billion per year. The majority of this cost is attributed to $1.1 billion in lost revenue due to mode shift to truck associated with train delay at the exchange points. The $116 million in annual fuel savings is not sufficient to offset other cost increases. Thus annual costs to the railroads are expected to increase with this technology.

The capital cost of electrification is approximately $35.5 billion. Approximately 89 percent of this capital cost is the overhead catenary traction power supply system. However, electrification has the lowest servicing facility cost.

The present value cost of this technology is $44.3 billion, the largest of all alternative locomotive technologies under study. Despite resulting in 100-percent emissions reduction before mode shift, in terms of relative economic efficiency of achieving emissions reductions, electrification compares less favorably with the other technologies due to its large capital cost.

11.5.6 Linear Synchronous Motor

Due to the limited information on LSM technology, the cost data is not complete. Based on the information available, LSM is likely to follow the same trends as those observed for electrification.

12 Qualitative Assessment of State-Wide Deployment Scenario

The previous sections of this study have all related to a quantitative analysis of the deployment of alternative reduced-emissions locomotive technology as a captive fleet within the South Coast basin. There are multiple factors to consider when extending this analysis to a potential scenario where the captive fleet of alternative technology locomotives is expanded to include the entire line-haul freight rail network in California.

12.1 General Capital Cost Considerations

State-wide deployment involves more locomotives, operating on more trains over more miles of track. As described in Section 3, expanding to state-wide deployment will increase the number of daily BNSF and UP trains subject to operation with new technology locomotives from 130 trains per day to 200. However, the time that each train spends travelling within California will be much greater than the time spent within the South Coast, greatly increasing the demand for new technology locomotives and fuel tenders, and proportionately increasing capital costs of operating equipment. At the same time, with a larger network and more trains operating with new technology locomotives within the reduced-emissions area, utilization of the captive new technology locomotives may improve and help control the overall number of new technology locomotives required to support operations.

While the line-haul freight network in the South Coast basin covers approximately 400 route-miles, the state-wide line-haul freight network covers approximately 5,000 route-miles. This ten-fold increase in track within the reduced-emissions area will be reflected by a similar increase in the capital and maintenance cost of overhead catenary traction supply system for electrification and LSM infrastructure.

With more origins and destinations within the state, additional servicing infrastructure will be required with correspondingly higher capital cost for servicing facilities and locomotive shops. However, the number of locomotive exchange points is nearly the same at seven (compared to six for the South Coast):

- UP at Klamath Falls, Oregon
- BNSF at Klamath Falls, Oregon
- UP (with BNSF trackage rights) at Reno, Nevada
- UP (with BNSF trackage rights) at Portola, California
- UP at Las Vegas, Nevada
- BNSF at Needles, California
- UP at Yuma, Arizona

Although several of these facilities will be larger than the smallest facilities required for the South Coast, the state-wide capital and operating cost of the exchange points will likely be a proportionately smaller cost factor than it is for the South Coast.

12.2 General Annual Non-Capital Cost Considerations

As alluded to in the previous section, state-wide deployment will result in increases in locomotive and catenary maintenance proportional to the expanded size of the network within the reduced-emissions area.

Exchange point operating cost and train delay will not increase in proportion to the increased size of the network but in proportion to the number of trains transiting the state boundary. Thus they are likely to become smaller cost factors in the context of state-wide deployment.

It is difficult to predict how mode shift will translate to the state-wide deployment scenario. Intrastate freight movements between Northern and Southern California that are truck competitive and very sensitive to transit time will now be operated entirely with new technology locomotives and not be subject to locomotive exchange delays when entering the South Coast. These short-haul intermodal train movements experienced some of the largest mode shifts in the South Coast deployment scenario. In the state-wide scenario these same train movements would not be subject to any mode shift. In pushing the exchange points to the state boundary, locomotive exchange delays are concentrated on longer-distance interstate freight traffic that is less sensitive to delay and less likely to shift to truck. However, the overall traffic volume through the exchange points will increase in the state-wide scenario. It is unclear which of these two factors will dominate and drive the revenue loss up or down. However, given that capital costs for the various technologies are likely to increase several times, the lost revenue may not dominate the economics to the same extent it does for the analysis in the South Coast.

Fuel savings will increase in proportion to both the number of trains and size of the network within the reduced-emissions region. However, given that other cost factors are also increasing by the same proportions, it seems unlikely that fuel savings have the potential to offset other increases in annual non-capital costs.

Statewide, over 200 trains are operated each day by BNSF and UP. Of these, approximately two-thirds originate, terminate or pass through the South Coast Air Basin in Southern California.

12.3 Scenario-Specific Considerations

The following sections document any specific challenges or benefits in scaling a particular technology to a state-wide application.

12.3.1 Tier 4 Diesel-Electric with After-Treatment

Since they are not anticipated to yield fuel cost savings, the economics of Tier 4 locomotives with after-treatment will not benefit from the increased size of the network and additional train runs. However, since the total present value cost of this technology within the South Coast is largely driven by lost revenue, the technology may benefit at a state-wide level if mode shift is reduced by eliminating locomotive exchange on intrastate intermodal freight movements.

12.3.2 Liquefied Natural Gas

Since they are not anticipated to yield fuel cost savings, the economics of diesel-LNG locomotives with after-treatment will not benefit from the increased size of the network and additional train runs. However, since the total present value cost of this technology within the South Coast is largely driven by lost revenue, the technology may benefit at a state-wide level if mode shift is reduced by eliminating locomotive exchange on intrastate intermodal freight movements.

12.3.3 Battery Tenders

In a state-wide application, the limited range of battery tenders will become a major challenge to obtaining substantial emissions benefits from a practical implementation of the technology. Allowing for a reasonable number of battery tenders, on most routes in California, battery tender locomotives are unlikely to have sufficient range to operate in electric mode for the entire distance between terminals. The battery tender locomotives may spend the majority of their time in diesel-electric mode with no emissions benefits. The only way to increase the number of “clean” miles would be to frequently stop the train to exchange depleted battery tenders for fully charged ones. However, operation in this manner would be completely impractical due to excessive train delay and unacceptably long transit times.

12.3.4 Solid-Oxide Fuel Cell

Since the efficiency of the SOFC locomotive allows it to achieve the largest fuel savings in the South Coast, the economics of this technology have the potential to benefit from the increased size of the network and additional train runs. The potential of the technology could also be improved at a state-wide level if mode shift is reduced by eliminating locomotive exchange on intrastate intermodal freight movements.

12.3.5 Electrification

The major challenge to electrification on a state-wide level is the capital cost of the overhead catenary traction power infrastructure when the size of the line-haul network is increased by a factor of ten. Although the per-mile cost of state-wide electrification in rural and undeveloped areas may be less than that assumed for the South Coast, this will likely be offset by the cost of electrification in several long tunnels and multiple snowsheds.

12.3.6 Linear Synchronous Motor

As with electrification, other than technical obstacles identified previously, the major challenge to LSM locomotives on a state-wide level is the capital cost of the overhead catenary traction power infrastructure when the size of the line-haul network is increased by a factor of ten.

13 North American Deployment Scenarios

The main quantitative analysis presented in this study focuses on the deployment of alternative reduced-emissions locomotive technology as a captive fleet within the South Coast basin. The previous sections demonstrate that a captive fleet requires locomotive exchange points that present substantial operational and economic challenges. The capital cost of the exchange point facilities, annual cost of train delay incurred at the exchange points and annual revenue loss due to these delays all decrease the economic attractiveness of the presented alternatives.

To eliminate the exchange points but still obtain line-haul freight emissions benefits in the South Coast basin, alternative technology locomotives could be deployed across the wider North American rail network. In such a scenario, trains originating or terminating in the basin would operate with the new-technology locomotives over their entire route. As part of the national fleet, it is assumed that reduced-emissions locomotives would not be captive to service on these trains. To ensure that reduced-emissions locomotives would always be available for service on trains to and from the basin, the group of new technology locomotives deployed within the national fleet would need to be larger than the size of the captive fleet introduced in the earlier analysis.

Compared to the South Coast basin captive fleet scenarios presented earlier in this study, deployment of alternative locomotive technology across the wider North American network offers the following potential benefits:

- Eliminates capital cost of the exchange facilities, including servicing facilities
- Eliminates operating cost of the exchange facilities
- Eliminates cost of train delay at the exchange points
- Eliminates revenue loss due to mode shift prompted by exchange point train delay
- Eliminates capital cost of new locomotive shop in the basin
- Fuel and emissions benefits of the alternative locomotive technology are obtained on the entire trip from origin to destination, not just the portion of the route in the basin

However, compared to a captive fleet, deployment across the North American network has potential dis-benefits and challenges:

- Requires capital investment in a larger fleet of alternative technology locomotives with associated maintenance costs
- Requires capital investment in new servicing infrastructure at multiple locations across the entire network
- Imposes constraints on locomotive assignment to ensure operation of line-haul freight service with alternative technology locomotives within the South Coast basin
- Infeasible for electrification and LSM without great capital investment in wayside energy distribution infrastructure across the entire network and recurring annual cost of maintaining this infrastructure

For comparison to the previous captive fleet scenarios with exchange points, the remainder of this section analyzes the costs and benefits of a North American deployment scenario for two different alternative reduced-emission locomotive technologies.

13.1 Locomotive Technologies for North American Deployment

Earlier in this report, six alternative reduced-emission locomotive technologies were examined within the context of a regional deployment within the South Coast basin. Two of the locomotive technologies, electrification and LSM, require wayside infrastructure to supply traction energy. The capital cost of installing (and recurring cost of maintaining) wayside infrastructure across the entire rail network does not make either locomotive technology an attractive option for North American deployment. Of the four remaining liquid-fuel options, the Tier 4 diesel-electric locomotives with after-treatment and SOFC-gas turbine locomotive fueled by LNG provided the largest emissions benefit per unit of present-value cost. Thus a modified Tier 4 diesel-electric locomotive with after-treatment and onboard battery storage was selected for the study of a North American deployment scenario along with the SOFC-gas turbine locomotive introduced previously.

13.1.1 Tier 4 Diesel-Electric with After-Treatment and Onboard Battery Storage

The conceptual Tier 4 diesel-electric locomotive with after-treatment considered for the purposes of this study was introduced in Section 2.2. Although this technology reduces emissions of criteria pollutants relative to Tier 2 and Tier 4 levels, it is assumed to not reduce CO_2 emissions.

One option to reduce carbon dioxide emissions is to decrease fuel consumption through an onboard battery system to recover and reuse dynamic braking energy. The battery system onboard the General Electric prototype “Evolution Hybrid” locomotive was estimated to reduce fuel consumption by 10 percent (Railway Gazette, 2007). In addition to reducing fuel consumption, the battery storage system may provide some low-speed zero-emission tack miles when moving in and out of terminal areas. It is estimated that reductions in fuel consumption of 15 to 20 percent could be obtained through onboard storage with improved battery technology in the future. By consuming less fuel, a similar percent reduction in criteria pollutant emissions, above and beyond those obtained from after-treatment, may be facilitated by the onboard battery storage system when both devices are installed on the same locomotive. Although a locomotive has limited weight capacity and space available for onboard systems, conceptual designs for a locomotive with a compact SCR/DOC device and onboard battery storage have been proposed.

For North American deployment, the concept introduced in Section 2.2 is modified to include battery storage. The analysis in the following considers a conceptual Tier 4 diesel-electric locomotive with after-treatment and onboard battery storage. For the purposes of this analysis, the conceptual Tier 4 locomotive with after-treatment and onboard battery storage is assumed to reduce fuel consumption by 15 percent.

13.1.2 Solid-Oxide Fuel Cell with LNG Turbine

The conceptual SOFC-gas turbine locomotive considered for the purposes of this study was introduced in Section 2.5. It is assumed that the SOFC-gas turbine locomotive operates on liquefied natural gas fuel supplied from a fuel tender. For the purposes of the analysis in this chapter, no modifications are made to the previously proposed concept.

13.2 Details of North American Deployment Scenario

The North American deployment scenario assumes that the 130 line-haul freight trains that originate, terminate or transit the South Coast air basin each day use alternative technology locomotives for their entire trip from origin destination. Thus, unlike the previous analysis with exchange points, South Coast line-haul trains will use alternative locomotive technology over the long portions of their routes lying outside the air basin.

As described in Section 4.4.3, a total of 2,022 locomotives are required to support line-haul operations of South Coast trains (both inside and outside the basin) at any given time. Assuming that each locomotive spends one-third of its time operating on trains serving the South Coast, a fleet of over 6,000 locomotives is required to supply the South Coast trains with 2,022 locomotives at any given time. The North American deployment scenario assumes that within the national fleet, 6,000 conventional diesel-electric locomotives are replaced by the same number of alternative technology locomotives to ensure adequate coverage for South Coast trains.

Due to constraints on new locomotive manufacturing capacity, the age of the current line-haul locomotive fleet and the large one-time capital cost, it is unlikely that 6,000 alternative technology locomotives would be implemented in a short period. The approach assumed for this analysis is to gradually introduce the alternative technology locomotives to the North American fleet over the course of a 15-year period, roughly corresponding to the front-line service life of a line-haul locomotive before it is cascaded down to secondary or terminal service. It is assumed that 400 new alternative locomotive technology locomotives enter service each year in place of 400 conventional locomotives that are retired or transitioned to non-line-haul service.

The assumed approach of phased deployment has several implications for the analysis. The capital cost of locomotive purchase is annualized in the present-value analysis. Maintenance costs and fuel savings increase proportionately as new technology locomotives are introduced to the fleet, requiring a gradient approach to the present-value analysis. Finally, on an annual basis, the full benefits of the alternative locomotive technology are not obtained until the final year of the 15-year period. Averaged over the entire 15-year study period, the alternative locomotive technology will only realize 50 percent of the benefits of full deployment.

There is one other key difference between the analysis of a North American deployment and the analysis of operation with exchange points presented previously. In the analysis of a captive fleet with exchange points, operations required a number of new technology locomotives in addition to the current fleet of conventional diesel-electric locomotives, increasing the overall fleet size. Compared to a baseline of operating with the current fleet, the additional cost to implement the alternative locomotive technology (and increase the fleet size) is the full capital and incremental maintenance cost of the new technology locomotives (and fuel tenders where required). In the North American deployment scenario, the new technology locomotives replace conventional locomotives as they are removed from service and the overall size of the fleet does not increase. In this case, compared to a baseline of maintaining operations with the current fleet and replacing 400 locomotives with 400 new Tier 4 diesel-electric locomotives each year, the additional cost to implement the alternative locomotive technology is the *incremental* capital and maintenance cost of replacement with new technology locomotives (and fuel tenders where required) instead of replacement with Tier 4 locomotives.

13.3 Emissions Benefits in the South Coast

The methodology for determining emissions benefits in the South Coast was introduced in Section 5. The same methodology is applied to the North American deployment scenario with one exception. The efficiency of the Tier 4 locomotive with after-treatment and onboard storage is increased from 39 to 46 percent to account for the fuel savings of the battery storage system.

Since, from the perspective of the South Coast air basin, the same trains are operating with the same locomotives in the captive fleet and North American deployment scenarios, the emissions benefits for the SOFC-gas turbine match those calculated earlier (Table 13.1). The only difference from Table 5.3 is a 15-percent decrease in the values for the Tier 4 diesel with after-treatment and onboard storage to account for its 15-percent reduction in fuel consumption. Note that the values in Table 13.1 correspond to the final year of the deployment period when all of the new technology locomotives enter service.

Table 13.1: Annual* South Coast Loco. Emissions (lbs) for N. American Deployment

Technology	CO_2	PM	HC	NOx	CO
Tier 4 Diesel (Baseline)	743,970,000	22,700	60,600	1,514,000	1,940,000
Tier 4 Diesel w/After-T & Battery Storage	632,400,000	4,800	51,600	322,000	1,649,000
SOFC-Gas Turbine w/ LNG	320,000,000	12,000	32,000	800,000	1,023,000

*At full deployment.

13.4 Locomotive Capital and Maintenance Cost

As described above, compared to a baseline of continued replacement and maintenance of the current fleet with new Tier 4 diesel-electric locomotives, railroads incur an incremental capital and maintenance cost for North American deployment of alternative locomotive technology in place of the new Tier 4 locomotives.

13.4.1 Incremental Capital Cost

At full deployment, 6,000 alternative technology locomotives are required to support reduced –emissions operations over the entire route of all South Coast trains. For the SOFC-gas turbine with LNG, 4,000 fuel tenders are required to supply these locomotives with LNG.

The North American deployment scenario assumes that 400 new alternative technology locomotives are introduced to the national fleet each year for 15 years. The new technology locomotives are introduced in place of conventional Tier 4 locomotives that would otherwise be deployed at a cost of $3 million per unit. For the SOFC-gas turbine, 267 tenders are purchased each year. In the present-value calculation, the incremental capital cost of the locomotives and tenders is an annual expense over the study period.

For the purposes of this study, it is assumed that each Tier 4 diesel-electric locomotive with after-treatment and onboard battery storage has a capital cost of $4 million per unit. A cost of $4 million per unit represents an incremental capital cost of $1 million per unit compared to conventional Tier 4 diesel-electric locomotives. For the required number of locomotives, this represents a capital cost of $400 million per year or a present-value cost of $3.042 billion over 15 years with a discount rate of 10 percent.

It is assumed that each SOFC-gas turbine locomotive has a capital cost of $5 million per unit. A cost of $5 million per unit represents an incremental capital cost of $2 million per unit compared to conventional Tier 4 diesel-electric locomotives. Each LNG tender has a full capital cost of $1 million per unit. For the required number of locomotives and LNG tenders, this represents a capital cost of $1.067 billion per year or a present-value cost of $8.115 billion.

13.4.2 Incremental Maintenance Cost

As described in Section 2.1.2, the annual maintenance expense per conventional diesel-electric locomotive is equivalent to $1.25 per locomotive-mile. Tier 4 diesel-electric locomotives are assumed to have a maintenance expense of $1.32 per locomotive-mile.

In Section 6.5, annual locomotive maintenance was calculated on the basis of locomotive-miles for the captive fleet within the South Coast. For the North American deployment scenario, incremental maintenance expenses are incurred for all locomotive-miles accumulated during the operation of South Coast trains over their entire route from origin to destination. Instead of the 25.7 million locomotive-miles accumulated each year by the captive fleet, when fully deployed, the alternative technology locomotives will accumulate 331 million locomotive-miles each year on South Coast trains. This larger value does not fully account for locomotive-miles accumulated while new technology locomotives are assigned to other trains on the national network that are outside the scope of this study.

To estimate additional locomotive-miles accumulated on non-South Coast trains, it is assumed that locomotive availability is 85 percent. With one-third of locomotive-hours spent on South Coast trains and 15 percent out of service, the remaining 52 percent are spent on non-South Coast trains. Assuming locomotive-miles are accumulated at the same rate as on South coast trains, an additional 522 million locomotive-miles are accumulated on non-South Coast trains each year.

For the purposes of this study, it is assumed that Tier 4 diesel-electric locomotives with after-treatment and onboard battery storage have an incremental maintenance cost of $0.50 per locomotive-mile compared to conventional Tier 4 locomotives. This rate is equivalent to $165.5 million per year on South Coast trains and $261 million per year on non-South Coast trains when fully deployed.

It is assumed that SOFC-gas turbine locomotives have an incremental maintenance cost of $2.43 per locomotive-mile compared to conventional Tier 4 locomotives. This rate is equivalent to $804 million per year on South Coast trains and $1,268 million per year on non-South Coast trains when fully deployed.

13.5 Benefits of Improved Efficiency and Energy Supply Costs

This section determines the potential efficiency and energy supply cost benefits of each alternative locomotive technology following the general methodology of Section 9.

13.5.1 Fuel Savings

Unlike the scenario of a captive fleet within the South Coast, for the North American deployment scenario, fuel savings are not limited to operations within the South Coast. The calculation of fuel cost must be expanded to include fuel consumed for all trains originating, terminating or transiting the South Coast over their entire route from origin to destination.

Since detailed train performance simulation was only performed for train operations within the South Coast, assumptions were required to determine the remaining energy consumption for South Coast trains outside the basin. From the train performance calculation, 16.9 billion ton-miles of freight rail transportation within the basin exchange points required 3,397 TJ of energy at the locomotive wheels. If transport outside the basin is assumed to have the same energy efficiency, the 215 billion ton-miles of freight rail transportation over the entire route is estimated to consume 43,317 TJ of energy at the locomotive wheels.

Both the baseline Tier 4 and alternative technology Tier 4 locomotives consume this same amount of energy each year. Energy consumption for the SOFC-gas turbine locomotive is increased slightly to account for the additional weight and train resistance of the LNG tenders (Table 13.2).

When energy is converted to diesel fuel consumption, compared to baseline operation with Tier 4 diesel-electric locomotives, the Tier 4 diesel-electric with after-treatment and onboard battery storage can save approximately 140 million gallons of diesel fuel each year when fully deployed. This savings is a direct result of the onboard battery storage system. The improved efficiency of the SOFC-gas turbine locomotive allows it to save the equivalent of 380 million gallons of diesel fuel each year at full deployment.

Table 13.2: Annual Energy/Fuel Consumption of South Coast Trains for North American Deployment

	Energy (TJ)			Electricity	Diesel	LNG	
Technology	At Wheels	Traction	Fuel/ Electricity	MWh	Gallons	Gallons	Diesel-Gallon-Equivalent
Tier 4 Diesel-electric (baseline)	43,317	50,961	130,670	--	914,247,000	--	--
Tier 4 Diesel-electric with After-treatment & Battery storage	43,317	50,961	110,785	--	775,123,000	--	--
SOFC-Gas Turbine with LNG	46,683	54,921	78,459	--	--	899,819,000	535,607,000

The values in Table 13.2 only consider fuel consumed when alternative technology locomotives are transporting South Coast trains. It was mentioned earlier that the fleet size of 6,000 locomotives was obtained by assuming that each locomotive only spends one-third of its time in service on South Coast trains. When used on other line-haul trains outside the scope of this study, the efficiencies of the new alternative technology locomotives will still be present, yielding additional fuel savings.

To estimate the magnitude of the additional fuel consumption and savings when operating the new technology locomotives on non-South Coast trains, the fuel consumed by South Coast trains is factored up by 1.577. This factor is calculated from the assumed locomotive availability of 85 percent, with South Coast assignment of 33 percent and non-South Coast assignment of 52 percent. Based on this factoring approach, the assumed additional fuel consumed on non-South Coast trains is as follows:

- 1.44 billion gallons of diesel for the Tier 4 baseline
- 1.22 billion gallons of diesel for the Tier 4 diesel-electric with after-treatment and battery storage
- 1.42 billion gallons of LNG (844 million diesel-gallon equivalents) for the SOFC gas-turbine locomotive with LNG

Using the methodology from Section 9, the alternative locomotive fuel consumption and cost factors are combined to calculate the expected energy supply cost of South Coast line-haul mainline freight locomotive operations over the entire route from origin to destination (Table 13.3). The improved efficiency of the battery hybrid system installed on the Tier 4 locomotive saves $434 million in fuel costs each year on South Coast trains and $684 million per year on non-South Coast trains when fully deployed. The efficiency of the SOFC-gas turbine with LNG saves nearly $1.5 billion per year on South Coast trains and $2.3 billion per year on non-South Coast trains when fully deployed. In early years, fuel savings are proportional to the number of alternative technology locomotives that have been introduced to the North American fleet.

Table 13.3: Change in Annual Locomotive Fuel Cost for North American Deployment

Technology	South Coast Total ($ million)	South Coast Reduction from Tier 4 ($ million)	Reduction from Tier 4 (%)	Non-South Coast Total ($ million)	Non-South Coast Reduction from Tier 4 ($ million)
Tier 4 Diesel-electric (baseline)	2,852	--	--	4,498	--
Tier 4 Diesel-electric with After-Treatment & Battery Storage	2,418	434	15.2	3,814	684
SOFC-Gas Turbine with LNG	1,360	1,492	52.3	2,145	2,353

13.5.2 Servicing Facilities

The presented fuel savings can only be achieved for a North American deployment if there is sufficient fuel supply and servicing infrastructure across the entire network to support the alternative reduced-emissions locomotive technologies.

The Tier 4 diesel-electric with after-treatment and onboard battery storage can use existing diesel fueling and servicing facilities.

The SOFC-gas turbine locomotive uses LNG fuel and must be supported by a national network of LNG fueling facilities. Since the main cost of LNG liquefaction plants is assumed to be part of the delivered cost of LNG, this analysis only considers the cost of the fueling pads themselves. Based on single consist estimates from Transport Canada (Barton, 2012), the capital cost of an LNG fueling facility is estimated as $10 million per terminal. To support North American deployment, LNG capability must be installed at approximately 40 locations (Hemphill, 2015). Thus the capital cost of the required LNG fueling facilities is estimated as $400 million. This cost is assumed to be incurred during the first year of the study period; all facilities must be in service to allow the first group of SOFC-gas turbine locomotives to move freely about the North American network.

13.6 Present-Value Cost

This section collects the capital and annual costs and benefits determined through the North American deployment analysis to provide an overall measure of the economic impact of each of the two alternative locomotive technologies relative to the Tier 4 baseline.

13.6.1 Total Annual Non-Capital Cost

The change in total annual cost of each alternative locomotive technology scenario relative to the baseline of conventional Tier 4 replacement includes all non-capital items (Table

13.4). Although several cost items are not present in the North American deployment scenario, they are listed in the table for consistency with those in Section 11. The annual cost items include:

- Incremental maintenance of new technology locomotives while in service on South Coast trains, ranging from $166 to 804 million per year depending on the locomotive technology.
- Incremental maintenance of new technology locomotives while in service on non-South Coast trains, ranging from $261 million to $1.3 billion per year depending on the locomotive technology.
- A credit for any fuel/energy cost savings relative to the Tier 4 baseline case, ranging from a decrease of $434 million to $1.5 billion per year for South Coast trains depending on the locomotive technology.
- A credit for any fuel/energy cost savings relative to the Tier 4 baseline case, ranging from a decrease of $684 million to $2.3 billion per year for non-South Coast trains depending on the locomotive technology.

The following items considered in Section 11 do not factor into the analysis since they no longer apply to the North American deployment scenario:

- Maintenance of overhead catenary traction power distribution infrastructure
- Operating cost of personnel at the locomotive exchange points
- Operating cost increase due to train delay encountered at the locomotive exchange points
- Annual revenue loss due to freight shifting to truck as a result of delays at locomotive exchange points

Note that the items in Table 13.4 reflect incremental cost increases or decreases over the baseline condition of phased replacement with conventional Tier 4 locomotives and not absolute operating costs. These figures also represent full deployment at the end of the 15-year period when all alternative technology locomotives are placed in service. Annual incremental costs and fuel savings would be pro-rated for earlier years based on the number of new technology locomotives within the North American fleet.

For the two technologies, the change in total annual non-capital cost at full deployment ranges from a decrease of approximately $691 million to $1.8 billion per year. The calculation of annual cost is dominated by the fuel savings of each technology. In both cases, potential annual benefits from reduced fuel costs are large enough to offset the incremental annual locomotive maintenance expense introduced by the new technology. This result contrasts sharply with the exchange point scenarios where the revenue lost from train delay more than offset any potential benefits of reduced fuel and energy costs.

13.6.2 Total Capital Cost

The capital cost of each alternative locomotive technology scenario (Table 13.5) includes all capital items:

- Incremental purchase cost of new locomotives and tenders (present value of annual expense over 15 years) ranging from $3.0 to $8.1 billion depending on the locomotive technology.
- The construction cost of LNG servicing and fueling facilities at $400 million for the SOFC-gas turbine locomotive

Table 13.4: Annual* Non-Capital Costs ($ million) for North American Deployment

Annual Cost	Tier 4 Bat	SOFC
Incremental Locomotive Maintenance (South Coast trains)	166	804
Incremental Locomotive Maintenance (non-South Coast trains)	261	1,268
Catenary Maintenance	--	--
Exchange Point Operating	--	--
Train Delay	--	--
Revenue Loss	--	--
Fuel Savings (South Coast trains)	-434	-1,492
Fuel Savings (non-South Coast trains)	-684	-2,353
Total	-691	-1,773

*At full deployment

The following items considered in Section 11 do not factor into the analysis since they no longer apply to the North American deployment scenario:

- Installed cost of the overhead catenary traction power distribution system for electrification and LSM infrastructure
- Construction cost of new locomotive shop facilities
- Construction cost of the locomotive exchange facilities

The overall capital cost of each alternative locomotive technology is shown as the "Subtotal Capital Cost" in Table 13.5. The capital cost of either technology is dominated by the cost of locomotives and tenders. Although spread over 15 years, acquiring 6,000 alternative technology locomotives and 4,000 LNG tenders still represents a substantial capital investment.

The $3 billion incremental capital investment for the Tier 4 locomotive with after-treatment and battery storage is roughly equivalent to the capital cost of the liquid-fueled alternatives in the exchange point analysis. Savings from not constructing the exchange points are offset by the larger fleet of alternative technology locomotives required for North American deployment. The capital cost of the SOFC-gas turbine is higher than the other liquid-fueled alternatives but still substantially lower than electrification and LSM with exchange points.

Table 13.5: Summary of Capital and Present Value Costs ($ million) for North American Deployment

Capital Cost	Tier 4 Bat	SOFC
Incremental Locomotive and Tenders	3,042	8,116
Overhead Catenary/LSM	--	--
Locomotive Shop	--	--
Exchange Facilities	--	--
Servicing Facilities	--	400
Subtotal Capital Cost	3,042	8,516
Present Value of Annual Non-Capital Costs (from Table 13.4)	-2,202	-5,645
Total Present Value Cost	840	2,781

13.6.3 Total Present Value Cost

To provide an overall measure of the economic impact of each alternative locomotive technology scenario the annual costs at full deployment (year 15) from Table 13.4 are combined with the capital costs from Table 13.5 in a present value calculation over the 15-year initial mainline service life of a line-haul freight locomotive.

The annual non-capital costs are transformed to present value by assuming they are incurred over 15 years with a discount rate of 10 percent. Since the magnitude of the annual non-capital costs grow each year as more alternative technology locomotives are introduced to the North American fleet, a gradient approach must be used in the present value calculation. Once discounted to present value (Table 13.5), the annual non-capital costs can be added to the total capital costs to determine the total present value cost of each alternative locomotive technology scenario.

In both cases the decrease in annual non-capital costs attributed to savings in the cost of fuel is not enough to offset the incremental capital cost of the new alternative technology locomotives (and fuel tenders where appropriate). However, the magnitude of the shortfall for these two North American deployment scenarios is far less than that observed for the captive fleet scenarios with exchange points. By eliminating the exchange points, associated delay and revenue loss from mode shift, plus accumulating fuel savings benefits over a longer route, the North American deployment scenario exhibits improved economics even though a much larger fleet of alternative technology locomotives must be acquired.

13.7 Emissions Benefits Outside the South Coast

Unlike the scenario of a captive fleet within the South Coast, for the North American deployment scenario, emissions benefits are not constrained to operations within the South Coast. The calculation of emissions benefits for all line-haul freight trains originating, terminating or transiting the South Coast can be expanded to include their entire route from origin to destination. Using the methodology from Section 5 and the fuel consumption for the entire route calculated in Table 13.2, emissions of each locomotive technology (in tons) were estimated for all South Coast trains over their entire route (Table 13.6). To cover the entire route, the emissions values in Table 13.6 include locomotive emissions inside the South Coast (Table 13.1) plus additional locomotive emissions outside of the air basin.

Table 13.6: Annual* Loco. Emissions (tons) for N. American Deployment on South Coast Trains

Technology	CO_2	PM	HC	NOx	CO
Tier 4 Diesel (Baseline)	10,300,000	314	838	21,000	26,800
Tier 4 Diesel w/After-T & Battery Storage	8,746,000	67	713	4,450	22,800
SOFC-Gas Turbine w/ LNG	4,422,000	166	442	11,100	14,100

*At full deployment. Includes emissions inside and outside the South Coast

The values in Table 13.6 only consider emissions when alternative technology locomotives are transporting South Coast trains. The fleet size of 6,000 locomotives was obtained by assuming each locomotive only spends one-third of its time in service on South Coast trains. When used on other line-haul trains outside the scope of this study, the emissions benefits of the new alternative technology locomotives will still be present, yielding additional emissions reductions. Using the factoring approach described in Section 13.5.1, total emissions of each locomotive technology for non-South Coast trains (in tons) can be estimated (Table 13.7).

Table 13.7: Annual* Loco. Emissions (tons) for N. American Deployment on non-South Coast Trains

Technology	CO_2	PM	HC	NOx	CO
Tier 4 Diesel (Baseline)	16,200,000	496	1,320	33,100	42,300
Tier 4 Diesel w/After-T & Battery Storage	13,792,000	105	1,120	7,000	36,000
SOFC-Gas Turbine w/ LNG	6,974,000	261	697	17,400	22,300

*At full deployment. All emissions are outside the South Coast

Combining the values from Tables 13.6 and 13.7 provides a more complete picture of the overall potential emission benefits of the each new locomotive technology on both South Coast and non-South Coast trains in a North American deployment scenario. Although only a portion of the line-haul freight locomotive emissions reductions are obtained within the South Coast, some of the emissions benefits may be obtained in other air basins and non-attainment areas. These broader emission reductions represent additional benefits that are important on a national scale.

13.8 Summary of North American Deployment Scenarios

The following sections summarize the cost and economic performance of both North American alternative locomotive technology deployment scenarios.

13.8.1 Tier 4 Diesel-Electric with After-Treatment and Onboard Battery Storage

The annual non-capital cost of Tier 4 diesel-electric locomotives with after-treatment and onboard battery storage is a savings of approximately $691 million per year. The majority of this savings is from reduced fuel consumption through the battery storage system. Annual non-capital costs to the railroads are expected to decrease with this technology if deployed in this manner.

The incremental capital cost of Tier 4 diesel-electric locomotives with after-treatment and battery storage is approximately $3.0 billion. This cost is wholly comprised of the incremental capital cost of replacing conventional locomotives with the Tier 4 after-treatment and battery hybrid technology compared to replacement with conventional Tier 4 diesel-electric technology.

The present value cost of this technology is $840 million. This cost is at least $11 billion lower than all of the exchange point scenarios summarized in Section 11. The calculated cost only includes very high-level assumptions on fuel savings realized while the new technology locomotives are operating on non-South Coast trains outside the scope of this study. A more detailed study of these other train assignments may alter the economics of the North American deployment scenario for this locomotive technology.

13.8.2 Solid-Oxide Fuel Cell

The annual non-capital cost of SOFC-gas turbine locomotives is a savings of approximately $1.8 billion per year. The majority of this savings is from reduced fuel consumption due to the improved overall energy efficiency of the SOFC-gas turbine combination. Annual non-capital costs to the railroads are expected to decrease with this technology if deployed in this manner.

The incremental capital cost of SOFC-gas turbine locomotives is approximately $8.5 billion. Approximately 95 percent of this capital cost is new locomotives and LNG tenders while the remaining 5 percent is the cost of LNG fueling and servicing facilities. This capital cost is higher than liquid fuel technologies deployed as a captive fleet in the South Coast with exchange points but substantially lower than electrification or battery tender locomotives.

The present value cost of this technology is $2.8 billion. This value is nearly $10 billion lower than the present value cost of the exchange point scenarios summarized in Section 11. As with the modified Tier 4 locomotives above, the economics of the SOFC locomotive could be altered by a more detailed consideration of the additional fuel savings realized when the alternative technology locomotives are in service on non-South Coast trains outside the scope of this study.

13.8.3 Conclusion

North American deployment of either examined locomotive technology appears to offer improved economics relative to operation with exchange points. Although North American deployment requires the purchase of more alternative technology locomotives, they can realize fuel savings over longer train runs and are not hindered by the capital cost, train delay and lost revenue associated with locomotive exchange points. The primary drawback of such a deployment scenario is that full emissions benefits are not obtained for 15 years or until the last of the alternative technology locomotives are acquired and placed in service. Another drawback is that careful management of the locomotive assignment process is required to ensure that South Coast trains always enter the air basin with alternative reduced-emission technology locomotives. Poor fleet management may result in trains being delayed until appropriate alternative technology locomotives are available. The cost of these delays and potential mode shift and revenue loss all negatively impact the economics of the deployment scenario.

North American deployment of Tier 4 diesel-electric with after-treatment and onboard battery storage technology appears to offer the best economics of any alternative studied in this report. While this technology is not yet commercialized, prototypes of the various systems exist and have been demonstrated in service.

In the longer-term, the SOFC-gas turbine locomotive with LNG appears to offer potential for North American deployment within the larger locomotive fleet. Although no working prototypes exist, modeling and simulation suggest that the efficiency of the SOFC-gas turbine may yield substantial fuel savings. As fuel and energy costs increase in the future, the magnitude of these savings will further improve the economics of the technology. In the near term, further research is needed to determine if it is feasible to construct a 4,400-horsepower line-haul locomotive powered by SOFC-gas turbine technology and if it exhibits the same levels of energy efficiency under line-haul service conditions.

14 Conclusions

North American Deployment Scenario:

Given the assumptions of this study, the economics of certain alternative locomotive technologies can be improved through North American deployment. Although North American deployment requires the purchase of more alternative technology locomotives, the fuel savings are realized over longer train runs and the capital cost and train delays associated with locomotive exchange points are eliminated.

Among the locomotive technologies evaluated, Tier 4 diesel-electric locomotives with after-treatment and SOFC-gas turbine locomotive fueled by LNG provided the largest emissions benefit per unit of present-value cost.

In the near- to mid-term, North American deployment of Tier 4 diesel-electric with after-treatment and onboard battery storage technology appears to offer the best economics of any alternatives studied in this report. While this technology is not yet commercialized, prototypes of the various systems exist and have been demonstrated in service.

In the longer-term, the SOFC gas turbine locomotive with LNG fuel appears to offer potential for North American deployment within the larger locomotive fleet. Further research is needed to determine if it is feasible to construct a 4,400 horsepower freight interstate line haul locomotive powered by SOFC-gas turbine technology.

SCAB Deployment Scenario:

None of the studied locomotive technologies can generate fuel and energy cost reductions large enough to offset increases in annual non-capital costs. This is the case even when mode shift is not considered in the calculation of annual costs. When mode shift is considered, the potential for $1.1 billion in lost revenue each year dominates the annual cost calculation. When combined into a net present value calculation over 15 years, the lost revenue also dominates the economics of the three liquid fueled locomotive technologies even though the locomotive capital costs range from $1.7 to $3.2 billion.

Only for electrification and battery tender locomotives is the revenue loss not the dominant factor in the total net present value calculation. This is due to the high capital cost of both of these technologies at $20.5 billion for battery tenders and $35.5 billion for electrification.

The total present value cost of each technology can be weighed against its relative percent emissions reduction from Tier 2 and Tier 4 levels to assess its performance. Based on the calculated percent reduction in emissions per billion dollars invested, the SOFC-gas turbine locomotive with LNG has the potential to yield the best emissions reduction performance compared to the other locomotive technologies. However, the emissions produced by trucks carrying freight shifted from rail limits the potential benefits of all of the reduced-emission locomotive technologies, even those that are locally “zero emissions”.

The above findings emphasize the importance of operational factors when evaluating new locomotive technology to reduce freight rail emissions in California. For several of the technologies, it is not the equipment capital cost and potential fuel savings that control economic feasibility, but instead other factors that arise from the difficulty of integrating new locomotive technology in captive service within a the interoperable rail network.

Need for Further Research:

The economic feasibility of new locomotive technology is sensitive to the level of service demanded by shippers, the cost of train delay and potential shift of freight to other modes.

The importance of these factors suggests that improved understanding of each is required beyond what was found in the literature or developed through this study.

The results of this study are limited in part by the information available on the potential of each technology and its current state of development. To provide a better economic analysis, further research needs to be conducted to determine the exact potential benefits of each locomotive technology:

- For Tier 4 locomotives with after-treatment and diesel-LNG, emissions testing of prototype and production units should be conducted under representative field conditions to determine how much additional reduction beyond Tier 4 levels can be achieved by these technologies. Diesel-LNG tests should also quantify the amount of methane leakage expected during refueling.
- For the SOFC locomotive and LSM, working prototypes need to be developed to demonstrate if each technology can feasibly provide the power and tractive effort required for line-haul freight operations.
- For the battery tender, working prototypes need to be developed to demonstrate the potential range and service life of the batteries under line-haul freight service conditions.

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Abbreviations and Acronyms

AAR	Association of American Railroads
AC	alternating current
ARB	California Air Resources Board
AREMA	American Railway Engineering and Maintenance-of-Way Association
BNSF	BNSF Railway
DC	direct current
DOC	diesel oxidation catalyst
DPF	diesel particulate filter
EGR	exhaust gas recirculation
EIA	Energy Information Administration
EMD	Electro-Motive Diesel
EPA	Environmental Protection Agency
FAF	Freight Analysis Framework
FRA	Federal Railroad Administration
FSAC	Freight Station Accounting Code
GE	General Electric
LNG	liquefied natural gas
LSM	linear synchronous motor
MGT	million gross tons
NCTD	North County Transit District
SCR	selective catalytic reduction
SOFC	solid-oxide fuel cell
STB	Surface Transportation Board
STCC	Standard Transportation Commodity Code
TPC	train performance calculator
TPD	trains per day
TRL	technology readiness level
UP	Union Pacific Railroad
USDOE	United States Department of Energy