Exchange Point Delay and Mode Shift Associated with Regional Deployment of Alternative Locomotive Technology on the North American Line-Haul Freight Network

Garrett Fullerton [a,1], C. Tyler Dick [a], Taesung Hwang, PhD [a]
Yanfeng Ouyang, PhD [a]
[a] Rail Transportation and Engineering Center (RailTEC),
University of Illinois at Urbana-Champaign.
205 N. Mathews Ave. Champaign, Illinois 61801, United States of America
[1] E-mail: gfuller2@illinois.edu, Phone: +1 (217) 244-6063

Abstract
In recent decades, the North American freight railroads have made tremendous improvements to increase fuel efficiency and reduce locomotive emissions. These improvements have been driven by a combination of industry desire to reduce operating expenses, federal regulations, and environmental stewardship. Impending EPA Tier 4 locomotive emissions standards may represent the practical minimum levels achievable by conventional diesel-electric locomotives. Further emissions reductions may require on-board after-treatment systems or a shift to an emerging alternative, ultra-low emission locomotive technology. While such reductions have been achieved within certain urban non-attainment areas with strict emissions standards in captive yard and terminal switching service, reducing the emissions of mainline freight rail operations in a region where new locomotive technology is introduced to line-haul traffic poses a much more difficult operational challenge for the industry. The practicalities of a phased transition may dictate that initial line-haul operations using a new locomotive technology are confined to a certain portion of the rail network creating the need for a locomotive exchange. The need to exchange locomotives mid-route will disrupt the seamless movement of freight typical in North America and generate the potential for a modal shift to truck due to increased transit times. In order to quantify the potential impact of a locomotive exchange on railroad operations, exchange times are quantified for different locomotive configurations and queuing models is applied to estimate further delay. These times are then applied to a logit modal split modal as delay and lost revenues are calculated for shipments of various value.

Keywords
Freight Rail, Climate Change, Queuing Model, Modal Shift,

1 Introduction

In recent decades, North American freight railroads have substantially increased fuel efficiency and reduced locomotive emissions. There are several motivations for the investment and technological development necessary to achieve this result. Annual freight ton-miles nearly doubled over the past 30 years while fuel consumption remained relatively constant (Figure 1). However, despite fairly stable fuel consumption of this interval, fuel cost as a percentage of total railroad operating expense nearly doubled. Although energy prices are currently declining, they have always been and will continue to be, a major

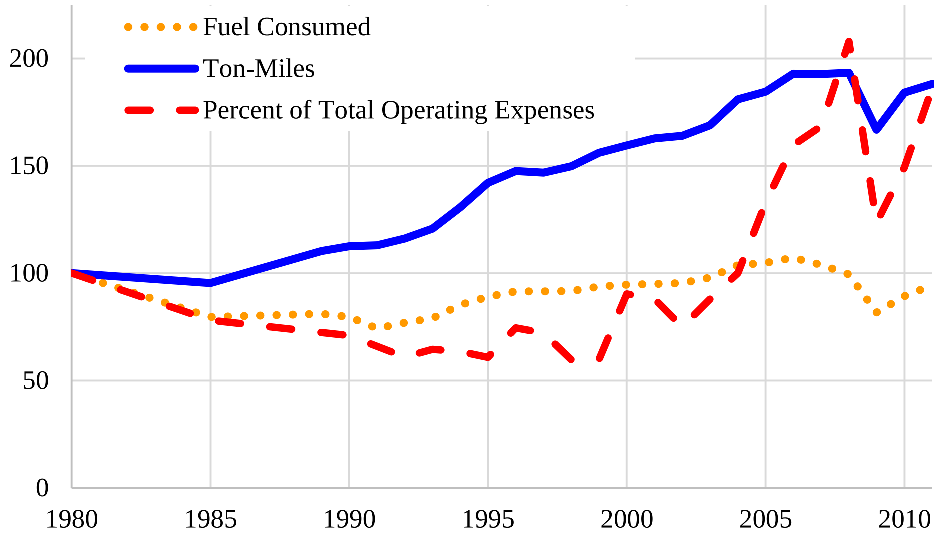

Figure 1. Fuel Consumption, Ton-Miles, and Percent of Operating Expenses Indexed to 1980 (AAR (2012))

portion of a railroad's operating cost. It is thus in the railroads best interest to explore alternative fuels as an approach to reduce fuel costs.

The second motivating factor is legislative pressure. The U.S. Environmental Protection Agency (EPA) has instituted a tiered emissions program for locomotives as an attempt to reduce emissions from the transportation sector. After 2014, all newly manufactured locomotives must adhere to an emissions limit 90 percent below pre-2000 levels (EPA (2004)). The mandate adds a fourth "tier" to the locomotive emission standards legislated by the EPA (EPA (2004)). Tier 4 locomotives likely represent the lowest possible emissions levels for a conventional diesel-electric locomotive (Stodolski (2002)). Further reductions would require a departure from conventional diesel-electric technology to include after-treatment systems or a completely new technology or different energy source. Any of these options introduces operational challenges including the logistics of distributing alternative after-treatment chemical and fuel distribution, management of a fleet of alternative fuel locomotives, and the substantial cost of new infrastructure requirements.

Reductions in locomotive emissions have been achieved within certain urban non-attainment areas with strict emissions standards via the deployment of new locomotive technology in captive yard and terminal switching service. When locomotives rarely travel far from their home facility or never leave the non-attainment area, there are fewer operational obstacles to replacing them with new, low-emissions locomotive technology. Reducing the emissions of line-haul, mainline freight traffic within the same urban non-attainment areas poses a more difficult operational challenge. The economics and the practicalities of a phased transition to new technologies may dictate that initial operations using a new locomotive technology are confined to portions of the freight rail network in non-attainment areas. In both of these cases, a tethered fleet that is dedicated to, and not leaving, the non-attainment area may be necessary.

Most railroad freight traffic travels long distances so it will encounter multiple non-attainment areas. Also, most of the proposed technologies do not have the energy capacity to complete the long hauls (Stodolsky (2012)). A tethered regional fleet within each area would require a locomotive change at the boundaries of the non-attainment areas as trains enter and leave while using conventional locomotives outside the area. Such mid-route locomotive changes are rare in North American freight railroad operations. The major rail roads in North America have standardized their diesel-electric locomotive fleets to support interoperability on the majority of routes. It is common for multiple railroads to operate a single, long-distance train using a pool of locomotives and railcars from multiple carriers and private owners. These "run-through trains" traverse the entire route on track owned by several different railroads. Railroads have worked to remove barriers thereby allowing the seamless movement of freight, resulting in great efficiencies. These efficiencies enable railroad intermodal service to compete with trucks for long-distance movement of time-sensitive freight.

Exchanging locomotives at one or more intermediate point will disrupt this seamless movement of freight. According to a study by Cambridge Systematics (2012), the direct cost of delay to trains at locomotive exchange points, and the potential for a shift of time-sensitive freight to the highway mode associated with this delay, is often cited as an impediment to deployment of new locomotive technology (Cambridge Systematics (2012)). Previous studies of alternative locomotive technology in North America have only described this effect in a qualitative or anecdotal manner. However, Fagan and Vassallo (2007) concluded that in Europe, motive power changes at international borders influences freight rail efficiency and market share. They stated that the elimination of barriers to interoperability could increase European freight rail market share 16 percent while Walker et. al. (2008) stressed the importance of interoperability of freight rail networks in order to compete with trucks for freight market share.

The aim of this research is to offer quantitative data on locomotive exchange delay and resulting freight modal shift in North America. This will be accomplished in two steps: determining a range of potential delay times at locomotive exchange points, and then developing an appropriate freight modal-shift model to calculate the impact of this delay on specific commodity groups being moved different distances. We will describe approaches for accomplishing both steps and illustrate the impact of locomotive exchange on three types of freight train service over varying shipment distances via a case study.

2 Methodology

The first step in quantifying the impact of locomotive exchange on line-haul freight rail operations is quantifying the delay to each train at a locomotive exchange point. This locomotive exchange yard will consist of an incoming lead track connecting to the mainline, the locomotive exchange facility tracks, and the outgoing connection to the mainline. Each of these three yard components has an associated delay. These can be further divided into two parts, the time it takes to complete each step in the process and the queuing time for each step given its respective capacity constraints. Determining the process times is best done through observation of actual train operations as they are difficult to quantify analytically. The queuing delays can be quantified using an appropriate queuing model. In this case, an M/D/1 model is applied to each lead and an M/M/n model is applied to the exchange facility tracks. The sum of these calculated times is then taken as the total delay experienced by a train due to the locomotive exchange process. This delay value is later applied to the mode shift model when the rail traffic impacts of the delay are calculated.

2.1 Locomotive Exchange Times.

Most trains in North America only have locomotives on the front end. This exchange would require two tracks of sufficient length and a crossover positioned at the front of the train for locomotive movement. However, placing locomotives in the middle or at the end of a consist combined with the locomotives at the head-end, known as “distributed power” (DP), is becoming increasingly common for the railroads in North America. Distributed power allows for increased economies of scale through longer trains while reducing in-train forces and improving braking performance. In order to accommodate DP, the exchange facility would need to have ample, properly spaced universal crossovers to allow for full operational flexibility during the exchange.

At a locomotive exchange point, removing locomotives from the end and middle of the train without fouling the lead tracks for extended periods requires several intermediate crossovers (Figure 2). Each high-level step in the exchange process consists of several smaller steps such as throwing switches, applying hand brakes and performing locomotive brake tests. These steps also require crew members to walk to various points in the train and to different turnout locations. The time required to perform these activities will vary with crew experience, time of day and weather conditions.

To capture and quantify these processes, a full-scale simulation of a locomotive exchange was performed at the Union Pacific Railroad Global 3 yard in Rochelle, Illinois, USA. The yard crew configured a train on a staging yard track with a single locomotive at both the front and end of the train as if it had just arrived in a locomotive exchange point from the mainline. The crew then simulated the process of securing the train, uncoupling the locomotives from the consist and moving them to an adjacent track. The crew then moved the locomotives back to the original track as a means to simulate a exchange to new technology locomotives, recoupling them to the consist and performing the required brake tests and distributed power link configuration between the front and rear locomotives. The times for each step in the process were recorded (Table 1).

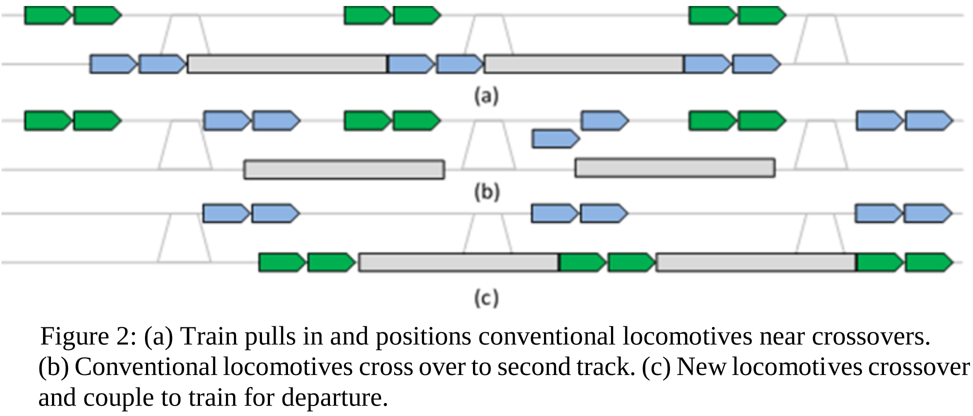

Figure 2: (a) Train pulls in and positions conventional locomotives near crossovers. (b) Conventional locomotives cross over to second track. (c) New locomotives crossover and couple to train for departure.

Table 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 specific configuration of locomotives within a train consist can greatly affect the exchange time, particularly for mid-train DP, because of the number and complication of the moves required to separate and recombine a train consist. The results from the full-scale experiment were extrapolated to estimate times for general cases of the four different DP configurations (Table 2). Each scenario is labelled as n-n-n: with each character corresponding to a locomotive consist position (front-middle-rear) and the number of locomotives in that position. For example, the front-only scenario with two locomotives can be represented as 2-0-0 while a train with three locomotives at the front, two in the middle and one at the rear would be 3-2-1.

Table 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**

The exchange times represent the critical path of the locomotive exchange meaning that they only include tasks that cannot be done concurrently. 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 or while a train is arriving and thus the overall exchange time is not affected. It is important to note that values presented in Table 2 do not account for time spent occupying the lead during arrival and departure as well as acceleration and deceleration time from and to mainline track speed. However, the values due include factors to account for crew experience and weather conditions in an attempt to provide conservative estimates of the required exchange time.

The times calculated represent an ideal case in which the headway between trains is not less than the time it takes to process the train before it, or the facility is large enough to accommodate every incoming train resulting in no additional queue time. This will rarely be the case for North American freight trains that arrive at closer intervals on a semi-random basis depending on service demands and delays elsewhere in the system. Even though terminal facilities are often sized to handle a peak load of 2.5 times the expected average number of trains per hour, bunched trains and competing train and locomotive movements on the lead tracks can lead to queuing delays. To account for potential additional delays due to queuing, an M/D/1 queuing model is applied to the lead track and an M/M/N (also known as M/M/c) queueing model is applied to the exchange point, as described in the following section.

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

When a train on the mainline is preparing to enter the locomotive exchange facility, 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 will be sized on the basis of 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 short with little variation. Following the nomenclature from “Principals of Highway Engineering and Traffic Analysis” by Mannering et al (2009), the average queue time under the given parameters can be calculated using [1]-[3]

$$\rho = \frac{\lambda}{\mu}. \tag{1}$$

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

.

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

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 dividing the daily flow rate of the 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 that requires two 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.

2.3 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 which assumes that trains arrive according to a rate with Poisson distribution, the processing times are exponentially distributed, and there are more than one servers (exchange tracks) 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 a relatively large sum of a series of individual sub-events. Deviation from the mean processing time has the potential to significantly affect results.

The assumption of independent parallel processes is simplifying in that there is potentially 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 . 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, it is important to note that trains queuing on the mainline would incur additional delays on any run-through traffic as well as on trains flowing through the facility against the direction of the queue. [4]-[6] provide the average queuing time for the given parameters. (Mannering et al (2009))

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

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

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

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)

As is evident from [4] and [5], if $\rho/N=1$ (i.e. the number of tracks requires 100 percent utilization to accommodate the average train flow rate) the equation is unsolvable. 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.

2.4 Mode Shift

The modal split between truck and rail was calculated using 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 value, and truck and rail shipment distance. The model calculates a predicted freight rail market share for nine individual commodity groups (Table 3) created on the basis of shipment value. The Standard Classification of Goods (SCTG) codes and 2-digit general Standard Transportation Commodity Codes (STCC) are assigned to the generalized groups as shown. Two different codes are assigned because the data in the model were acquired from two different sources: the Bureau of Transportation Statistics (BTS) and the Surface Transportation Board (STB) which use the SCTG code and STCC respectively to classify shipments.

Table 3: STCC Codes and Descriptions Corresponding to Value-Based Commodity Groups ((FHWA (2009); STB (2011))

Commodity Group	SCTG	STCC	STCC Commodity Description
1	1-3, 5	01	Farm Products
		09	Fresh Fish or Other Marine Products
2	4,6,7	21	Tobacco Products; except Insecticides
		20	Food or Kindred Products
3	10-12, 14	10	Metallic Ores
		32	Clay, Concrete, Glass or Stone Products
4	15-19	11	Coal
		13	Crude Petroleum, Natural Gas or Gasoline
		29	Petroleum or Coal Products
5	8,9, 20-24	28	Chemicals or Allied Products
		30	Rubber or Miscellaneous Plastics Products
		48	Hazardous Wastes
		49	Hazardous Materials
6	25-30	08	Forest Products
		22	Textile Mill Products
		24	Lumber or Wood Products; except Furniture
		26	Pulp, Paper or Allied Products
		27	Printed Matter
		31	Leather or Leather Products
7	13, 31-35	14	Nonmetallic Minerals; except Fuels
		19	Ordnance or Accessories
		33	Primary Metal Products, including Galvanized
		34	Fabricated Metal Products; except Ordnance
		35	Machinery; except Electrical
		36	Electrical Machinery, Equipment or Supplies
8	36-38	37	Transportation Equipment
		38	Instruments, Photographic Goods, Optical Goods, Watches or Cl
9	39-43	23	Apparel, or Other Finished Textile Products or Knit Apparel
		25	Furniture or Fixtures
		39	Miscellaneous Products of Manufacturing
		40	Waste or Scrap Materials Not Identified by Producing Industry
		41	Miscellaneous Freight Shipments
		42	Containers, Carriers or Devices, Shipping, Returned Empty
		43	Mail, Express or Other Contract Traffic
		44	Freight Forwarder Traffic
		45	Shipper Association or Similar Traffic
		46	Miscellaneous Mixed Shipments
		47	Small Packaged Freight Shipments
		50	Bulk Commodity Shipments in Boxcars

The base case for the model calculates the truck and rail market share for equal shipping distances. As travel time is not an input for the model, truck shipping distance is used as a proxy for travel time in order to evaluate the impact of locomotive exchange delay on rail market share. Truck shipment distance is shortened by taking the proportion of the original travel time and the shortened travel time accounting for rail delay [7]. An average truck speed is also needed to complete the calculation. Assigning tonnages and revenues per ton-mile to each group allows for a comparison of different shipment values and priorities, such as comparing intermodal traffic to manifest carload traffic.

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

where:

D^* = modified truck distance
D = original shipment distance
V_T = average truck velocity
T_E = exchange point delay

3 Case Study

In order to quantify the magnitude of the potential impact of locomotive exchange delay on railroad traffic, a case study is performed on a theoretical exchange facility built to accommodate a mainline with 48 freight trains per day. It is assumed that all freight trains in both directions will need to enter the exchange facility to exchange locomotives.

The baseline freight modal split between truck and rail is strongly influenced by shipment distance because it takes a certain shipment length for the economics of rail to surpass the speed of trucks. Depending on the base shipment distance, a given delay could impact the mode share differently. To study these impacts, three shipment distances – 1,000, 1,750, and 2,500 miles – are analysed at the three delay times corresponding to exchange of 2-0-0, 2-0-2, and 2-2-2 locomotive configurations. These nine case study conditions are repeated for three different train operations: priority intermodal, general manifest, and bulk unit trains.

The number of track pairs (N) available within the facility is calculated depending on the locomotive exchange time for each case. Generally, a facility is designed to accommodate 2.5 times the expected number of trains based on a given train flow according to Little’s Law and an average train flow rate of two trains per hour [8] (Sztrik (2012)).

$$Expected\ Trains\ in\ Facility = Hourly\ Flow\ Rate\ \times\ Processing\ Time \tag{8}$$

Using this peaking factor and the given train flow rate, the facility would require 20 service channels or 40 tracks to effectively accommodate the traffic under the exchange time associated with a full 2-2-2 distributed power configuration. This may seem extreme but it is impractical to design a facility based on the hourly flow rate because of the unscheduled nature of the North American freight rail network and the high probability of bunched trains and multiple train arrivals during a short duration. If operations only use the conventional head-end locomotive configuration, the facility can be reduced to 8 service channels.

Table 4 shows the difference in queuing delays for facilities designed for an hourly flow and a peak flow. It is expected that the delay times for the larger facility will be smaller but by sizing them for the peak flow, the average queue time becomes almost negligible.

Table 4: Exchange Facility Queuing Time Comparison

	2-0-0		2-0-2		2-2-2	
	N	$\bar{w}$ (hrs)	N	$\bar{w}$ (hrs)	N	$\bar{w}$ (hrs)
Average Hourly Flow	3	0.44	5	1.11	8	4.17
Peak Design Flow	8	1.91E-04	13	6.34E-05	20	2.52E-05

The larger facilities will be used for the rest of the analysis.

The total delays for each locomotive configuration and respective facility size that will be applied to the case study are shown in Table 5. The lead occupation comes from the combination of the time it takes for a train entering and leaving the yard, plus the time the locomotives occupy the lead when moving to and from the exchange tracks. For the train entering and leaving the yard, a design train length of 10,000 ft. traveling at a yard speed limit of 10 mph, means it would take 12 minutes to clear the lead. The locomotive moves are shorter and are estimated to only take 3 minutes on the lead. This gives a total lead occupation time of 30 minutes or 0.5 hours per train. The flow rate used in the lead queuing model is the inverse of the train processing time multiplied by the flow rate per hour. The time assumed for processing each move is 7.5 minutes, which is the average length of the moves that block the lead. This gives a μ of 8. The λ and μ values for the exchange queuing delay are 2 and 1/exchange time, respectively.

Table 5: Total Exchange Point Delay Times (hours)

Locomotive Configuration	2-0-0	2-0-2	2-2-2
Lead Occupation Time	0.50	0.50	0.50
Lead Queue Delay	0.09	0.11	0.12
Exchange Time	1.00	2.00	3.67
Exchange Queuing Delay	1.91E-04	6.34E-05	2.52E-05
Total Delay	**1.59**	**2.61**	**4.29**

The mode shift model is performed on three different commodity distributions corresponding to typical North American intermodal, manifest, and bulk train movements (Table 6). The values per ton were calculated using the value and tons data from the BTS Commodity Flow Survey for 2007 for all U.S. shipments. Table 6 also details the commodity-specific revenue for each train service type. The remaining parameters were calculated using the STB Waybill database, aggregated by the given service type designation of either 1 for manifest or 2 for intermodal. The percentage of cars is the total for all shipments of each shipment type. The values per ton, tons per car and revenues per ton-mile are weighted averages of the shipment level data for each group and shipment type accordingly. The bulk train used in this case study is carrying grain rather than a representation of all bulk traffic as are the intermodal and manifest trains.

Table 6: Case Study Inputs ((BTS (2009); STB (2011))

Group	Commodity Description	Value per Ton ($)	Intermodal			Manifest			Bulk		
			% of Cars	Tons/ Car	Rev/ Ton-Mi.	% of Cars	Tons/ Car	Rev/ Ton-Mi.	% of Cars	Tons/ Car	Rev/ Ton-Mi.
1	Farm and Marine Products	1,421	2%	24	$0.03	1%	84	$0.05	100%	100	$0.03
2	Food or Kindred Products	899	4%	17	$0.05	12%	91	$0.04	-	-	-
3	Ore, Aggregates, and Glass	85	-	-	-	5%	105	$0.06	-	-	-
4	Coal, Gas, and Oil	506	-	-	-	1%	82	$0.06	-	-	-
5	Chemicals	9,239	6%	15	$0.07	31%	91	$0.05	-	-	-
6	Wood and Textiles	2,854	3%	14	$0.05	3%	80	$0.06	-	-	-
7	Metal Products and Machinery	6,564	2%	13	$0.08	43%	92	$0.07	-	-	-
8	Transportation Equipment	36,202	3%	12	$0.09	4%	30	$0.14	-	-	-
9	Intermodal	4,780	79%	13	$0.06	6%	107	$0.06	-	-	-

As previously stated, the freight mode share model uses oil price, value per ton by commodity, truck distance, and rail distance in order to calculate the predicted rail mode share. (Hwang (2014)) The oil price used in the case study is the West Texas Intermediate (WTI) price per barrel average from 2013 of $97.91 (EIA (2014)). For a baseline case with no delay at each shipment distance, the truck and rail distances are assumed to be equal. The truck distance is adjusted using [7] according to the total delay for each scenario, outlined in Table 5.Once the rail market share is known, the total freight rail tonnage and revenue for each exchange delay case can be calculated using the number of cars, tons per car, and revenue per ton-mile values assuming a 100-car train (Table 6). These values are then compared to the no-delay baseline for each combination of train service, shipment distance and locomotive configuration. The percent changes in total rail tons and revenues for the different cases are calculated to evaluate the impact of delay on rail operations (Table 7).

The overall trend of these results is what might be expected: the longer delay times have a higher impact on market share and the longer rail shipments have a lower sensitivity to the exchange point delay. The more interesting result is the range of the magnitude of the impacts. The lowest predicted impact of about 3% for the long distance bulk train at the lowest delay would still cost the railroad almost $8 million per train per year. The maximum percent change in revenue of about 31% for the short haul manifest train at maximum exchange delay would cost the railroad $60 million per year for each daily train operated. According to the model, the highest absolute revenue loss per train is $128.6 million for the long haul manifest train with maximum delay over an entire year. It is highly unlikely that 100% of trains will have the 2-2-2 locomotive configuration so these numbers are greatly exaggerated. The average revenue lost is $32 million per year per train over all cases

It is evident that the manifest freight flow is more sensitive to mode shift than the intermodal traffic. The shipment values are equal so the rail mode share is the same, but the manifest flow had more tons of freight per car giving it higher revenues.

Table 7: Impact of Locomotive Exchange Delay on Total Rail Shipment Tons and Revenue (Percent Change from Case with No Delay)

		Total Tons			Total Revenue		
	Dist.	2-0-0	2-0-2	2-2-2	2-0-0	2-0-2	2-2-2
Intermodal	1000	-10.77%	-16.88%	-26.10%	-11.05%	-17.30%	-26.70%
	1750	-11.82%	-17.74%	-26.69%	-11.94%	-18.03%	-27.21%
	2500	-9.89%	-15.55%	-24.17%	-10.29%	-16.17%	-25.08%
Manifest	1000	-12.11%	-18.82%	-28.72%	-13.00%	-20.14%	-30.55%
	1750	-11.32%	-17.65%	-27.03%	-12.27%	-19.06%	-29.03%
	2500	-9.85%	-15.50%	-24.09%	-10.75%	-16.88%	-26.12%
Bulk	1000	-8.76%	-13.88%	-21.81%	-8.76%	-13.88%	-21.81%
	1750	-7.19%	-11.50%	-18.37%	-7.19%	-11.50%	-18.37%
	2500	-3.11%	-5.10%	-8.52%	-3.11%	-5.10%	-8.52%

4 Conclusions

The results of the case study suggest that there are potentially large and costly impacts on market share due to locomotive exchange delay. The lost revenues for the general case study range from $3 million to $130 million with an average of $32 million. For a conservatively designed facility, the lead queue is the bottleneck for the system, but a more economical facility would see queuing delays for the exchange tracks significantly impacting overall exchange time. This would further increase the modal shift to truck as indicated by the negative trend of lost revenues for higher delays.

In practice, mode choice is determined by the factors in the model, along with factors such as mode accessibility, prior contracts, business relationships, convenience, etc. These external factors are difficult to quantify so the model is likely to overestimate freight modal split. Lost revenues are only part of the total economic impact of locomotive exchanges. Railroads will incur the capital cost of building the exchange facilities, buying additional locomotives, building or modifying maintenance facilities, and any other infrastructure required to support or operate alternate technology locomotives.

Queuing could have a more substantial impact on delays in an actual yard because, as mentioned above, the yard will be sized according to a distribution of the exchange times rather than assuming that all trains will be the worst case scenario. With a smaller facility, multiple 2-2-2 distributed power trains arriving at once will incur more delay. External factors such as irregular locomotive configurations, locomotive shortages, crew availability, and seasonal peaking could all affect the exchange process making the distribution of times wider and creating larger queuing delays. The exchange process may also become a severe bottleneck when the railroad is trying to operate at maximum capacity to recover from delays, track maintenance, derailments, or other service disruptions on the route. If the exchange point processing capacity is too far below the practical short-term capacity of the nearby mainline, the route may never have the ability to recover from the disruption without large numbers of train cancellations and forgone revenue from shipment demand.

The economic impact from the locomotive exchange delays is not unique to the railroads; less freight on the railroads means more freight on the highway. The negative externalities due to more trucks on the highway, including increased congestion, highway delay, pavement damage, emissions, could offset any benefits gained from reduced emissions of line-haul freight train operation. A railcar is about three times the capacity of a truck and 3-4 times more fuel efficient so legislation to improve emissions from the rail sector has the potential to actually increase freight transportation emissions.

EPA non-attainment areas where line-haul freight operations may be targeted for emission reductions are also the primary destinations for freight as they correspond to major population centers. It is not uncommon to have several similarly-sized freight flows from different origins coming into a populous city, especially one with a port. Enacting a clean line-haul locomotive area would require taking this analysis and applying it to all rail lines flowing into and through the non-attainment area and multiplying the impacts summarized above by the number of impacted rail lines. Shipments that completely transit the area would be subject to double exchange point delays, further increasing the likelihood of their shift to another freight transportation mode.

5 Further Study

For future analysis of specific non-attainment areas, the model parameters should be adjusted to represent the actual properties of the area the actual trains operations on impacted mainlines. Distributions of shipment values, revenues, distances, and DP configurations should be estimated for the area to make the model more robust for the specific analysis.

The queuing model is also a subject of further research. The assumptions of exponentially distributed exchange times, randomly distributed traffic, and the independence of the lead and exchange facility queues should be further examined to improve the analysis. Simulation software will be utilized to help determine the validity of these assumptions.

Acknowledgements

This research is sponsored by the National University Rail (NURail) Center, a Tier-1 University Transportation Center (UTC) under the United States Department of Transportation (USDOT) Office of the Assistant Secretary for Research and Technology (OST) program. The authors would also like to thank Mike Iden and Bob Toy of Union Pacific Railroad for arranging the full scale locomotive exchange trial at the Global 3 yard in Rochelle, Illinois in August 2014.

References

Association of American Railroads, 2012, "Railroad Facts, 2012 Edition". Washington D.C.

Cambridge Systematics Inc., 2012. “Task 8.3 Analysis of Freight Rail Electrification in the SCAG Region”, *Comprehensive Regional Goods Movement Plan and Implementation Strategy,* pp 4-28 Prepared for the Southern California Associate of Governments.

Hwang T., Ouyang, Y., 2014. “Freight Shipment Modal Split and its Environmental Impacts: an Exploratory Study”, *Journal of the Air & Waste Management Association,* 64:1, 2-12, DOI: 10.1080/10962247.2013.831799

Mannering, F.L., Washburn, S.S., Kilareski, W.P., 2009. “Queuing Theory and Traffic Flow Analysis”, *In: Principals of Highway Engineering and Traffic Analysis 4th ed.,* John Wiley and Sons, Inc.

Stodolski, F., 2002. “Railroad and Locomotive Technology Roadmap” U.S. Department of Energy, Report ANL/ESD/02-6, Argonne, Il. Sztrik, J., 2012. “Basic Queuing Theory”. University of Debrecen, Debrecen, Hungary

U.S. Bureau of Transportation Statistics, 2009. “O-D Geography by Commodity” In: 2007 Commodity Flow Survey, U.S. Department of Transportation, Washington, D.C.

U.S. Energy Information Administration, 2014. “Short-Term Energy Outlook November 2014”, Washingotn D.C.

U.S. Environmental Protection Agency, 2004. “Regulatory Announcement: Clean Air Nonroad Diesel Rule”, Report EPA420-F-04-032, Ann Arbor Michigan.

U.S. Federal Highway Administration, 1997, “FAF Commodity Classification” U.S. Department of Transportation, Report R4, Washington D.C.

U.S. Surface Transportation Board, 2012. “2012 Surface Transportation Board Carload Waybill Sample”, U.S. Department of Transportation, Washington, D.C.

Vassallo, J., Fagan, MA., 2006. "Nature or Nurture: Why Do Railroads Carry Greater Freight Share in the United States Than In Europe?", *Transportation, Vol. 34(2), pp 177-193.*

Walker, Warren E., et al. "Assessing barriers to improving rail interoperability in European countries." *Transportation Research Record: Journal of the Transportation Research Board,* 2043.1 (2008): 20-30, Washington, D.C.