Determining Freight Train Delay Costs on Railroad Lines in North America

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Abstract

Delayed freight trains inflict costs on many different stakeholders including the railroad, shippers, and the public. Quantifying the cost of train delay experienced by each group of stakeholders is necessary to understand the impact of a track outage or other operational disturbance, or to conduct a benefit-cost analysis to justify potential line capacity improvements. The railroad delay costs vary greatly based on the train composition and operating conditions, so a single value is not sufficient. Outside of the railroad, shippers are concerned about the cost of delayed cargo and the cost of holding additional inventory due to uncertainty in delivery times. The public may be concerned with environmental effects of increased idling as well as delay to roadway traffic at level crossings. This paper details the cost components applicable to each of the stakeholders and a methodology to determine the delay cost under three distinct operating situations: bulk, manifest, and intermodal trains.

Keywords

Train delay, delay costs, shipper impact, public impacts

1 Introduction

There are many stakeholders affected by the performance of freight trains, including the railroads, shippers, and the public. In the North American market, where the railroads both own the track and operate the freight trains, the costs of delayed trains are considered internally. This differs from many foreign contexts where delay penalty costs are often negotiated explicitly in the contracts between train operators and rail infrastructure owners. Outside of railroad costs, shippers are affected by both the declining value of goods and the cost of holding inventory due to uncertainty in delivery times. There are also externalities experienced by the public in the form of emissions and level crossing delays that can be attributed to train delay. Since the costs of these externalities aren't explicitly incurred by the railroad, they may not consider them when using delay costs as input to maintenance and infrastructure planning.

There have been many attempts to determine the delay costs to railroads, and have resulted in values ranging from $200 to over $1,000 (Schafer and Barkan (2008); Dingler et al. (2011); Schlake et al. (2011); Lai and Barkan (2009); RSAC (1999); Smith et al. (1990)), but these do not appear to have considered all of the operational costs. Specific costs of train delay have been identified for individual public-private capital projects, such as the Tower 55 Surface Improvement Project (BNSF Railway Company (2015)), and some guidance is given for its calculation by the United States Department of Transportation

(USDOT) (USDOT (2014)). However, there does not appear to be a generalized approach to determining delay costs to all parties involved. While understanding the external costs may not be of direct interest to railroads, it can be beneficial when planning and financing improvements. If benefits to the other stakeholders can be identified, railroads can potentially negotiate financial assistance based on the cost reductions and public entities can justify appropriate contribution levels. In the case of shippers, this information can be beneficial for determining acceptable delivery windows and late fees.

Delay can be divided into two general categories: routine and irregular. Each of these will affect different types of costs and will occur under different circumstances. Routine delays are those experienced during normal operations, including crew changes, meets, passes, and civil speed restrictions. Irregular delays are those that would not be expected to occur on a typical run, including maintenance, accidents, and short-term speed restrictions based on track conditions.

This paper is broken into two parts: determining the costs associated with each stakeholder and determining how the costs apply to different train operations. Although the cost formulation here is for Class I railroads operating in the United States of America, similar analysis can be performed with infrastructure owners and railroad operators in other regions.

2 Costs Associated With Delay

There are a variety of costs associated with train delay experienced by all of the stakeholders, and they are largely unique to each. Since delay is difficult to measure directly, it is defined in this paper as the difference between the free-flow time to traverse the route at the posted maximum speed and the actual running time. This measure of delay includes any routine or irregular delays.

2.1 Railroad Costs

The railroad costs of train delay fall into five categories: crew, locomotives, fuel, railcars, and lading. These categories are largely drawn from the work of Schafer and Dingler (Dingler (2010); Schafer (2008)), but depending on how the trains are operated and where the delay is experienced, different categories of cost may or may not apply. Individual shipper-specific late fees negotiated with the railroad through private contract for particular shipments and services will not be considered in this analysis, as the costs involved are proprietary, difficult to generalize, and are relatively easy to apply in specific circumstances.

North American freight trains typically operate with two crew members. Due to restrictions on the working hours of train crews, train delay may result in the need to hire new personnel rather than having the existing crews work overtime. The cost of a new employee includes their hourly wage and fringe benefits. For 2012, the average train crew wage was \$27.89 per hour plus fringe benefits of 43% (STB (2012b); AAR (2012a)). This results in an average crew cost of \$79.53 per train-hour.

Locomotives can either be purchased or leased. A new mainline diesel-electric locomotive has a purchase price between \$1 and 2 million depending on the model and the options selected (Murray (2008)). With seasonal fluctuations in demand, locomotives are typically leased on a daily basis during specific periods when additional power is needed. Locomotives lease rates range from under \$100 to over \$500 a day depending on the model and condition (Kruglinski (2008)). Due to the variability in lease rates and the fact that only one-fifth of locomotives are leased in the United States (AAR (2012b)), this analysis considers the hourly locomotive ownership cost from its purchase price. The discounted annual purchase cost is determined using the reported purchase price of one common mainline locomotive of \$1.93 million and discount rate of 11% (Murray (2008); AAR (2012b)) along with assumptions of a \$200,000 salvage value and 25-year economic life (Dingler (2010)). This results in a locomotive ownership cost of \$26.36 per locomotive-hour. Additionally, the operating cost of a locomotive (excluding fuel) can be approximated as \$66.73 per locomotive-hour or \$1.90 per locomotive-km (\$3.05 per locomotive-mile) (AAR (2012b)). Since this paper deals primarily with the impacts of time delay, the hourly operating cost will be used.

Since the late 1970’s, almost all locomotives in North American freight service have been diesel-electric (Hay (1982)). The amount of fuel used by such locomotives in moving freight varies greatly according to the type of locomotive, number of locomotives, and operating conditions. For the purpose of this paper, the amount of fuel used per train-hour is approximated based on average duty-cycle throttle notch occupancy applied to an SD-70 locomotive (EPA (1998); Frey and Graver (2012)). For a fuel cost of \$0.84 per liter of diesel (\$3.17 per gallon) (AAR (2012b)), this results in an average running fuel cost of \$185 per locomotive-hour. If actual train and operation data are available, energy models or rail simulators may provide more accurate fuel use values for specific conditions.

The majority of North American freight railcars are not owned by the railroad (AAR (2012a)). To meet freight transportation demand, the railroad hires railcars from shippers or leasing companies. Car hire rates may have a time and distance component, but typically only the time-based rate is used (Buchanan (2009)). For some cars, these rates are contractually agreed upon, while others are publically available (R.E.R Publishing Corporation (2007)). The rates are based on the car type, age, value, and amenities. For railcars that are owned by the railroad, the car hire rate equates to an opportunity cost associated with the railroad either not being able to use that car elsewhere or having to hire a car from a leasing company rather than using the railroad-owned car. For this analysis, the values in Table 1 will be taken as representative.

Unless a shipper charges a late fee, there is not an explicit railroad cost to delayed lading. However the railroad is subject to an opportunity cost of foregone demand (and revenue) that occurs when delays prevent freight from being moved, either due to insufficient capacity to transport the delayed goods or the lading being shifted to a competing transportation mode. Under normal operations, trains are run such that there is excess capacity in the system, allowing for additional trains to be run during delay recovery periods to make up for missed shipping opportunities (AREMA (2010)). However, if the delay is too large or the line is being operated too close to the theoretical capacity, some trains may need to be canceled in order to maintain the flow of traffic, resulting in lost revenue. Another instance where the lading cost would be considered is if improvements increase the capacity of the line. In this case, the lading cost would indicate the additional revenue the railroad may be able to realize if there is additional demand. As lines through the country carry different types and amounts of freight, the lading cost will be different for each line, but average values can be used for illustration. For cases where lading is affected, the United States national average of \$2,594 per car and \$948 per intermodal container will be used (AAR (2012b); STB (2012b)). To determine the actual lost revenue per hour, the cycle time, empty return ratio, and car availability rate needs to be considered. Using the updated revenue per car and the methodology described by Dingler (Dingler (2010)), the hourly lading delay cost comes to \$523 per train-hour. For intermodal trains this value is \$1,172 based on Dingler's methodology and average intermodal revenue per container (Dingler (2010); STB (2012a)).

Table 1: Railroad cost categories and values

Cost Category	Hourly Cost
Crew (per train-hour)	$79.53
Locomotive ownership (per locomotive-hour)	$26.36
Locomotive operating (per locomotive-hour)	$66.73
Locomotive fuel (per locomotive-hour)	$185
Bulk cars (per car-hour)	$0.58
Manifest cars (per car-hour)	$0.84
Intermodal cars (per car-hour)	$1.00
Bulk and Manifest Lading (per car-hour)	$523
Intermodal Lading (per car-hour)	$1,172

2.2 Shipper costs

Railroad shippers incur two primary costs due to delays: inventory devaluation and holding costs. Every product has a useful life, either because it is perishable or becomes obsolete. The longer the good takes to arrive at the destination where it can be used, the less of that useful life is available for the end consumer. Different types of products have varying useful lives, and therefore different discount rates. For example, gravel would have a low discount rate because an additional day in transit would not have much effect on its useful life, but it would affect the shipper's ability to sell it. However, fruit would have a much higher discount rate because it is perishable (Winston & Shirley (2004)). While these costs are incurred any time goods are transported, shippers are more concerned with irregular delays because they result in additional transportation costs not already considered in their supply chain plans. Some recommended values are given in Table 2.

Table 2: Daily discount rates (Winston & Shirley (2004))

Commodities	Daily discount rate
Perishable	0.15
Bulk	0.05
Other	0.10

Part of the negotiation process between shipper and railroad is determining the window when deliveries can be expected to arrive, which are typically several hours long. If the deliveries are delayed more than a few hours, there may be a negotiated penalty to the railroad representing lost revenue or increased costs to the shipper. However, if delivery time is highly variable, due to travel time variability, the shipper will need to have larger safety stock. The holding costs of inventory are typically approximated as approximately 25% of the value of the good, but vary depending on the industry and location. A more complete description of how these costs can be calculated is found in Stock and Lambert (Stock & Lambert (2001)). Since holding costs are primarily affected by the variability of delivery rather than the absolute delay, they will not be considered explicitly in this paper.

2.3 Public Costs

The costs described in the previous section impact the public indirectly through increased cost of rail transportation and its corresponding effect on the cost of purchased goods. Two additional costs of train delay that impact the public are emissions and level crossing delay. These costs are externalities because neither the railroad, shippers, nor public are directly accountable for these costs.

When trains are delayed, they produce more locomotive emissions because they are on the line longer. The USDOT summarizes emissions costs in certain funding application resources. These costs are designed to take into account potential impacts to health, property value, and climate change (Office of Regulatory Analysis and Evaluation (2012)). Based on the operating characteristics of the SD-70 locomotive and the USDOT emissions costs, the emissions costs for an average hour of locomotive operation were calculated (Table 3) (USDOT (2014); Frey and Graver (2012)).

Table 3: Locomotive emissions cost

Pollutant	**Running Cost ($/locomotive-hour)**
CO_2	$25.35
NO_X	$103.02
PM	$175.42
Total	$303.79

The public is further impacted by train delay at level crossings. The longer a train takes to traverse a line, the longer level crossings are occupied, and the more drivers are delayed on average. Not all travelers value their time the same, but the values can be approximated in aggregate. It can be assumed that only travelers on local roads are affected since intercity routes are likely to be level separated. This results in a travel time value of $12.98 per person-hour assuming a mix of business and personal travelers (USDOT (2014)). For general analysis, it will be assumed that the delay is evenly distributed among all crossings on a line, but if certain crossings are known to accumulate more delay, then they should be weighted accordingly. The amount of road delay experienced by drivers can be calculated using

$$T_R = \frac{L_R}{S_R} + T_D, \tag{1}$$

$$T_X = (L_T + L_X)\frac{T_R}{L_R} + 2T_S, \tag{2}$$

$$C_X = \frac{1}{2}T_X^2 \times N_X \times N_V \times N_P \times C_P. \tag{3}$$

Where:

T_R – Time for a train to traverse the route
L_R – Route length
S_R – Nominal track speed
T_D – Additional time on the line
T_X – Average time each train occupies a crossing
L_T – Average train length
L_X – Average crossing length
T_S – Average time the crossing is activated before a train reaches the crossing and after it passes (time when the lights flash and horn sounds)
C_X – Crossing delay cost per train
N_X – Number of affected crossings
N_V – Average vehicle arrival rate at a crossing
N_P – Average number of people per vehicle
C_P – Average delay cost per person-time

3 Delay Applications

The previous sections provided a discussion of the various cost components attributable to train delay. However, different types of train operations will incur various combinations of these delay costs components in different manners. To illustrate this phenomena, this section examines the accumulation of delay cost for example operations of unit, manifest, and intermodal trains on three different route lengths: 805, 2,012 and 3,219 km (500, 1,250 and 2,000 miles). The general assumptions listed in Table 4 are used in all of the following example applications.

Table 4: Assumed parameter values for illustrative applications

Parameter	**Value**
Locomotive length	22.9 m (75 ft.) (EMD (2012))
Number of locomotives	3 (AAR (2012b)
Fuel cost	$185 per train-hour
Crew cost	$79.53 per train-hour
Locomotive ownership cost	$26.36 per locomotive-hour
Locomotive operating cost	$66.73 per locomotive-hour
Emissions cost	$304 per locomotive-hour
Railcar length	19.8 m (65 ft.)
Road user cost	$12.98 per person-hour (USDOT (2014))
Level crossing spacing	3.2 km (2 mile)
Vehicle arrival rate	500 vehicles/day
Average crossing length	9.1 m (30 ft.)
Average crossing activation time	30 sec
Average vehicle occupancy	1.36 (BTS (2012))

3.1 Unit Trains

Unit trains consist entirely of railcars that are all carrying a single good between the same shipper origin and destination. In this way they effectively work as a conveyor belt, moving goods from the source to the point of use without intermediate stops for switching or marshalling. For example, a coal train will take loaded cars from a mine to a power plant, and then return the empty cars back to the mine to be reloaded for the next trip back to the power plant. To illustrate the impact of train delay on such an operation, assume there is an average of one unit train departure per day and six hours of processing time per train at each end of the route for loading and unloading. Other variables and assumptions are given in Table 5.

Table 5: Assumed unit train parameter values

Parameter	**Value**
Line speed	40 km/h (25 mph)
Loading time	6 hours
Unloading time	6 hours
Service frequency	1 train per day
Train Length	99 railcars (Cambridge Systematics (2007); Dingler (2010))
Railcar cost	\$0.58 per car-hour (R.E.R Publishing Corporation (2007); Dingler (2010))
Consist	Railcars and locomotives remain together

As unit trains are delayed on the route, for every hour of delay they incur additional crew, fuel and locomotive operating cost at the hourly rates in Table 4. The relationship between delay and ownership cost of locomotives and railcars is slightly more complicated. Since the unit train locomotives and railcars are in dedicated service, for a period of months or years, the ownership cost of the rolling stock is fixed regardless of the delay it experiences while making trips between origin and destination. However, in order to provide the service frequency required by the shipper, the trainset must make a minimum number of trips during this period. If cumulative train delays prevent a trainset from achieving the required number of loaded trips, then additional trainsets must be added to the system to compensate for missed shipping opportunities and preserve overall traffic demand.

For a 2,012 km (1,250 mile) one-way route, the baseline cycle time with no delay is 112 hours (50 hours each way plus 12 hours of loading and unloading time). To meet the daily service requirement under these ideal conditions, five trainsets must operate continuously within the system. Every sixth train departure, at intervals of 120 hours, is served by the same trainset. Since a given trainset will arrive back at the loading origin 112 hours after it departed, there is an eight hour buffer built into the operation. Thus any delay less than eight hours is absorbed by this buffer time with no additional locomotive or railcar ownership cost. However, if the delay during a particular cycle exceeds 8 hours, the train will miss its next intended departure and a new trainset must be introduced into the system at additional railcar and locomotive ownership expense. The threshold delay at which this additional cost is incurred will vary with the service frequency and baseline cycle time (itself a function of route length and train speed).

Under these conditions, the cost of train delay per hour can be calculated as the incremental change in overall operating cost per hour of delay added to a given base cycle time. This is illustrated as the slope of the cost curve for several route lengths with varying amounts of delay shown in Figure 1. As described above since trainsets are a discrete asset, the addition of a trainset at critical threshold values of delay per cycle results in discontinuities of Figure 1 (e.g. 2,012 km route at 8 hours of delay). Given these discontinuities, the average slope equates to \$834 per train-hour of unit train delay for all route lengths.

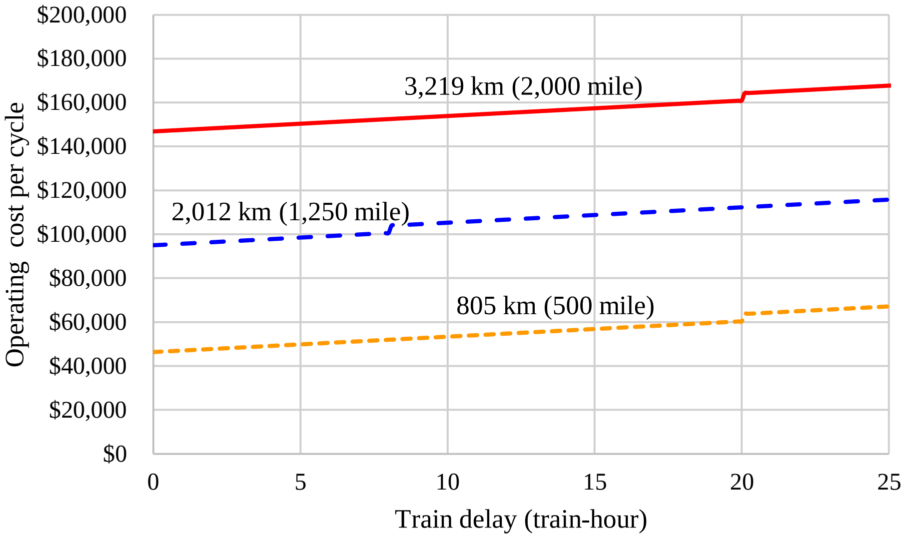

Figure 1: Variation of operating cost with respect to delay and route length

In this situation there should not be any additional impact to shippers since the average delivery rate will remain constant in the long term due to the addition of trainsets. However, there will likely be variability in actual arrival times, which will affect the necessary inventory safety stock. The public will be affected because more trains will be on the route for longer periods, resulting in higher emissions and level crossing occupancy. While the emissions per train-hour will remain constant, total emissions per cycle will increase with delay, and every time an additional trainset is needed, total emissions at a given point in time will increase.

For level crossings, Equations (1-3) can be used to calculate the delay cost associated with each train cycle. Assuming four hours of delay per cycle on an 805 km (500 mile) route, with the same level crossings affected on both legs of the cycle, the crossing delay cost is $11,572 per train or $2,893 per train-hour of delay. While the hourly railroad and emissions delay cost is comparable between the three route lengths, the hourly cost for level crossings is dependent on the number of crossings rather than just the cycle length, resulting in a non-linear relationship between train delay and level crossing delay cost. This can be seen in Figure 2, where the 805 km (500 mile) route begins with the lowest crossing cost, but as delay increases the cost difference decreases until the 805 km (500 mile) route has the highest cost. This is likely because higher delay results in a disproportional impact on each crossing on the shorter route.

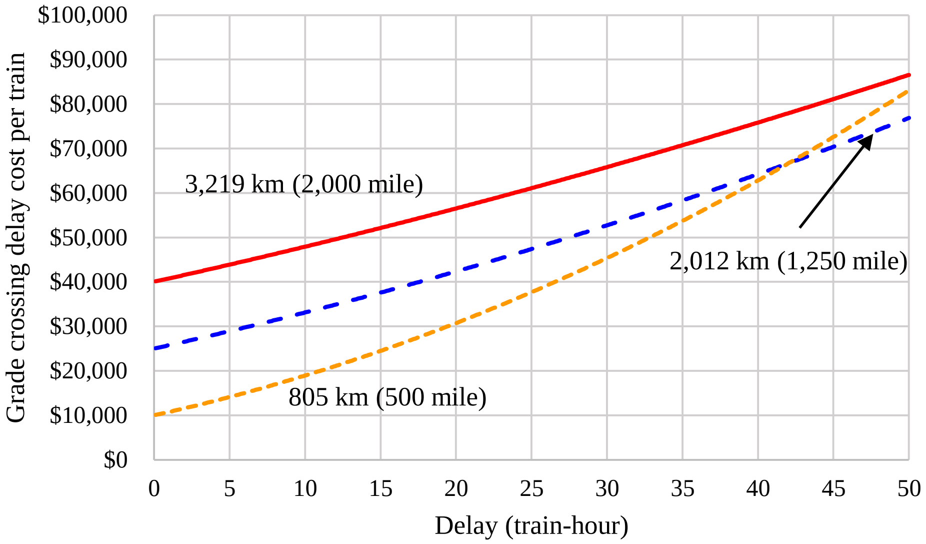

Figure 2: Variation of level crossing delay cost with respect to delay and route length

A summary of costs for four hours of delay is provided in Table 6. The values may vary because of averaging over the discontinuities.

Table 6: Incremental cost for four hours of delay per unit train-cycle

Cost Category	**805 km (500 miles)**	**2,012 km (1,250 mile)**	**3,219 km (2,000 mile)**
Locomotive ownership	$0	$0	$0
Locomotive operating	$267	$267	$267
Locomotive fuel	$2,221	$2,221	$2,221
Railcar	$0	$1,378	$0
Crew	$318	$318	$318
Emissions	$3,645	$3,645	$3,645
Level Crossing	$3,239	$3,103	$3,069

3.2 Manifest Trains

For manifest train operations, the rolling stock is not committed to a single origin and destination. Railcars and locomotives are used on any route they are needed for, and routes between major marshalling yards are dictated by freight transportation demand. In this case, each train can be considered independently when calculating line delay between yards. However, each delayed train has a probability of either delaying a subsequent train or having a cut of cars miss their connection at the next marshalling yard. Each car or locomotive in a manifest train has a given yard availability time measured as the difference between the rolling stock arrival time at the yard and its planned departure time. The probability of a railcar or locomotive making its intended connection, P-MAKE, is a function of the yard availability time and the efficiency of the yard operation. A more efficient yard will have a smaller required yard availability time to achieve a P-MAKE of 1 to guarantee a successful connection (Tykulsker (1981)).

The delay cost of a manifest train operating between terminals in this situation (Equation 4) consists of three parts: the line delay cost, the cost of the locomotives missing their connection, and the cost of the railcars missing their connection. This cost is given as

$$C_D = \big((C_O + C_F) \times N_L + C_W\big) \times T_D + \ C_{YL} + \ C_{YC}. \tag{4}$$

Where:
C_D – Cost of delay ($/train-hour)
C_O – Locomotive operating cost ($/locomotive-hour)
C_F – Fuel cost ($/locomotive-hour)
N_L – Average number of locomotives
C_W – Crew cost ($/train-hour)
T_D – Length of delay (hours)
C_{YL} – Cost of locomotives missing a connection
C_{YC} – Cost of railcars missing a connection

The average yard delay cost associated with the locomotives being delayed is

$$C_{YL} = (T_{YL}(T_D) - T_{YL}\ (0)) \times N_L \times C_L, \tag{5}$$
$$T_{YL}(t) = P_L(t) \times T_{AL} + \big(1 - P_L(t)\big) \times (T_{AL} + T_{LI}). \tag{6}$$

Where:
C_L – Locomotive ownership cost ($/locomotive-hour)
P_L – P-MAKE function for a locomotive with delay time t
T_{AL} – Average planned locomotive yard availability (hours)
T_{LI} – Average time between scheduled locomotive departures (hours)
Other variables as previously defined.

The average yard delay costs associated with railcars being late is

$$C_{YC} = \big(T_{YC}(T_D) - T_{YC}(0)\big) \times N_C \times C_C, \tag{7}$$
$$T_{YC}(t) = P_C(t) \times T_{AC} + \big(1 - P_C(t)\big) \times (T_{AC} + T_{CI}). \tag{8}$$

Where:
C_C – Average hourly car hire rate ($/car-hour)
N_C – Average number of railcars per train
P_C – P-MAKE function for a railcar with delay time t
T_{AC} – Average planned railcar yard availability (hours)
T_{CI} – Time between scheduled train (block) departures to destination (hours)
Other variables as previously defined.

An example will be provided using the assumptions above, and the values in Table 7.

Table 7: Assumed manifest train parameter values

Parameter	Value
Planned locomotive avail.	2 hours
Planned railcar availability	6 hours
Loco. departure interval	2 hours
Block departure interval	24 hours
Train length	81 railcars (Cambridge Systematics (2007))
Railcar cost	\$0.84 per car-hour (R.E.R Publishing Corporation (2007))
Lading cost	\$523 per train-hour
Consist	Cars and locomotives separate at yards and terminals

The probability of a railcar or locomotive making a connection is based on the yard and traffic conditions, but it is typically approximated with a straight line between a certain minimum and maximum availability time (Tykulsker (1981)). Given the planned locomotive and railcar availability (Table 7), and a delay time *t* the distribution of P-MAKE is assumed as

$$P_L(t) = \begin{cases} 0, & T_{AL} - t < 0.5\ hours \\ \frac{2}{5}(T_{AL} - t) - \frac{1}{5}, & 0.5 < T_{AL} - t < 3\ hours \\ 1, & T_{AL} - t > 3\ hours \end{cases} \tag{9}$$

$$P_C(t) = \begin{cases} 0, & T_{AC} - t < 2\ hours \\ \frac{1}{10}(T_{AC} - t) - \frac{1}{5}, & 2 < T_{AC} - t < 12\ hours \\ 1, & T_{AC} - t > 12\ hours \end{cases} \tag{10}$$

The form of the P-MAKE equations and the distribution of planned railcar connection times will combine to determine if the marshalling yard dampens or amplifies the line delay. For example, if a train consisting predominantly of railcars with planned connection times in excess of 12 hours arrives at the yard with little delay, very few railcars will experience a change in expected yard time and outbound delay. In this case the yard serves as a buffer, absorbing the line delay out of the system. However, if a train consisting predominantly of railcars with short planned connection times experiences a larger delay, almost all of the railcars will experience an increased probability of missed connection. In this case, the marshalling yard can amplify the line delay time, with the average railcar departing the terminal with even greater delay time than the initial arrival delay. As shown in Figure 3, locomotive and car yard costs increase until the probability of making a connection reaches zero. At that point the average amount of time a locomotive or car will wait in the yard is the sum of the planned availability and the departure interval. While the yard delay costs remain constant after that point, the train will still be accumulating delay on the line with direct costs of fuel and crew time.

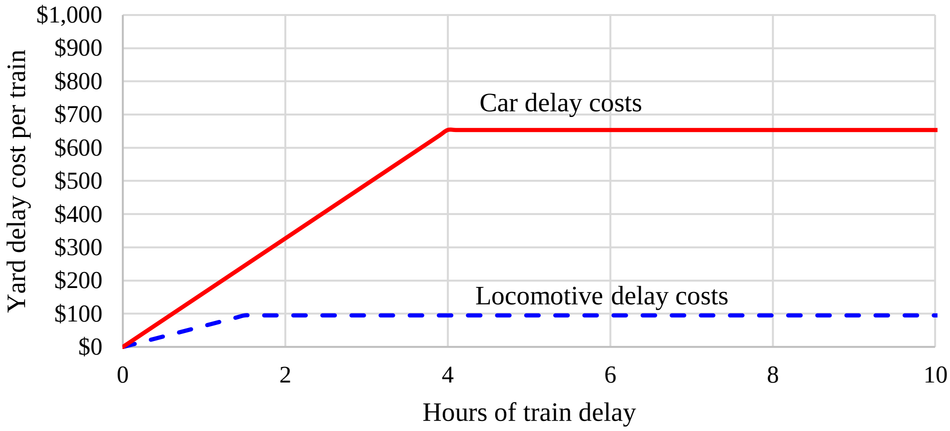

Figure 3: Yard delay cost

If a train is four hours late into the yard, the line delay cost would range from $4,088 to $6,180. If all trains during the service disruption can be accommodated though schedule adjustments, then the lower value can be used, but if all trains during the service disruption need to be canceled then the higher value should be used to consider the effects of forgone lading revenue. Since locomotive and railcar yard costs plateau, there is not a constant hourly delay cost. The hourly cost is $1,062 for the first 1.5 hours of delay, but then the hourly value declines as the fixed yard costs are distributed over more hours of delay. For 12 hours of delay, the average delay cost is approximately $900.

In this situation, there will be a delay cost to shippers. Due to the buffer time in the yard, the line delay does not directly translate to delay to the shipper. For a four-hour line delay, the yard will average less than half an hour of delay per car leaving the yard. Assuming the manifest trains are carrying goods that are neither perishable nor bulk, this would result in an overall average 0.2% reduction in the value of the lading for a four-hour line delay. However, if the intended route of the shipment requires connections at multiple marshalling yards, these costs will compound at each yard. Additionally, a more optimized yard with tighter planned connections will result in a higher average shipper cost for each hour of line delay because there will be a higher probability of a railcar or locomotive missing a connection if there are additional delays.

The costs to the public will be largely the same as in the unit train case. The emissions cost will not be affected directly by the yard delay because the locomotives will connect to the next train once they enter the yard, so only the line delay results in additional emissions. The level crossings are also only affected by the line delay, and calculated in the same manner as for unit trains (except only one direction should be considered). A summary of manifest train delay cost is provided in Table 8.

Table 8: Incremental cost for four hours of manifest train delay for different route lengths

Cost Category	805 km (500 miles)	2,012 km (1,250 mile)	3,219 km (2,000 mile)
Locomotive operating	$801	$801	$801
Locomotive fuel	$2,221	$2,221	$2,221
Crew	$318	$318	$318
Emissions	$3,645	$3,645	$3,645
Level Crossing	$2,429	$2,290	$2,255
Locomotive yard delay	$95	$95	$95
Car yard delay	$653	$653	$653

3.3 Intermodal Trains

From an operations perspective, intermodal trains have characteristics of both bulk and manifest trains. They typically travel in dedicated service between a port and an intermodal facility and back, similar to bulk trains. However, to accommodate preferred truck and business schedules at intermodal terminals, the time between unloading an intermodal train at a facility in the morning and its scheduled departure in the evening can be quite long. Due to this dwell time, the locomotives shift from one intermodal train to another like a manifest train. Since locomotives will be moved to other trains, locomotive delay cost will be similar to the manifest train. The railcar delay cost will be similar to the unit train because the cars are typically kept together rather than being separated and a new train being built. Since the railcars lay over at each intermodal terminal until the next scheduled departure, there is a buffer in the system to absorb railcar delay. However, locomotives will have tighter connections than the container and trailer shipments themselves, since they are decoupled from the railcars, will be directly impacted by line delay.

If containers or trailers are continuing by rail, they are typically removed from the railcar and transported to the new train by truck rather than the railcars themselves being interchanged (Rickett (2013)). Due to the higher priority of intermodal freight and its suitability for highway transport, there is a strong possibility of mode shift to highway as the delays increase. The mode shift can be determined by using a freight mode choice model. One such model was developed based on the value of the shipment, distance traveled by truck and rail, and the price of oil, with different model coefficients for each of ten classifications (Hwang (2014)). An example is shown using the values in Table 4 and Table 9.

Table 9: Assumed intermodal train values

Parameter	Value
Line speed	97 km/h (60 mph)
Total loading and unloading time	8 hours (Rickett (2013))
Train length	85 railcars (Cambridge Systematics (2007); Dingler (2010))
Railcar cost	$1.00 per car-hour (R.E.R Publishing Corporation (2007); Dingler (2010))
Deliveries per day	1
Revenue per container	$978 (STB (2012a))
Revenue per ton	$68 (STB (2012a))
Price of crude oil	$81 per barrel (Bloomberg (2014))
Lading cost per container-hour	$1,153
Consist	Locomotives change and railcars stay together

The minimum number of railcars required in the system are calculated in the same way as the unit trains, using the total loading and unloading times instead of the processing times. Since the locomotives will be shifted to other uses when the intermodal trains are not running, the loading and unloading times are not considered.

For this analysis, intermodal shipments are assumed to be “Furniture, mixed freight, and miscellaneous manufactured product” (Hwang (2014)), although a variety of goods are shipped via intermodal containers (STB (2012a)). Since the value of the freight is not generally known, it was approximated based on the average cost of shipping goods by intermodal and the assumption that shipping costs are approximately 25% of the value of the good. This resulted in an average value per ton of $272. The truck and rail shipment distances were assumed to be the same. To use the freight mode choice model to estimate mode shift due to train delay, the train shipment distance was increased proportionally based on the amount of train delay experienced.

Assuming an 805 km (500 mile) route with four hours of delay per direction, the rail distance would be 1,191 km (740 miles). Compared to the zero-delay condition, the rail mode share would be reduced from 4.9% to 0.3%. This is equivalent to a revenue loss of $207 per train. Since the lost revenue is a function of shipment distance, if the base route length is increased to 2,012 km (1,250 miles) and 3,219 km (2,000 miles), the lost revenue would be $574 and $1,034 per train respectively. This implies that for this particular commodity, the farther the freight is traveling, the larger the impact delay has on the mode shift. Note that this mode shift effect is very sensitive to commodity type and value, so the actual revenue loss will vary from these figures.

Due to the mode shift being a function of route length, the total train delay cost for each route length will vary. These are approximately $1,062, $1,138, and $1,258 for the 805, 2,012, 3,219 km (500, 1,250, and 2,000 mile) routes respectively. If the delay results in trains being canceled and revenue lost, then these values could increase to $2,215, $2,291, and $2,411 respectively depending on the severity of the disruption. A summary of incremental values is given in Table 10.

Table 10: Incremental delay costs for four hours of delay per intermodal train-route

Cost Category	**805 km (500 miles)**	**2,012 km (1,250 mile)**	**3,219 km (2,000 mile)**
Locomotive ownership	$105	$105	$105
Locomotive operating	$267	$267	$267
Locomotive fuel	$2,221	$2,221	$2,221
Railcar	$272	$272	$272
Crew	$318	$318	$318
Lading	$4,612	$4,612	$4,612
Mode shift (revenue loss)	$207	$574	$1,034
Emissions	$3,645	$3,645	$3,645
Level Crossing	$2,429	$2,290	$2,255

4 Conclusions

Many stakeholders are affected by railroad performance and train delay. The railroads are affected by the cost of locomotives, crews, fuel, railcars, and lost lading revenue. Shippers are concerned with the costs of holding inventory and the lost value of shipments. The public experiences the externalities of emissions and level crossing delays. Many of these are constant and continuous over different operating conditions, including crews, locomotive operations, car hire, fuel, lost shipment value, and emissions. Others have constant costs, but are accrued in discrete amounts, such as locomotive ownership. The rest are affected by the route length and other factors.

For certain common types of train operations in North America, these factors combine in specific ways to produce varying hourly train delay costs as summarized in Table 11. Bulk trains maintain a constant hourly delay cost across all route distances. In addition to crew, fuel and locomotive operating costs associated with line delay, the need to insert additional trainsets into a dedicated unit train operation contributes to their hourly delay cost.

For manifest trains, the hourly delay cost is a function of both the line delay cost and the sensitivity of planned yard operations to inbound delays. Marshalling yards can either absorb or amplify line delay, depending on the efficiency of the yard operation, planned connection times and amount of inbound line delay. Shipments that travel through multiple marshalling yards may be subject to compounding delays that will affect their associated delay cost.

For intermodal trains, due to the high potential for mode shift to the highway and lost revenue, the hourly delay cost is greatly influenced by the type of goods being shipped and the distance traveled. Shippers will experience similar cost variations.

Although several train types exhibit relationships where an hour of train delay has equal cost regardless of route length, this does not imply that all of these trains have the same sensitivity to delay. Although the cost of an hour of train delay is equal, the delay cost for a short route represents a larger share of the revenue than the same delay on a long route. Thus the profitability of trains operating short distances is more sensitive to train delay than those operating over longer distances. From an occurrence perspective, many railroad operations in North America establish line capacity according to a specific level of service measured by delay per 100 train-miles (Sogin et al. (2012)). Thus, trains operating over longer routes are likely to accrue more total train delay cost than those operating over shorter routes.

Emissions costs have a constant value, but will vary based on the types of pollution considered and the number and type of locomotives in use. The delay to drivers at level crossings will vary based on the route length, crossing spacing and traffic, and the number of trains per day. However, if all of these are held constant expect for route length, each hour of delay will have an increasing per hour cost for shorter routes.

Since they include yard & terminals and are based on entire train operating cycles, the hourly delay costs provided in Table 11 and the methodology used to calculate them are an improvement over previous published values that only examined the direct costs of delay on line-haul operations. Practitioners can use this approach and the presented generalized values to help in evaluating the benefits and costs of planned track maintenance and capital infrastructure expansion activities. They can also be used by practitioners when evaluating line capacity and the cost of delay associated with heterogeneity between different types of trains.

Table 11: Variable railroad train delay costs for different route lengths

Cost Category	**805 km (500 miles)**	**2,012 km (1,250 mile)**	**3,219 km (2,000 mile)**
Bulk trains	$834	$834	$834
Manifest trains (no lading cost)	$900	$900	$900
Manifest trains (with lading cost)	$1,423	$1,423	$1,423
Intermodal (no lading cost)	$1,062	$1,138	$1,258
Intermodal (with lading cost)	$2,215	$2,291	$2,411

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