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Pipeline and Hazardous Materials
Safety Administration

# COST OF DELAY FROM HAZMAT RAIL INCIDENTS

***Office of Planning and Analytics***

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## Notice

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This report presents the results of research estimating the social cost of delay resulting from hazardous material in rail incidents. The analysis estimates the delay experienced by freight and passenger rail, and roadway users due to track closures resulting from rail incidents due to the presence of hazardous materials. Delay occurs due to trains waiting for track to reopen or rerouting around incident sites. Costs include additional crew hours, passenger wait time, the opportunity cost of locomotives and railcars, fuel, and emissions.

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**Standard Form 298 (Rev. 8-98)**
Prescribed by ANSI Std. Z39.18

| * (MODERN METRIC) CONVERSION FACTORS | | | | |
|---|---|---|---|---|
| **APPROXIMATE CONVERSIONS TO SI UNITS** | | | | |
| **Symbol** | **When You Know** | **Multiply By** | **To Find** | **Symbol** |
| | | **LENGTH** | | |
| **in** | inches | 25.4 | millimeters | mm |
| **ft** | feet | 0.305 | meters | m |
| **yd** | yards | 0.914 | meters | m |
| **mi** | miles | 1.61 | kilometers | km |
| | | **AREA** | | |
| **$in^2$** | square inches | 645.2 | square millimeters | $mm^2$ |
| **$ft^2$** | square feet | 0.093 | square meters | $m^2$ |
| **$yd^2$** | square yard | 0.836 | square meters | $m^2$ |
| **ac** | acres | 0.405 | hectares | ha |
| **$mi^2$** | square miles | 2.59 | square kilometers | $km^2$ |
| | | **VOLUME** | | |
| **fl oz** | fluid ounces | 29.57 | milliliters | mL |
| **gal** | gallons | 3.785 | liters | L |
| **$ft^3$** | cubic feet | 0.028 | cubic meters | $m^3$ |
| **$yd^3$** | cubic yards | 0.765 | cubic meters | $m^3$ |
| NOTE: volumes greater than 1000 L shall be shown in $m^3$ | | | | |
| | | **MASS** | | |
| **oz** | ounces | 28.35 | grams | g |
| **lb** | pounds | 0.454 | kilograms | kg |
| **T** | short tons (2000 lb) | 0.907 | megagrams (or "metric ton") | Mg (or "t") |
| **oz** | ounces | 28.35 | grams | g |
| | | **TEMPERATURE (exact degrees)** | | |
| **°F** | Fahrenheit | 5 (F-32)/9<br>or (F-32)/1.8 | Celsius | °C |
| | | **ILLUMINATION** | | |
| **fc** | foot-candles | 10.76 | lux | lx |
| **fl** | foot-Lamberts | 3.426 | candela/$m^2$ | cd/$m^2$ |
| | | **FORCE and PRESSURE or STRESS** | | |
| **lbf** | poundforce | 4.45 | newtons | N |
| **lbf/$in^2$** | poundforce per square inch | 6.89 | kilopascals | kPa |
| **APPROXIMATE CONVERSIONS FROM SI UNITS** | | | | |
| **Symbol** | **When You Know** | **Multiply By** | **To Find** | **Symbol** |
| | | **LENGTH** | | |
| **mm** | millimeters | 0.039 | inches | in |
| **m** | meters | 3.28 | feet | ft |
| **m** | meters | 1.09 | yards | yd |
| **km** | kilometers | 0.621 | miles | mi |
| | | **AREA** | | |
| **$mm^2$** | square millimeters | 0.0016 | square inches | $in^2$ |
| **$m^2$** | square meters | 10.764 | square feet | $ft^2$ |
| **$m^2$** | square meters | 1.195 | square yards | $yd^2$ |
| **ha** | hectares | 2.47 | acres | ac |
| **$km^2$** | square kilometers | 0.386 | square miles | $mi^2$ |
| | | **VOLUME** | | |
| **mL** | milliliters | 0.034 | fluid ounces | fl oz |
| **L** | liters | 0.264 | gallons | gal |
| **$m^3$** | cubic meters | 35.314 | cubic feet | $ft^3$ |
| **$m^3$** | cubic meters | 1.307 | cubic yards | $yd^3$ |
| **mL** | milliliters | 0.034 | fluid ounces | fl oz |
| | | **MASS** | | |
| **g** | grams | 0.035 | ounces | oz |
| **kg** | kilograms | 2.202 | pounds | lb |
| **Mg (or "t")** | megagrams (or "metric ton") | 1.103 | short tons (2000 lb) | T |
| **g** | grams | 0.035 | ounces | oz |
| | | **TEMPERATURE (exact degrees)** | | |
| **°C** | Celsius | 1.8C+32 | Fahrenheit | °F |
| | | **ILLUMINATION** | | |
| **lx** | lux | 0.0929 | foot-candles | fc |
| **cd/$m^2$** | candela/$m^2$ | 0.2919 | foot-Lamberts | fl |
| | | **FORCE and PRESSURE or STRESS** | | |
| **N** | newtons | 0.225 | poundforce | lbf |
| **kPa** | Kilopascals | 0.145 | poundforce per square inch | lbf/$in^2$ |

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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# List of Abbreviations

| Abbreviation | Term |
|---|---|
| AAR | American Association of Railroads |
| AESS | Automatic Engine Start/Stop |
| AR | Accident Release |
| BLS | Bureau of Labor Statistics |
| BHP-HR | Brake Horsepower-Hour |
| CN | Canadian National |
| CTC | Centralized Traffic Control |
| CO | Carbon Monoxide |
| COFC | Container on Flat Car |
| DB | Dynamic Braking |
| EMD | Electro-Motive Division |
| EPA | Environmental Protection Agency |
| FHWA | Federal Highway Administration |
| FIPS | Federal Information Processing Standards |
| FRA | Federal Railroad Administration |
| FSEO | Fuel-Specific Engine Output |
| GIS | Geographic Information System |
| GTFS | General Transit Feed Specifications |
| HAZMAT | Hazardous Materials |
| HMIR | Hazardous Materials Incident Report |
| HMR | Hazardous Materials Regulation |
| MPH | Miles per Hour |
| NAR | Non-Accident Release |
| NARN | North American Rail Network |
| NCHRP | National Cooperative Highway Research Program |
| NEC | Northeast Corridor |
| NOx | Nitrogen Oxides |
| NRC | National Response Center |
| NTD | National Transit Database |
| NTSB | National Transportation Safety Board |
| OLS | Ordinary Least Squares |
| PHMSA | Pipeline and Hazardous Materials Administration |
| PM | Particulate Matter |
| PSU | Primary Sampling Unit |
| PTC | Positive Train Control |
| RTC | Rail Traffic Controller |
| STB | Surface Transportation Board |
| TCS | Traffic Control System |

| Abbreviation | Term |
|---|---|
| THC | Total Hydrocarbons |
| TMAS | Traffic Monitoring Analysis System |
| TOFC | Trailer on Flat Car |
| TPD | Trains per Day |
| USDOT | U.S. Department of Transportation |
| VOCs | Volatile Organic Compounds |
| VOR | Value of Reliability |
| VOT | Value of Time |

# List of Equation Indices

| Equation Index or Parameter | Meaning |
|---|---|
| $j$ | j = AR, j = NAR |
| $l$ | Index of location |
| $d$ | Duration of closure |
| $f$ | Index of facility type |
| $i$ | Index of Incident type |
| $\mathrm{A}$ | Share of closure probability or duration not attributable to HAZMAT, $\mathrm{A}$ = 0%, 50%, 100% |
| $X$ | Train type share of traffic |
| $n$ | Number of train types |
| $\mu$ | Number of locomotive engines |
| $\varepsilon$ | Emissions rate in grams per brake horsepower-hour |
| $EI$ | Emission inventory |
| $FI$ | Fuel consumption inventory |
| $\sigma$ | Index of operation mode |
| $\tau$ | Index of traffic type (passenger or freight) |
| $\rho$ | Horsepower |
| $\eta$ | Index of notch position |
| $\lambda$ | Fraction of operating hours spent in a particular notch position |
| $N$ | Set of all notch positions |
| $\alpha$ | Index of criteria pollutants |
| $\omega$ | Fuel rate in brake horsepower-hour per gallon of diesel |
| $A$ | Hour when freight trains can start moving out of the queue past the location of the closure |
| $FL$ | Length of queue in freight trains |
| $B$ | The hour when the queue has dissipated |
| $h$ | Index of hour |
| $af$ | Arrival rate of freight trains |
| $c$ | Link capacity in trains per hour |
| $a$ | Arrival rate of all trains |
| $k$ | Index of links in the network |
| $x$ | Percent double track |
| $\iota$ | Traffic mix |
| $z$ | Index of track type (single or double) |
| $S$ | Delay constant |
| $T$ | Delay constant |
| $\kappa$ | Congestion factor |
| $e$ | Euler's number |
| $PL$ | Length of queue in passenger trains |

| Equation Index or Parameter | Meaning |
|---|---|
| $t$ | Index of arriving trains |
| $r$ | Index of routes |
| $s$ | Index of service types |
| $a, b, c, d, e, f$ | Vehicle delay parameters |

# Executive Summary

This final report presents the results of a research and modeling effort to estimate the social cost of delay resulting from the presence of hazardous materials (HAZMAT) in rail incidents. The estimates of the cost of delay developed in this research can be combined with estimates of other components of the cost of an incident (property damage, fatalities and injuries, environmental clean-up/remediation/restoration, repair, evacuation, emergency response, etc.) to generate an estimate of the total social cost of a HAZMAT rail incident. The report presents the data, methodology, assumptions used, and results. The estimates are based on freight rail traffic from the 2018 confidential Carload Waybill Sample provided by the Surface Transportation Board. The information on frequency and severity of HAZMAT rail incidents is from PHMSA Form 5800.1 data for the 10-year period of January 1, 2010 through December 31, 2019. Monetized costs are presented in 2021 dollars unless otherwise noted.

Traffic delay may result from some HAZMAT rail incidents if the track is closed to clear damaged or derailed train equipment, clean up the HAZMAT, and/or repair the track. As a result of the track being closed, rail traffic needs to either wait until an incident is cleared and track is repaired or reroute around an incident. If traffic reroutes around the incident, that traffic not only incurs higher costs due to longer travel time but the increased traffic may result in additional congestion-caused delay on the alternate route. The delay would be experienced by the freight rail traffic and any passenger rail traffic that may use the impacted rail lines. A nearby roadway may also be closed if the incident blocks a grade-crossing, if debris from the incident blocks or damages the roadway, if the area falls under an evacuation order due to the possibility of a HAZMAT release, or if the roadway is needed to stage equipment for the response effort. In such cases, delay is also experienced by roadway users.

## Costs to Freight Rail

The cost of delay resulting from freight railroads choosing to wait for the incident to be cleared and the track reopened is estimated using a standard bottleneck model that estimates the total hours of train delay as a function of the duration of the closure, traffic level, and the capacity of the site of the closure. The traffic levels are estimated by routing one year of waybill records over a geospatial representation of the North American freight rail network. Freight railroads also have the option to reroute around the site of the closure. Based on feedback from the railroad industry, it is assumed that only high priority traffic (intermodal and finished autos) would be considered for rerouting. This analysis estimates the increase in costs associated with rerouting the high priority traffic over a longer route by routing the waybill records over the geospatial representation of the rail network modified to remove a particular location and analyzing the resulting traffic flows. The analysis also estimates the cost associated with additional congestion due to increased traffic on the alternate routes. The costs of the rerouting relate to the labor, fuel, and equipment costs related to the longer transit times. The model then adopts the social cost of the option (have all traffic wait or reroute high priority traffic while low priority traffic waits) that has the lower business costs for the railroad.

## Costs to Passenger Rail

Passenger trains, if their routes use the track segment closed due to the incident, will also experience delay. For shorter duration closures, this analysis assumes passenger trains simply wait for the incident to clear. For longer duration closures, this analysis assumes that a "bus bridge" will be established to transport passengers around the site of the closure. The cost of delay is related to the costs of operating the buses needed to transport the passengers, the passengers' value of time for the longer travel times, and the additional time worked by the crew of the passenger trains plus the operating costs of the trains.

## Costs to Roadway Users

If a rail incident closes a nearby roadway, the costs to roadway users are estimated using the model provided in Hagemann et al (2013). That report estimates the costs of truck crashes and provides a generalizable model that produces an estimate of total hours of vehicle delay based on traffic volume, roadway type, and duration of the closure.

## Scenarios

This analysis explores a variety of network locations, each experiencing different levels of traffic and having different capacities.

Another component of the scenarios used to develop an overall expected cost of delay is duration of a closure due to a HAZMAT rail incident. Non-accident releases (NARs) are modelled at their median duration of four hours since the entire period of closure is the result of the presence of HAZMAT at the site. Accident releases (ARs) have a median duration of 24 hours. However, ARs are treated differently than NARs because a portion of the closure duration may be due to the accident itself, not the presence of HAZMAT. A key challenge for the analysis, therefore, is estimating the portion of the closure duration that is due to the presence of HAZMAT. The analysis task is estimating the closure duration *but for* the presence of HAZMAT. Complicating that estimation process is that duration of closure information is only available for HAZMAT incidents, i.e., those that are reported using PHMSA Form 5800.1. No data involving duration of closure information for a comparison group of *non*-HAZMAT incidents is available. As a result of this data gap, the central analysis assumes any differentials in the probability of a closure or the duration of a closure associated with fires or evacuations can be attributed to the presence of HAZMAT. For incidents without a fire or evacuation, there is assumed to be no impact from the presence of HAZMAT. That is, HAZMAT incidents without a fire or evacuation are likely to have the same closure duration as non-HAZMAT incidents. Thus, for the 67 percent of ARs that do not involve a fire or evacuation, the additional cost of delay due to HAZMAT is zero in the central analysis. The estimated cost attributed to HAZMAT is due to additional delay time seen with incidents involving fire or evacuation. However, this method may underestimate the true cost of delay resulting from HAZMAT incidents. Therefore, this report includes a sensitivity analysis (separate from the central analysis) that relaxes that assumption.

## Results of Central Analysis

The results of the central analysis are based on a sample of 229 rail segments throughout the U.S. freight rail network, each representing subdivisions of a Class 1 railroad or a Class 2/3 railroad. [1] At each rail segment, the analysis models the delay impacts of closing the rail segment due to a HAZMAT incident. The results are then averaged across sample locations using relative weights based on train-miles on the Class 1 subdivision or Class 2/3 railroad.[2]

Some results are based on the idea that all freight traffic will wait for the closure to end and for the track segment to be returned to service. The cost of waiting is estimated using a straightforward bottleneck model. Other results consider the possibility that a freight railroad will choose to reroute high priority traffic, i.e., intermodal and finished automobiles, around the site of a closure, if rerouting results in lower costs to the business compared to waiting for the incident to be cleared and returned to service.

- For NARs (with a typical closure period of four hours), this analysis assumes that all freight traffic will wait and uses only the bottleneck model to estimate the cost of delay. For the 229 sampled locations on the U.S. rail network, the four-hour closure has a typical delay cost of roughly $28,000, or between $22,000 and $34,000 with a 95 percent confidence interval. Over the ten-year period of analysis (January 1, 2010 through December 31, 2019) there were 9.2 NARs with closures per year on average; therefore, the annual delay cost of NARs is estimated to be approximately $258,000.[3]
- This analysis finds that the typical cost attributable to HAZMAT in an AR is roughly $157,000, when analyzed assuming that all railroad freight traffic will wait for the incident to be cleared, or between $117,000 and $197,000 with a 95 percent confidence interval. During the analysis period, there were 26.8 ARs per year on average. The typical annual cost of delay due to the presence of HAZMAT in an ARs is estimated to be roughly $4,203,000.[4]
- When estimated under the possibility that railroads might chose to reroute high priority traffic if

[1] The sample also includes some network locations where subdivision information is missing.

[2] The weights are also adjusted to reflect the relative frequency of HAZMAT incidents on Class 1 railroads compared to Class 2/3 railroads.

[3] All estimates are reported in 2021 dollars.

[4] Because the analysis of ARs accounts for not only the impact of HAZMAT on the duration of closure but also the probability of a closure, the HAZMAT-related delay cost is estimated for all ARs (not just those with closures).

that option results in lower costs to the business, this analysis finds that for ARs, the average cost of delay attributable to HAZMAT is approximately $124,000, or between $83,000 and $166,000 with a 95 percent confidence interval. Thus, the possibility of rerouting lowers estimated delay costs from HAZMAT by roughly one fifth from the waiting-only value. During the 10-year period of analysis, there were 26.8 ARs annually on average. The typical annual cost of delay attributable to the presence of HAZMAT in ARs is estimated to be $3,586,000.

**Summary of Social Cost of Delay due to HAZMAT in Rail Incidents**

| Incident Type | Social Cost per Incident (2021$) | Incidents per Year | Average Annual Social Cost of Delay (2021$) |
|---|---|---|---|
| NAR with Closure | $28,027 | 9.2 | $257,846 |
| AR (Rerouting High Priority Freight) | $124,172 | 26.8 | $3,327,811 |
| **Total** | N/A | N/A | $3,585,658 |

# Results of Sensitivity Analyses and Case Study

In the central analysis discussed above, data related to certain key issues was not available and therefore the modeling used either incomplete data or made informed assumptions. The impact of alternative means of addressing two of those key issues is explored in this report: the assumptions related to the impact of the presence of HAZMAT on probability and duration of closure in ARs, and an investigation of alternative estimates of the emissions from locomotives.

The first sensitivity analysis considers two alternative assumptions related to the impact of the presence of HAZMAT on the probability and duration of closure for ARs that do not involve a fire or evacuation. One is an extreme case where all of the delay as a result of the AR is ascribed to the presence of HAZMAT. The other is a middle case where half of the probability of closure and half of the duration of a closure is ascribed to the presence of HAZMAT. Those two sensitivities, combined with the central case where none of the delay for incidents without fires or evacuations is ascribed to HAZMAT, explores the full range of possibilities of the social cost of delay due to HAZMAT in ARs related to this issue.

**Social Cost of Delay Under Alternative Assumptions Related to Impact of HAZMAT on Probability and Duration of Closure (2021$)**

| Category | Presence of HAZMAT accounts for 0% of probability and duration of closure in incidents without fire/evacuations<br><br>Central Case | Presence of HAZMAT accounts for 50% of probability and duration of closure in incidents without fire/evacuations | Presence of HAZMAT accounts for 100% of probability and duration of closure in incidents without fire/evacuations |
|---|---|---|---|
| Social Cost of Delay for AR (2021$) | $124,172 | $198,742 | $214,369 |
| Percent Change Compared to Central Case | N/A | +60% | +73% |

The second sensitivity analysis considers the impact of changing locomotive emission assumptions. The central analysis used the emissions profile of two specific locomotives used in line-haul operations in North Carolina. The locomotives were manufactured in the 1970s and rebuilt between 2008 and 2012. The emissions rates found for those locomotives in some cases exceeded even Tier 0 standards. Although many such older locomotives are owned and operated by freight railroads, newer and cleaner locomotives have also been added to railroad fleets and would likely be used for line-haul operations while older locomotives might be used more often for yard operations. This sensitivity analysis performs some high-level adjustments to find the impact to the social cost of delay if higher-tier locomotives were used in line-haul operations of freight and passenger trains.

**Social Cost of Delay Due to Presence of HAZMAT with Alternative Emissions Profiles**

| Category | Tier 0 (Central Case) | Tier 1 | Tier 2/3 | Tier 4 |
|---|---|---|---|---|
| Social Cost Delay for NAR with Closure (2021$) | $28,027 | $27,896 | $22,765 | $19,100 |
| Percent Change Compared to Central Case | 0% | -0.5% | -19% | -32% |
| Social Cost of Delay for AR (2021$) | $124,172 | $123,940 | $106,974 | $96,589 |
| Percent Change Compared to Central Case | 0% | -0.2% | -14% | -22% |

Feedback from reviewers noted that the analysis period of 2010 to 2019, used to understand the characteristics of HAZMAT rail incidents in the central analysis, did not accurately reflect the impacts of recent regulations implemented regarding safety for the transport of Class 3 flammable liquids. Reviewers also noted that during this period, crude oil volumes were unusually high. That period involved the use of older designs of tank cars which have since been phased out due to regulatory actions. To address the reviewers' concern, this case study presents an alternative estimate of the social cost of delay due to HAZMAT rail incidents that assumes there are no crude oil releases during that 10-year period. The results of the case study suggest that the improved tank car design and lower volumes of crude oil by rail have provided a $0.8 million benefit per year in the form of avoided delay.

# 1. Introduction

This report presents the results of a research and modeling effort to estimate the delay costs resulting from presence of hazardous materials (HAZMAT) in incidents on rail. The research is sponsored by the Pipeline and Hazardous Materials Safety Administration (PHMSA) in coordination with the Federal Railroad Administration (FRA) and in partnership with John A. Volpe National Transportation Systems Center.

Obtaining a better understanding of the total social costs of a HAZMAT rail incident is useful for several purposes:

- Executive Order 12866 requires an assessment of the costs and benefits of significant regulatory and deregulatory changes: "a reasoned determination that the benefits justify the costs."[5]
- Less formal analysis of potential changes to policy, outreach, guidance, special permits, and petitions will benefit from more complete understanding of the costs of a HAZMAT incident.
- U.S. Department of Transportation (USDOT) evaluates potential projects for competitive grant awards such as Infrastructure for Rebuilding America, Rebuilding American Infrastructure with Sustainability and Equity, and Consolidated Rail Infrastructure and Safety Improvement, and for loans such as Railroad Rehabilitation & Improvement Financing. The evaluations consider the safety benefits of projects which would include the avoided costs of delay.

The estimates of the cost of delay developed in this research can be combined with estimates of other components of the cost of an incident (property damage, fatalities and injuries, environmental clean-up/remediation/restoration, repair, evacuation, emergency response, etc.) to generate an estimate of the total social cost of a HAZMAT rail incident. Table 1, below, summarizes the categories of costs that are estimated in this report.

**Table 1. Categories of HAZMAT Incident Costs Estimated in this Report**

| Costs estimated in this report | Costs not estimated in this report |
|---|---|
| • Delay costs resulting from rail network users (railroads, shippers, passengers)<br>• Delay costs resulting from roadway users (vehicular traffic at and around site of incident) | • Fatalities/injuries<br>• Property damage<br>• Emergency services<br>• Environmental damage<br>• HAZMAT release<br>• HAZMAT cleanup<br>• Cost of evacuation (lodging, meals) |

A report providing initial results of the research was shared with stakeholders and an academic reviewer

[5] Executive Order 12866, "Regulatory Planning and Review," Federal Register Vol. 58. No. 190, October 4, 1993 at https://www.archives.gov/files/federal-register/executive-orders/pdf/12866.pdf.

in June 2021.[6] Based on the feedback provided to the initial result, several adjustments were made to the methodology including:

- altering the routing algorithm to more accurately reflect railroad routing practices in Washington State and in the east Texas and Arkansas area;
- reflecting more recent railroad practices by increasing assumed train lengths in the modeling;
- modifying the analysis so that only high priority traffic (intermodal and finished autos) has the option to reroute because railroad industry representatives indicated that this assumption would be more realistic than assuming that all traffic could potentially reroute;
- sampling additional high traffic rail segments to make the analysis sample more representative of the U.S. rail network;
- updating the geospatial representation of the rail network to a version provided by FRA on March 21, 2022.
- updating unit costs to 2021 dollars;
- adjusting the modeling of emissions from freight locomotives to use EPA's duty cycle assumptions;
- incorporating the most current USDOT guidance on the cost of carbon and other emissions;
- providing a suggested method for updating the estimates in the future;
- conducting sensitivity analysis on certain key assumptions, and
- including a case study showing how the model can be used to estimate the impact of improved designs of tank cars used to transport crude oil.

The remainder of this report is organized as follows. Section 2 provides an overview of the analysis; Section 3 provides freight data, input, and methods; Section 4 discusses passenger data, input, and methods; Section 5 describes roadway data, input, and methods; Section 6 describes scenario development; Section 7 presents results of the central analysis of the cost of delay attributable to HAZMAT in rail incidents; Section 8 presents a suggested method for updating monetization factors such as cost of fuel or social cost of carbon in the future; Section 9 discusses the results of various sensitivity analyses; Section 10 presents the results of a case study applying model to analyze the impact of improved design of tank cars for crude oil; and Section 11 is the conclusion. Appendix A contains a review of relevant literature. Appendix B, a separate document, contains maps showing how traffic reroutes if certain network segments are closed.

# 2. Overview of Analysis

The purpose of this research project is to estimate the social cost of delay resulting from HAZMAT in rail incidents, i.e., incidents on rail that involve HAZMAT releases or HAZMAT-related evacuations. Some HAZMAT rail incidents result in the track being closed in order to clear the damaged or derailed train equipment, clean up the HAZMAT, and/or repair the track. As a result of the track being closed, rail

[6] The academic reviewer was compensated for their time.

traffic needs to either wait until an incident is cleared and track is repaired or reroute around an incident. If traffic reroutes around the incident, that traffic not only incurs higher costs due to longer transit costs, but the increased traffic may result in additional congestion-caused delay on the alternate route. The delay is experienced by the freight rail traffic and any passenger rail traffic that may use the impacted rail lines. A nearby roadway may also be closed if the incident blocks a grade-crossing, if debris from the incident blocks or damages the roadway, if the area falls under and evacuation order due to the possibility of a HAZMAT release, or if the roadway is needed to stage equipment for the response effort. In such cases, delay is also experienced by roadway users. The total cost of delay is then the sum of the cost of delay experienced by freight rail, passenger rail, and roadway users as shown in Figure 1, below. Each of those components is discussed separately in later sections of this report whereas this initial discussion is intended to give an overview of the framework used in this analysis.

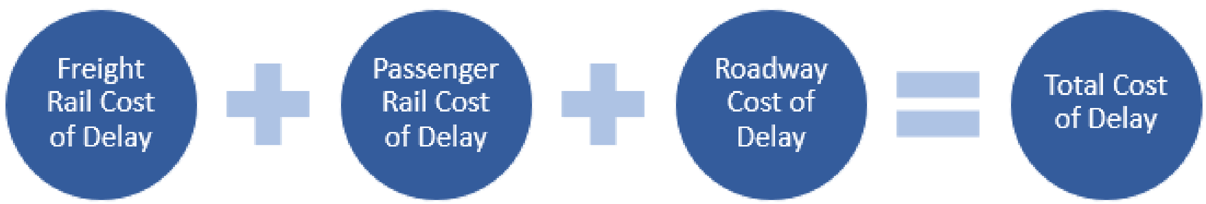


**Figure 1. Components of Total Cost of Delay**

The cost of delay resulting from a HAZMAT rail incident is driven by the following factors:

- Whether there is a rail line closure due to the incident;
- The duration of the closure;
- Whether there is a roadway closure due to the incident;
- The location of the closure, which determines:
    - How much freight rail traffic is impacted,
    - How much, if any, passenger rail traffic is impacted,
    - The capacity of the rail line which determines how quickly the impacted traffic can resume normal operations after a closure ends, and
    - The characteristics of alternate rail routes around the site of the closure.

The questions of whether there is a rail line closure due to the incident and the length of the closure are closely related in this analysis. The probability of a rail line closure and its typical duration are analyzed separately for accident releases (ARs) and non-accident releases (NARs).

An AR is a HAZMAT release that is the result of a rail accident such as a derailment or collision. According to data from PHMSA Form 5800.1, during the 10-year period January 1, 2010 through December 31, 2019, there were 268 ARs involving rail.[7] Of these ARs, 109 (41 percent) resulted in the closure of a rail line of one hour or more and those incidents had a median closure duration of 24

[7] Details of data used for these counts are categorized and provided in Section 3.1.

hours.[8,9] However, the full duration of closure cannot necessarily be attributed to the presence of HAZMAT on the train involved in the incident**.** That is, the track would likely have been closed for some period of time in order to facilitate recovery efforts even if no HAZMAT had been involved. This analysis uses regression analysis to estimate the probability of closure with and without HAZMAT and the duration of the closure with and without HAZMAT for ARs. That duration analysis is discussed in more detail in Section 3.2.

A NAR results from a failure of the HAZMAT packaging that is not related to a rail accident. For instance, a malfunctioning valve on a tank car might result in a HAZMAT release independent of any collision or derailment. For NARs, the analysis is more straightforward. In the 10-year period of 2010-2019, there were 5,888 NARs and 92 of those (1.6 percent) resulted in the closure of a major transportation artery of one hour or more. Those NAR closures had a median duration of four hours, and this analysis assumes that the entire four hours of closure can be attributed to the presence of HAZMAT.

This report provides the results of estimating the delay costs associated with those HAZMAT incident rail line closures and roadway closures. It is possible that HAZMAT incidents may also result in delay if traffic continues to operate on the line but at a slower speed. However, due to lack of data describing such incidents, they are not included in this analysis.

Information regarding whether there is a roadway closure due to the incident was gathered by reviewing information related to historic incidents using media reports, National Transportation Safety Board (NTSB) reports, and National Response Center (NRC) reports. The review found that in 29 percent of NARs with rail line closures and 71 percent of ARs, a nearby roadway was also closed or an evacuation occurred.[10]

Because the delay costs associated with a HAZMAT rail incident vary depending on the location of the closure, this analysis takes a scenario-based approach that explores a variety of randomly selected potential incident locations from the freight rail network in the United States. Those different locations exhibit a variety of different freight and passenger rail traffic volumes and capacities. The freight traffic volumes for a particular location are derived from routing waybill records data over a geospatial representation of the rail network in North America. Details of that work is provided in Section 3.3. The presence and volume of passenger rail traffic at a location is derived from general transit feed specifications (GTFS) data for intercity Amtrak and commuter rail service that was overlaid on to the geographic information system (GIS) rail network.

The availability and attractiveness of alternate rail routes around the incident is also determined by

[8] In 12 of these 109 cases, no HAZMAT was released. The rail line was shut down due to the danger of a potential release.
[9] Form 5800.1 captures information on whether a "major transportation artery" was closed due to the HAZMAT incident. This analysis assumes that in all cases where the incident occurs on rail it is a rail line that was closed for the duration listed on Form 5800.1
[10] Details on the review are provided in Section 5.1.

incident location using the same rail network (see Section 3.3.4). The capacity of the rail line at the location of the incident is based on information found in a 2007 study sponsored by the American Association of Railroads (AAR), *National Rail Freight Infrastructure Capacity and Investment Study* (Cambridge Systematics, 2007).

For each scenario (a specified closure duration and incident location), the railroad has the option to either wait for the track to be cleared and repaired or reroute traffic around the closure. During the period that the track is closed, trains will continue to arrive, and a queue will form. Once the track is reopened, the queue of trains can pass through the site of the closure, but the departure rate will be constrained by the capacity of the rail line. Alternatively, a railroad may choose to route the traffic around the site of the closure. The alternate route would be expected to take longer to traverse and be more costly to the railroad in terms of crew time, fuel burn, etc. than the baseline routing. Because railroad industry representatives have pointed out that rerouting is generally only considered for high priority traffic such as intermodal and finished autos, this analysis considers rerouting as an option only for high priority traffic. The analysis further assumes a railroad will choose the option (having all traffic wait or rerouting high priority traffic) with the lowest cost incurred by the railroad, and that railroads are able to accurately estimate the duration of the closure and their expected costs based on the location and characteristics of the incident at the onset of the incident. Thus, this analysis first estimates the costs incurred by railroads for both waiting and rerouting around the delay. Then the analysis estimates the total *social* cost associated with the railroad's lower cost option.

In this analysis, the costs incurred by the railroad are termed "business costs" and include the costs associated with crew time, equipment, fuel (including taxes), and the time value of freight. The time value of freight is used as a proxy for penalties that a railroad may need to pay to a shipper for late delivery. Information on the actual levels of the penalties is not publicly available but in some cases can be expected to be fairly high. Because the information on penalties is not available, this analysis may underestimate the frequency with which railroads would actually choose to reroute high priority traffic (as opposed to waiting). The social cost of delay includes those same cost elements plus the social costs of emissions from additional fuel burn, minus the cost of fuel taxes which are considered a transfer in social cost accounting. In addition to the costs accruing to freight railroads, the social cost of delay also includes the costs accrued to highway users and passenger rail operations. The social costs of delay for passenger rail operations includes costs related to crew time, equipment, passenger value of time (VOT), additional fuel burn, and emissions due to additional fuel burn. In addition, passenger rail traffic (commuter and intercity Amtrak service) may opt to use buses to transport passengers around an incident which incurs additional costs. In this analysis, roadway users' cost of delay includes costs related the passenger and driver VOT, additional fuel burn, and emissions.

Table 2. Components of Business Costs and Social Costs

| Component | Business Costs of Delay | Social Costs of Delay |
|---|---|---|
| Freight Rail | • Crew time<br>• Equipment<br>• Fuel (including taxes)<br>• Time Value of Freight (proxy for penalties charged by shippers) | • Crew time<br>• Equipment<br>• Fuel (not including taxes)<br>• Emissions<br>• Time Value of Freight |
| Passenger Rail | N/A | • Crew time<br>• Equipment<br>• Fuel (not including taxes)<br>• Emissions<br>• Passenger VOT<br>• Cost of a "Bus Bridge" |
| Roadway Users | N/A | • Passenger and Truck Driver VOT<br>• Fuel (not including taxes)<br>• Emissions |

# 3. Freight Rail Cost of Delay

This section provides detail concerning the data, inputs, and model used in order to determine the cost of freight delay from a HAZMAT incident. Section 3.1 describes the major data sources used in the analysis. Section 3.2 provides detailed explanation of the duration of closure analysis for ARs and NARs. Sections 3.3 and 3.4 describe the process of routing waybills and determining freight traffic volumes, as well as rail line capacity estimates. Further inputs described are the monetization factors applied in the model as described in Section 3.5, which are used to determine the business and social costs of delay for freight rail. Finally, Sections 3.6 and 3.7 describe the freight delay model, including both waiting and rerouting options for freight and a comparison of costs of waiting to costs of rerouting for freight rail.

## 3.1 Characteristics of Incidents

The starting point of this analysis is understanding the general characteristics of HAZMAT rail incidents that have occurred in the past. The 10-year period of January 1, 2010 through December 31, 2019 is used as the historic analysis period upon which to characterize HAZMAT rail incidents. More recent incident data (i.e., 2020 through 2022) was not available at the time of drafting this report and implementing the computationally intensive aspects of the analysis. The primary source of data for this effort is the reporting of HAZMAT incidents that occur on rail to PHMSA. This information is augmented, where possible, by reporting to FRA related to rail incidents. Additional information is gathered for some incidents from other sources such as reporting to the NRC and media reports. Each of these data sources is described below.

### 3.1.1 PHMSA Hazardous Material Incident Reporting

Reporting to PHMSA of HAZMAT incidents is required under the Hazardous Materials Regulations (HMR; 49 CFR Parts 171-180) whenever one of several types of incidents occur during transportation of HAZMAT (which includes “loading, unloading, and temporary storage”).[11] The entity (person or business) physically in possession of the hazardous material when the incident occurs is required to complete and submit a Hazardous Materials Incident Report (HMIR) on DOT Form F 5800.1 within 30 days of discovery of the incident.[12] Incidents may occur on any mode where hazardous material are transported. Incidents must be reported per HMR if:

1. As a direct result of a hazardous material,

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[11] 49 CFR Parts 171 (2012) https://www.govinfo.gov/content/pkg/CFR-2012-title49-vol2/xml/CFR-2012-title49-vol2-subtitleB-chapI-subchapC.xml#seqnum171.16

[12] A single incident may have several records or data entries associated with it because one incident may involve multiple hazardous materials, multiple packagings or packaging types, multiple shippers, etc. A derailment involving several rail tank cars, for example, may have multiple entries under a single report number. To resolve this, reports were collapsed down to a single incident level report based on the report number.

- A person is killed;
- A person receives an injury requiring admittance to a hospital;
- The general public is evacuated for one hour or more; or
- A major transportation artery or facility is closed or shut down for one hour or more;

2. Fire, breakage, spillage, or suspected radioactive contamination occurs involving a radioactive material;
3. Fire, breakage, spillage, or suspected contamination occurs involving an infectious substance other than a regulated medical waste;
4. A situation exists of such a nature (e.g., a continuing danger to life exists at the scene of the incident) that, in the judgment of the person in possession of the hazardous material, it should be reported to the NRC even though it does not meet the criteria of paragraphs (b)(1), (2), (3) or (4) of this section; or
5. An unintentional release of a hazardous material or the discharge of any quantity of hazardous waste;
6. A specification cargo tank with a capacity of 1,000 gallons or greater containing any hazardous material suffers structural damage to the lading retention system or damage that requires repair to a system intended to protect the lading retention system, even if there is no release of hazardous material;
7. An undeclared hazardous material is discovered; or
8. A fire, violent rupture, explosion or dangerous evolution of heat (i.e., an amount of heat sufficient to be dangerous to packaging or personal safety to include charring of packaging, melting of packaging, scorching of packaging, or other evidence) occurs as a direct result of a battery or battery-powered device.
9. In addition, a HMIR must be updated within one year of the date of occurrence of the incident whenever: (1) A death results from injury caused by a hazardous material; (2) There was a misidentification of the hazardous material or package information on a prior incident report; (3) Damage, loss or related cost that was not known when the initial incident report was filed becomes known; or (4) Damage, loss, or related cost changes by $25,000 or more, or 10 percent of the prior total estimate, whichever is greater.

PHMSA's Office of Hazardous Materials Safety collects and manages the data reported on DOT Form F 5800.1 (Form 5800.1) and makes the data publicly available on the PHMSA website after completing a quality assurance process (PHMSA, 2023).

Several descriptors of the incident are of interest for this analysis. This analysis is concerned with the universe of incidents involving HAZMAT transported by rail, and therefore the “Mode of Transportation” field is used to exclude all non-rail incidents prior to analysis. Also of primary interest are “Major Artery Closed” and “Major Artery Hours Closed” since in this model, delay is caused by the closure of a rail line. The major transportation artery mentioned in the report might in theory be a rail line or a roadway, however, this analysis assumes that in all cases it is a rail line that was closed for the duration listed on Form 5800.1. Also, note that Form 5800.1 only records closures of one hour or more.

Information from the PHMSA Form 5800.1 allows identification of NARs. The AAR describes a NAR as follows:[13]

> *"[T]he unintentional release of a HAZMAT while in transportation, including loading and unloading while in railroad possession, that is not caused by a derailment, collision or other rail related accident. NARs consist of leaks, splashes, and other releases from improperly secured or defective valves, fittings, and tank shells, and also include venting of non-atmospheric gases from safety relief devices. (Normal safety venting of atmospheric gases such as carbon dioxide and nitrogen is not considered a NAR)."*

In contrast, an AR is the release of HAZMAT as the result of derailment, collision, or other rail-related accident.

While an accident is not explicitly identified as a NAR or AR in the Form 5800.1 data, the data contain a "Failure Cause Description" field. This variable can be used to indicate if the release of material was due to an accident or not. The following values were present in the "Failure Cause Description" field, with some observations having multiple failure causes listed. A derailment, rollover accident, or vehicular crash or accident damage were interpreted as an AR cause, and any incident that included any of these three values (regardless of other identified causes) was coded as an AR. For example, a release coded as "abrasion" and "defective component or device" (both NARs) would be coded as a NAR. A release coded as "abrasion" and "derailment" would be coded as an AR. A complete list of failure cause descriptions, along with how these incidents were coded, is presented in Table 3. The definition of AR used in this analysis also includes a small number of incidents (12 incidents over 10 years) where no HAZMAT was released. The rail line was shut down due to the possible danger of a release.

**Table 3. Coding NAR and AR Incidents**

| Failure Cause Description | Release Type |
|---|---|
| [BLANK] | Unknown |
| N/A | Unknown |
| Abrasion | NAR |
| Broken Component or Device | NAR |
| Commodity Polymerization | NAR |
| Commodity Self-Ignition | NAR |
| Conveyer or Material Handling Equipment Mishap | NAR |
| Corrosion – Exterior | NAR |
| Corrosion – Interior | NAR |
| Defective Component or Device | NAR |
| Derailment | ***AR*** |
| Deterioration or Aging | NAR |
| Dropped | NAR |
| Fire Temperature or Heat | NAR |
| Forklift Accident | NAR |

[13] Association of American Railroads, Bureau of Explosives. (2018). *Annual Report of Hazardous Materials Transported by Rail* (BOE 17-1; p. 44).

| Failure Cause Description | Release Type |
|---|---|
| Freezing | NAR |
| Human Error | NAR |
| Impact with Sharp or Protruding Object (e.g., nails) | NAR |
| Improper Preparation for Transportation | NAR |
| Inadequate Accident Damage Protection | NAR |
| Inadequate Blocking and Bracing | NAR |
| Inadequate Maintenance | NAR |
| Inadequate Preparation for Transportation | NAR |
| Inadequate Procedures | NAR |
| Inadequate Training | NAR |
| Incompatible Product | NAR |
| Incorrectly Sized Component or Device | NAR |
| Leaked | NAR |
| Loose Closure Component or Device | NAR |
| Misaligned Material Component or Device | NAR |
| Missing Component or Device | NAR |
| Overfilled | NAR |
| Over-pressurized | NAR |
| Rollover Accident | ***AR*** |
| Stub Sill Separation from Tank (Tank Cars) | NAR |
| Threads Worn or Cross Threaded | NAR |
| Too Much Weight on Package | NAR |
| Valve Open | NAR |
| Vandalism | NAR |
| Vehicular Crash or Accident Damage | ***AR*** |
| Water Damage | NAR |

Some incidents had no failure cause indicated in the "Failure Cause Description" field. For those incidents the "Description of Events" field was used. A manual review of these narrative descriptions of events indicated that reference to "derail" or related words such as derailment, "collision", or "NTSB" in the narrative was an indicator that the incident was an AR. For incidents where "Failure Cause Description" was blank, the presence of "derail", "collision", or "NTSB" in the "Description of Events" field was used to assign the incident as an AR, where its absence indicated a NAR.[14]

As a result of categorizing the incidents from PHMSA Form 5800.1 data in the manner described above, this analysis finds that in total over the period 2010 through 2019, there were 268 ARs of which 109 (41 percent) resulted in the closure of a major transportation artery. There were 5,888 NARs of which 92 (1.6 percent) resulted in the closure of a major transportation artery (see Table 4).

[14] Incidents categorized as ARs based on text search were reviewed to confirm their narratives were consistent with an AR, as the terms could potentially have been used in another sense, and NTSB could potentially have been prompted by a NAR resulting in a fatality, substantial property damage, or significant environmental impact.

Table 4. Closure of a Major Transportation Artery

| Incident Type | Number of Incidents | Number of Closures | Percent with Closures |
|---|---|---|---|
| NAR | 5,888 | 92 | 1.6% |
| AR | 268 | 109 | 41% |

### 3.1.2 FRA Accident Detail Reporting

In some cases, the PHMSA data is combined with FRA data and other data to provide additional detail on the incidents. Rail accident/incident reporting is required by all railroads, with some limited exceptions for small railroads not integrated into the national rail network (Office of Railroad Safety, 2011). Reportable incidents include several categories such as highway-rail grade crossing incidents and death, injury, and occupational illness incidents. Of primary focus are rail equipment accidents/incidents, which railroads report to FRA via Form FRA F 6180.54 - Rail Equipment Accident/Incident Report.[15] Rail equipment incidents include "collisions, derailments, fires, explosions, acts of God, and other events involving the operation of on-track equipment (standing or moving) that result in damages higher than the current reporting threshold." The reporting threshold applies to the sum of all damage costs incurred by all involved railroads, including on-track equipment, track, track structures, and other costs associated with acquiring new equipment.

Table 5 lists reporting thresholds for previous years through the present.[16]

Table 5. Rail Equipment Incident Reporting Threshold

| Calendar Year(s) | Reporting Threshold |
|---|---|
| 2002-2005 | $6,700 |
| 2006 | $7,700 |
| 2007 | $8,200 |
| 2008 | $8,500 |
| 2009 | $8,900 |
| 2010 | $9,200 |
| 2011 | $9,400 |
| 2012 | $9,500 |
| 2013 | $9,900 |
| 2014-2016 | $10,500 |
| 2017-2020 | $10,700 |
| 2021 | $11,200 |
| 2022 | $11,300 |
| 2023 | $11,500 |

[15] These incidents overlap with the other categories including highway-rail grade crossings and incidents involving death or injury. An incident meeting reporting requirements for multiple incident categories must be reported via *each* form.

[16] Federal Railroad Administration, "Monetary Threshold Notice," https://railroads.dot.gov/forms-guides-publications/guides/monetary-threshold-notice. Last accessed January 23, 2023.

The FRA data contains additional descriptors of the incidents including attributes of the trains involved such as how many cars, how many cars derailed, and the number of HAZMAT cars. It also contains information on location of the incident such as the track class, track type (main, yard, siding, or industry), type of railroad involved (railroad class), and latitude and longitude coordinates for more recent incidents.

The FRA data may contain multiple reports per incident because a single incident may have several parties obligated to report it and there is not a uniform incident number used for all related reports. Rather, each reporting railroad includes its own incident number, the incident number used by one other involved railroad (if applicable) and the incident number used by the railroad responsible for maintenance on the involved track. Therefore, preparing these report data for use involved collapsing multiple reports for a single incident into a single incident level observation for analysis.

### 3.1.3 Combining PHMSA and FRA Incident Data

As there is not a common identifier between the PHMSA and FRA data sets, the two were combined by using date and time of incident and county location of the incident.[17] For matching, FRA incidents with date and time information and which reported at least one HAZMAT car were used. The postal code provided in the PHMSA data was linked to a county or counties.[18] Incidents within three hours of the PHMSA reported date and time that shared the same county location were considered matched. Where multiple matches occurred, the FRA incident closest in time of occurrence was matched to the PHMSA incident. However, not all incidents were matched. Of the 268 ARs identified in the PHMSA data, 80 incidents (30 percent) were not matched to FRA incidents. In order to account for this, in estimating closure durations, those incidents which were not matched receive "unknown" designation for FRA variables used. Failure to find a match may be due to the incident failing to meet the reporting requirements for the FRA data, due to discrepancies in the time of the incident reported across forms, or in misreporting the presence of HAZMAT in the FRA data. No matches are expected for NARs because they do not involve an accident related to rail equipment.

## 3.2 Duration of Closure Analysis

This analysis accounts for the estimated impact that the presence of HAZMAT has on the probability of a closure and the duration of a closure. For NARs, the entire duration of the rail line closure (typically four hours) is attributed to the presence of HAZMAT. For ARs, how much of the closure duration is due to the presence of HAZMAT is not obvious. Rail accident recovery can occur concurrently with any HAZMAT-related cleanup efforts, and it is not clear that the HAZMAT activities necessarily take longer than the

[17] Town name and latitude and longitude was considered but city/town information was not found to be reliable.
[18] As some postal codes cover multiple counties, all possible counties were used in the matching process.

work needed to repair track or clear rail cars that would occur in any rail accident (HAZMAT or non-HAZMAT).

To illustrate the idea that HAZMAT may or may not increase the duration of a rail line closure, Figure 2 and Figure 3 present two illustrative scenarios.[19]

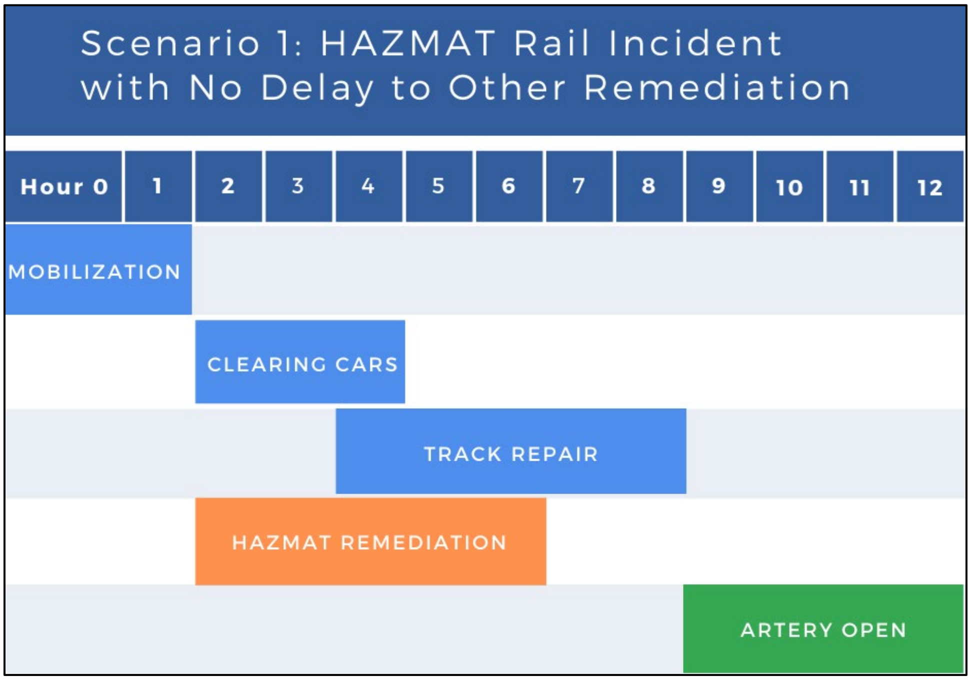


**Figure 2. Gantt Chart of Possible Delay Scenario One for a HAZMAT Incident**

[19] These Gantt charts are illustrative of hypothetical incidents and remediation processes and are not representative of any particular accident response.

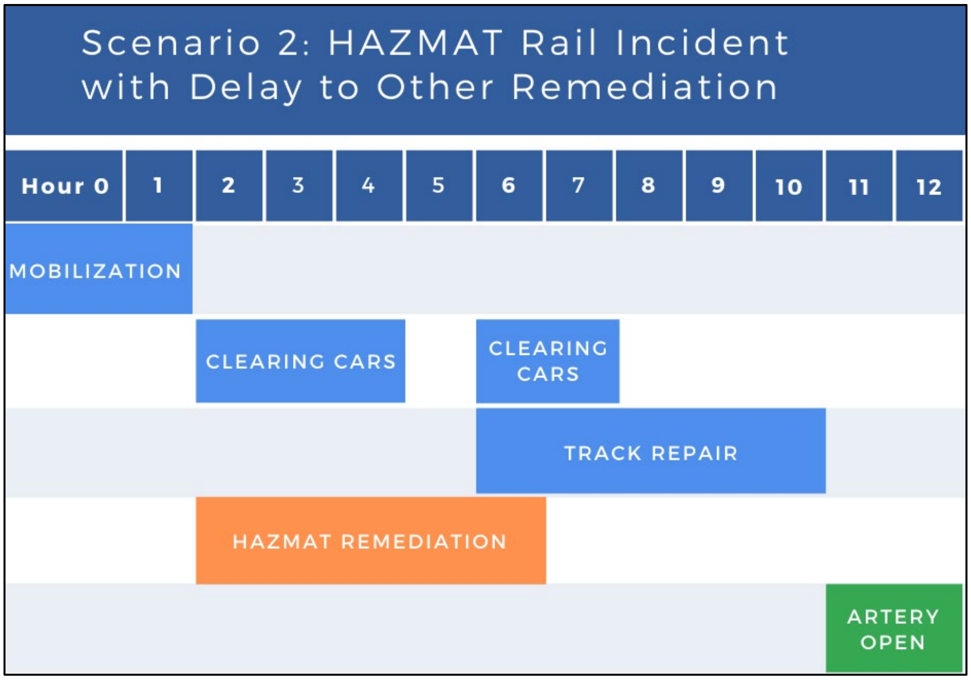


**Figure 3. Gantt Chart of Possible Delay Scenario Two for a HAZMAT Incident**

In the first scenario (Figure 2), the artery is closed from hour zero to hour eight. HAZMAT remediation is performed *concurrently* with non-HAZMAT response efforts (mobilization, clearing cars, and track repair), and therefore HAZMAT does not contribute to the length of the closure. In the second scenario (Figure 3), the artery is closed from hour zero to hour ten. HAZMAT remediation cannot occur concurrently with non-HAZMAT response for a portion of those activities occurring during hour five, adding to the duration of the closure. In other scenarios, not illustrated here, incidents could result in an investigation, which does not have a clear impact on the artery closure. It is possible that investigations would require the artery to remain closed even after the track is operable in some scenarios but not in others, dependent on the directives of the investigators.

The impact of HAZMAT on the duration of a rail line closure for ARs is then an empirical question. Regression analysis is used to estimate the impact of HAZMAT-related features on the probability of the incident causing a closure and the duration of a closure. A key challenge for the analysis is that duration of closure information is only available for HAZMAT incidents, i.e., those that are reported using Form 5800.1. No data involving duration of closure information for a comparison group of non-HAZMAT incidents is available.

The central analysis, to address this data gap, makes the assumption that HAZMAT incidents that do not include a fire or an evacuation are similar in duration to incidents that involve no HAZMAT at all because fires and evacuations are generally more likely to occur in HAZMAT incidents than in non-HAZMAT incidents. Therefore, the central analysis assumes that any differentials in the probability of a closure or the duration of a closure associated with fires or evacuations can be attributed to the presence of

HAZMAT. Thus, for the 67 percent of ARs that do not involve a fire or evacuation, the additional cost of *delay due to HAZMAT* is zero in this analysis. However, this method may underestimate the true cost of delay resulting from HAZMAT incidents by assuming that if there is no fire or evacuation, there is no additional cost of delay attributable to HAZMAT. This assumption is explored further by allowing for the possibility that for AR incidents without fire or evacuation, some portion of delay probability and/or delay duration is attributable to HAZMAT (see Section 3.2.5).

### 3.2.1 Data

The incidents reported using PHMSA Form 5800.1 during the 10-year period January 1, 2010 through December 31, 2019 form the basis for this analysis.[20] During this period, there were 268 total ARs, including 109 incidents with a closure of one hour or more, and 5,888 NARs, 92 of which resulted in a closure. This data included four ARs with fatalities and one NAR with a fatality.[21] However, in all four AR cases, the fatalities were not related to HAZMAT and in the NAR case, the incident did not result in a closure.[22] For NARs, the median duration of a closure was four hours (see Table 6), all of which can be attributed to the presence of HAZMAT. For ARs the median duration was 24 hours and the analysis to estimate the impact of the presence of HAZMAT is described below.

**Table 6. Summary Statistics for Closure Duration (Hours)**

| Incident Type | Median | Mean | Std. Deviation |
|---|---|---|---|
| NARs (N=92) | 4 | 6.61 | 9.22 |
| ARs (N=109) | 24 | 33.82 | 46.39 |

For ARs, the HAZMAT incident reports from the Form 5800.1 data were matched with a corresponding FRA incident report using location and time characteristics. However, a match in the FRA data was not found for 80 ARs. Therefore, some incident characteristics derived from the FRA data are described simply as “unknown” in this analysis. The estimation data set describes the 268 ARs with the following

[20] This time period was chosen to cover a decade prior to the beginning of this research effort and does not include earlier releases. For example, the large Cherry Valley, Illinois crash in June 2009 that resulted in a large release of ethanol and a loss of life is prior to period of data analysis.

[21] Report numbers for ARs with a non-HAZMAT related fatality: I-2012050222, I-2012060157, X-2014100027, X-2016070619. Report number for NAR with HAZMAT-related fatality but no closure of a major transportation artery: E-2011100306.

[22] When a HAZMAT incident involves a fatality, PHMSA's Office of Hazardous Materials Safety collects additional information about the incident, such as police or coroner's reports or death certificates, and for purposes of the 5800.1 data collection, makes a determination whether exposure to the hazardous material directly caused or contributed to the fatality(ies). For example, if an automobile collided with a cargo tank carrying gasoline and the automobile driver was killed due to the collision, then the fatality was not caused by the hazardous material. If, however, the accident resulted in the release of gasoline from the cargo tank and a resulting fire killed the automobile driver, then the fatality was caused by the hazardous material.
Source: Guide for Preparing Hazardous Materials Incident Reports, https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/docs/reporting_instructions_rev.pdf

descriptors: [23]

- Indicator for whether there was a closure of one hour or longer (yes or no)
- The duration of the closure in hours
- Indicators for influence of HAZMAT:[24]
    - Indicator for whether the incident resulted in a fire (yes or no)
    - Indicator for whether the incident resulted in an evacuation (yes or no)
- The facility type where the incident occurred (mainline, siding/yard/industry siding, or unknown)
- Indicator for whether the incident involved a non-HAZMAT fatality (yes or no)[25,26]

The summary statistics for these variables are shown in Table 7, below for all ARs (N=268) and only ARs resulting in a closure (N=109), respectively.

**Table 7. Summary Statistics for ARs**

| Statistic | All ARs | ARs with Closure |
|---|---|---|
| Number of Incidents | 268 | 109 |
| Percent with Closure | 41% | 100% |
| Percent with No Fire or Evacuation | 67% | 49% |
| Percent with Fire Only (no evacuation) | 5% | 7% |
| Percent with Evacuation Only (no fire) | 21% | 28% |
| Percent with Fire and Evacuation | 7% | 16% |
| Percent on Mainline | 43% | 65% |
| Percent on Siding/yard/industry siding | 28% | 12% |
| Percent on Unknown Facility Type | 30% | 23% |
| Percent with Fatality (non-HAZMAT) | 1% | 3% |

---

[23] Other variables not found to be informative in explaining the duration of a closure were the speed of the train, detail on incident cause (i.e., collision versus derailment), and whether the incident occurred at a grade crossing. Furthermore, the number of HAZMAT cars and HAZMAT cars derailed was considered, but because this information is available only for the 70 percent of ARs that were matched to the FRA incident data, it was not included in the final analysis.

[24] Other indicators of the influence of HAZMAT were investigated but not found significant. The indicator for explosions were found to be strongly associated with fire indicator and did not provide additional explanatory power. Indicators for the incident involving toxic by inhalation (TIH) commodities and the presence of environmental damage were also not statistically significant.

[25] The data does contain an indicator for HAZMAT fatalities. However, there were no ARs resulting in a HAZMAT fatality in the data.

[26] Railroad industry stakeholders suggested that NTSB investigations are also a determinant of duration of track closure. The model does not explicitly account for the effect of an NTBS investigation, so the results implicitly assume that NTSB investigations are present at the typical experienced frequency.

### 3.2.2 Regression Results

Variables representing the influence of HAZMAT (yes/no if a fire or evacuation occurred) and several controls were examined for their statistical significance in explaining closures using two stages of regressions. The first stage was a probit model, which used all ARs (268 observations) models the probability of a closure of one hour or more. The probit model allows the dependent variable to take only two values (closure or no closure). The resulting coefficients are z-scores that ultimately can be converted to probabilities to estimate the probability of a closure. The second stage model uses ordinary least squares (OLS) to determine the impact of the variables on the natural log of the closure duration, given that a closure occurred, and uses only the ARs with a closure (109 observations).

Table 8 shows the results for the first stage probit model. *Evacuation Only* and *Fire and Evacuation* variable coefficients are positive and significant showing that incidents with these characteristics are more likely to result in the closure of a rail line. In addition, the model results show that incidents on a siding or yard are less likely to result in a closure than an incident on a mainline (which matches expectations). Incidents for which the facility type is unknown (because a match for the incident was not found in the FRA data) are also less likely to result in a closure than an incident known to have occurred on a mainline. The coefficient on *Non-HAZMAT Fatality* is not statistically significant but is included to control for the possibility that incidents with fatalities tend to be more likely to result in a line closure and may be correlated with fires or evacuations.

**Table 8. Regression Results for Stage One (Probit)**

| Variables | Closure (Z-Score) |
|---|---|
| Evacuation Only | 0.479** |
| N/A | (0.206) |
| Fire and Evacuation | 1.242*** |
| N/A | (0.381) |
| Siding/Yard | -1.112*** |
| N/A | (0.216) |
| Facility Type Unknown | -0.617*** |
| N/A | (0.198) |
| Non-HAZMAT Fatality | 0.449 |
| N/A | (0.795) |
| Constant | 0.028 |
| N/A | (0.144) |
| Observations | 268 |
| Log Likelihood | -151.478 |
| Akaike Inf. Crit. | 314.956 |

Note: **p<0.05; ***p<0.01

Table 9 shows the results of the second stage model of closure duration. *Fire Only* and *Fire and Evacuation* variables are positive and significant showing that incidents with these characteristics have longer closure durations. The OLS model shows that closures from incidents on sidings or in yards have lower durations than incidents on mainline. Again, *Non-HAZMAT Fatality* is not statistically significant but is included to control the possibility that incidents with fatalities tend to result in longer duration closures and may be correlated with fires or evacuations.

**Table 9. Regression Results for Stage Two (OLS)**

| Variables | Ln(Closure Duration) |
|---|---|
| Fire Only | 1.304*** |
| N/A | (0.400) |
| Fire and Evacuation | 0.797*** |
| N/A | (0.296) |
| Siding/Yard | -1.123*** |
| N/A | (0.322) |
| Facility Type Unknown | -0.402 |
| N/A | (0.250) |
| Non-HAZMAT Fatality | 0.710 |
| N/A | (0.648) |
| Constant | 2.920*** |
| N/A | (0.145) |
| Observations | 109 |
| $R^2$ | 0.287 |
| Adjusted $R^2$ | 0.253 |
| Residual Std. Error | 1.051 (df = 103) |
| F Statistic | 8.304*** (df = 5; 103) |

Note: **p<0.05; ***p<0.01

### 3.2.3 Interpretation

An estimated parameter from the Stage One probit regression represents the expected change in the z-score for a one-unit change in the explanatory variable it is associated with (in this case all explanatory variables are indicator variables). A z-score represents the number of standard deviations away from the mean a data point is. These z-scores can be converted to represent the probability that an incident will result in a closure, given an incident's characteristics, using the cumulative distribution function of a standard normal distribution.[27] These probabilities can be generated for all three facility types present in this analysis: mainline, siding/yard, or unknown. Specific to each facility type (indexed by $f$), the probit results can be used to calculate an estimated probability of a closure depending on the incident type (indexed by $i$):

- $i = 0$ for incidents with no evacuation or fire,
- $i = 1$ for incidents with a fire only,
- $i = 2$ for incidents with only an evacuation, and
- $i = 3$ for incidents with both a fire and an evacuation.

[27] The standard normal distribution has a mean of zero and a standard deviation of one. For example, if the z-score for an incident is zero, the score lies at the mean of the normal distribution, and converting to probability using the standard normal distribution would result in a 50 percent probability of a closure.

The probability of a closure for each of these facility and incident types are provided in Table 10. Note that the estimates in Table 10 apply only to incidents that do not involve a fatality.

**Table 10. Predicted Probability of Closure by Incident Type and Facility Type (for Non-Fatal ARs)**

| Facility Type ($f$) | No Evacuation or Fire ($i$=0) | Fire ($i$ = 1) | Evacuation ($i$ = 2) | Fire and Evacuation ($i$ = 3) |
|---|---|---|---|---|
| Mainline | 51% | 51% | 69% | 90% |
| Siding/Yard | 14% | 14% | 27% | 56% |
| Unknown | 28% | 28% | 46% | 74% |

The Stage Two (natural log OLS) regression produces estimates of the expected duration of a closure (given that there is one), for each facility type ($f$) and incident type ($i$). The predicted durations of closures (for incidents that do not result in a non-HAZMAT fatality) are provided in Table 11.

**Table 11. Predicted Duration of Closure given a Closure by Incident Type and Facility Type (Hours) (for Non-Fatal ARs)**

| Facility Type ($f$) | No Evacuation or Fire ($i$=0) | Fire ($i$ = 1) | Evacuation ($i$ = 2) | Fire and Evacuation ($i$ = 3) |
|---|---|---|---|---|
| Mainline | 18.5 | 68.3 | 18.5 | 41.1 |
| Siding/Yard | 6.0 | 22.2 | 6.0 | 13.4 |
| Unknown | 12.4 | 45.7 | 12.4 | 27.5 |

As can be seen in Table 11, incidents with *fire only* ($i$=1) have a longer predicted duration than incidents resulting in a *fire and evacuation* ($i$ = 3) across all facility types. At first glance, this appears to be an unexpected result. However, there may be other characteristics of the incidents not accounted for in the analysis which contribute to their duration.[28] One possible explanation for this result is the proportion of each type of closure which also involves explosions, as shown in Table 12. Incidents with a *fire and evacuation* have a higher proportion of incidents with explosions than those with fire alone. As incidents resulting in explosions may result in faster cleanup because of the quick consumption of materials by the explosions themselves, this serves as one possible explanation. In addition, as can be seen in Table 15, the number of non-fatal ARs with *fire and evacuation* (n=18) or *fire only* (n=13) are relatively small compared to those with *evacuation only* (n=55) or *no fire or evacuation* (n=178). The unintuitive discrepancy in comparative duration length may be the result of the small sample size.

Another possible explanation is the packing group of the materials involved in each incident. Packing groups are used to designate the danger level of HAZMAT shipped, with Packing Group I being the highest danger and Packing Group III being the least danger.[29] Closure incidents with a *fire and evacuation* have a higher proportion of incidents where the materials involved are in Packing Group I, whereas the majority of incidents with a *fire only* involve materials in Packing Group II, as seen in Table

[28] Other explanatory variable for the duration analysis were explored but not found to be statistically significant.
[29] 49 CFR § 173 (2011) https://www.govinfo.gov/app/details/CFR-2011-title49-vol2/CFR-2011-title49-vol2-part173.

13.[30] This could indicate that when an evacuation is involved in addition to a fire, there may be faster clean-up of an incident due to the danger presented by the materials involved, which may have also caused the evacuation. While these explanations provide possible reasons for the differences in duration across the two categories, it should be noted that duration of closures may be affected by many other factors which are not quantified here, such as the location, shipping package type, specific HAZMAT involved, and environmental reporting requirements.[31]

**Table 12. Percent of Closure Incidents with Explosions by Incident Type**

| Incident Type ($i$) | Percent with Explosions |
|---|---|
| Fire Only | 13% |
| Fire and Evacuation | 24% |

**Table 13. Percent of Closure Incidents by Packing Group and Incident Type**

| Incident Type ($i$) | Packing Group I | Packing Group II | Packing Group III | N/A |
|---|---|---|---|---|
| Fire Only | 0% | 88% | 0% | 13% |
| Fire and Evacuation | 47% | 35% | 18% | 0% |

### 3.2.4 Application

The regression analyses described above produce estimates of expected probability of closure and expected duration of a closure for incidents with fire and/or evacuations ($i$ = 1, 2, or 3) and for incidents without fires or evacuations ($i$ = 0). To estimate the cost of delay related to presence of HAZMAT, the social cost of delay is estimated for the durations of closure listed in Table 11. The *expected* social cost of delay for each incident type is generated by multiplying the social cost of delay for the duration associated with a fire or evacuation by the probability of a closure from Table 10 for each incident type. Then the expected social cost of delay for incidents *with* fire or evacuations are compared to the counterfactual, i.e. the expected social cost of delay for incidents *without* a fire or evacuation. The difference in costs is then weighted by the percent of incidents in the 10-year incident history with those characteristics. Table 14 shows those percentages for each facillty type and incident type from the 10-year incident history. Recall that 1.5 percent of AR incidents involved a fatality, and in all cases those fatalities were not related to the presence of HAZMAT. This analysis assumes that any above average closure durations for those incidents were most likely related to those non-HAZMAT fatalities and thus assigns a zero HAZMAT-related cost to them.

Of the remaining 98.5 percent of incidents, 42 percent occurred on a mainline, 28 percent occurred on a

[30] Not all HAZMAT can be categorized into packing groups. The N/A column in Table 13. Percent of Closure Incidents by Packing Group and Incident Type involves flammable gasses, which do not have a packing group.
[31]There may be more than one packing group per incident, as an incident can involve release of multiple materials. For illustrative purposes, the most severe packing group was taken from each incident to represent the danger of materials involved, where Packing Group I is the most dangerous, and assuming items without a packing group are least dangerous.

siding/yard, and 30 percent occurred on an unknown facility type (unable to match with an FRA incident record) as shown in Table 15. Of the mainline incidents, 50 percent did not involve a fire or evacuation. As explained above, in the central analysis no delay cost is estimated for those incidents because there is not a basis for estimating the incremental delay created by the presence of HAZMAT in the rail accident and they are used as a counterfactual condition to represent the expected probability of a closure and duration of a closure for incident that does not involve HAZMAT. For the remaining 50 percent, the delay cost attributed to the presence of HAZMAT is generated by first estimating the delay cost given the duration of closure associated with incidents that include fires and/or evacuations ($I$ = 1, 2, or 3) and subtracting the estimated cost of delay given the probability of closure and duration of closure associated with incidents without fires or evacuations ($i$ = 0). For example, mainline incidents with a fire and evacuation are expected to cause a closure of 41.1 hours. The cost of delay estimated for a 41.1 hour closure is compared to the cost of delay estimated for a closure of 18.5 hours (the duration associated with a mainline incident with no fire or evacuation), after each is weighted by its respective probability of closure from Table 10 (90 percent for incidents with *fire and evacuation* and 51 percent for incidents with *no fire or evacuation*). The difference in cost is then weighted by the percent of incidents in the 10-year history that were of that type (13 percent from Table 15).

**Table 14. Count and Percent of Incidents by Facility Type (for Non-Fatal ARs)**

| Facility Type ($f$) | All Non-Fatal ARs p($f$) |
|---|---|
| Mainline | 111 (42%) |
| Siding/Yard | 74 (28%) |
| Unknown | 79 (30%) |

**Table 15. Count and Percent of Incidents by Facility Type and Incident Type (for Non-Fatal ARs)**

| Facility Type ($f$) | No Evacuation or Fire $p(i=0\|f)$ | Fire $p(i=1\|f)$ | Evacuation $p(i=2\|f)$ | Fire and Evacuation $p(i=3\|f)$ |
|---|---|---|---|---|
| Mainline | 55 (50%) | 8 (7%) | 34 (31%) | 14 (13%) |
| Siding/Yard | 60 (81%) | 0 (0%) | 12 (16%) | 2 (3%) |
| Unknown | 63 (80%) | 5 (6%) | 9 (11%) | 2 (3%) |

Equation 1 provides a formal representation of the expected social cost of delay from HAZMAT for an AR ($j=AR$) at a specific location $l$. $SocialCost(l,d_{i,f})$ refers to the social cost of delay for an incident at location $l$ with the duration of closure $d$ associated with incident type $i$ on facility type $f$ which can be found in Table 11 and similarly $SocialCost(l,d_{i=0})$ refers to the social cost of delay for an incident at location $l$ with the duration associated with an incident with *no fire or evacuation* ($i$=0), which is a representation of the counterfactual where there is no HAZMAT involved in the incident. Both of those social costs are weighted by the estimated probability of a closure $q(i,f)$ for an incident of that type and facility type from Table 10 and the difference is taken and weighted by $p(i/f)$, the conditional probability of an incident of type $i$ occurring, given that the incident occurs on facility type $f$. The weighted differences are then summed across all incident types ($i$ = 0, 1, 2, 3). The resulting expected cost of delay for each facility type is then weighted by $p(f)$, the probability of an incident occurring on the facility type, to produce the expected social delay cost of an AR at location $l$ if there are no fatalities. That total value is then multiplied by 98.5 percent to represent the percent of ARs that do not have non-HAZMAT fatalities. A cost attributable to HAZMAT of $0 is implied for the 1.5 percent of ARs that do have fatality, since those fatalities were not related to the presence of HAZMAT. The method for estimating the social cost of a closure of duration $d$ at any location $l$ is discussed in the following sections.

$$ExpectedSocialCost_{j=AR,l} = 0.985 \times \sum_f p(f) \sum_i p(i|f) \times [q(i,f) \times SocialCost(l, d_{i,f}) - q(i=0,f) \times SocialCost(l, d_{i=0})] + 0.015 \times \$0$$

**Equation 1. Expected Social Cost of Delay due to HAZMAT in an AR**

### 3.2.5 Sensitivity Analyses – Closure Probability and Duration Attributable to HAZMAT

The duration of closure parameters used in the central analysis were developed by assuming that only differentials in the probability of a closure or the duration of a closure associated with HAZMAT incidents with fires or evacuations (i.e., $i > 0$) compared to HAZMAT incidents without fires or evacuations (i.e., $i = 0$) can be attributed to the presence of HAZMAT. That is, the probability of closure and expected duration of HAZMAT incidents without fires or evacuations $(i = 0)$ is used as a counterfactual to represent the characteristics of a non-HAZMAT incident. Because the counterfactual characteristics for non-fire/non-evacuation HAZMAT incidents are largely the same as the observed characteristics, the model does not estimate any impact of HAZMAT for those incidents. This method may result in underestimation of the impacts of HAZMAT on closure duration. To account for the possibility that some portion of the probability of closure and closure duration in those incidents without fire or evacuation is attributable to HAZMAT, sensitivity analyses were performed in which an alternative counterfactual incident type ($i=4$), is introduced. For this alternative counterfactual incident type, the probability of closure and duration due to HAZMAT is a linear function of the probability and duration for incidents without fire or evacuation ($i=0$) as shown in Equation 2 and Equation 3, where $\mathrm{A}$ has a value between 0% and 100%. The estimated social cost of delay is then described by Equation 4, below.

$$q(i=4,f) = \mathrm{A} \times q(i=0,f)$$

**Equation 2. Probability of Closure for an Incident with No HAZMAT Estimated for Sensitivity Analysis**

$$d_{i=4,f} = \mathrm{A} \times d_{i=0,f}$$

**Equation 3. Duration of Closure for an Incident with no HAZMAT Estimated for Sensitivity Analysis**

$$ExpectedSocialCost_{j=AR,l} = 0.985 \times \sum_f p(f) \sum_i p(i|f) \times [q(i,f) \times SocialCost(l, d_{i,f}) - q(i=4,f) \times SocialCost(l, d_{i=4})] + 0.015 \times \$0$$

**Equation 4. Expected Social Cost of Delay due to HAZMAT in an AR for Sensitivity Analysis**

The central analysis assumes that 0 percent of the probability of closure is attributable to HAZMAT (A = 100%) for incidents without fires or evacuations. In comparison, the sensitivity analyses assume that 50 percent (A=50%) and 100 percent (*A*=0%) is attributable to HAZMAT. These probability values for the alternative counterfactual incident ($i$ = 4) are shown in Table 16.

**Table 16. Predicted Probability of Closure by Facility Type and Incident Type used in Sensitivity Analyses (for Non-Fatal ARs)**

| Facility Type ($f$) | No Evacuation or Fire ($i$=4), $A$=100% (Central Analysis) | No Evacuation or Fire ($i$=4), $A$=50% (Sensitivity) | No Evacuation or Fire ($i$=4), $A$=0% (Sensitivity) |
|---|---|---|---|
| Mainline | 51% | 26% | 0% |
| Siding/Yard | 14% | 7% | 0% |
| Unknown | 28% | 14% | 0% |

Similarly, the counterfactual incident durations ($i$ = 4) are estimated by assuming that a non-zero proportion of the closure duration experienced for incidents without fires or evacuations is attributable to HAZMAT, using values for A of 50 percent and 0 percent of the duration as shown in Table 17.

**Table 17. Predicted Duration of Closure given a Closure by Incident Type and Facility Type (Hours) (for Non-Fatal ARs) used in Sensitivity Analyses**

| Facility Type ($f$) | No Evacuation or Fire ($i$=4), ($A$ = 100%) (Central Analysis) | No Evacuation or Fire ($i$=4), ($A$= 50%) (Sensitivity) | No Evacuation or Fire ($i$=4), ($A$= 0%) (Sensitivity) |
|---|---|---|---|
| Mainline | 18.5 | 9.3 | 0.0 |
| Siding/Yard | 6.0 | 3.0 | 0.0 |
| Unknown | 12.4 | 6.2 | 0.0 |

Two sensitivity analyses are explored. One sensitivity analysis assumes that both the probability of closure and duration of closure are 50 percent attributable to HAZMAT (A=50% in Equation 2 and Equation 3). The other sensitivity analysis assumes that the probability of closure is 100 percent attributable to HAZMAT, and therefore the probability and duration are both equal to zero (A=0% Equation 2 and Equation 3).

The probabilities of closure and duration values for the counterfactual incident are smaller than those used in the central analysis, therefore the overall expected social cost of delay attributable to HAZMAT in these sensitivity analyses is larger than in the central analysis. Using the central analysis, which assumes that zero percent of the closure probability and duration are attributable to HAZMAT for $i = 0$ incidents, as well as the sensitivity where the entirety of the closure probability and duration for $i = 0$ is attributable to HAZMAT, allows for the estimation of lower and upper bounds impacts of presence of HAZMAT on the social cost of delay, respectively. The results of these sensitivity analyses are presented in Section 9.

## 3.3 Flowing Waybills to Determine Freight Traffic Volumes

To identify the amount of freight traffic that would be impacted by a rail line closure at a particular point in the rail network, this analysis flows freight rail waybill records over a geospatial representation of the rail network in North America. The total annual carloads passing over each link were then transformed into average trains per day (TPD). The rail network, the waybill data, and the routing algorithm used to flow the waybills are discussed below.

### 3.3.1 Rail Network

The geospatial rail network used in this analysis is the North American Rail Network (NARN), developed and maintained by FRA and published by the Bureau of Transportation Statistics.[32] The NARN contains the links and nodes of the network represented in GIS shapefiles and the version used for this analysis was obtained from the FRA on March 21, 2022. Among other descriptors, the data included in the NARN includes:

- Link owner railroads, as well as fields listing trackage rights for other railroads;
- Number of mainline tracks;
- Link length in miles; and
- Track Class.

[32] Federal Railroad Administration "Maps – Geographic Information Systems" https://railroads.dot.gov/maps-and-data/maps-geographic-information-system/maps-geographic-information-system


**Figure 4. Mainline Number of Tracks**

### 3.3.2 Waybill Data

The waybill data used in this analysis is from the 2018 confidential Carload Waybill Sample provided by the Surface Transportation Board (STB).[33] The data represent a sample of carload waybills for all U.S. rail traffic submitted by railroads that terminate 4,500 or more revenue carloads annually. Each waybill provides the commodity, car type, number of carloads represented by the waybill, the origin and destination of the shipment plus any intermediate interchanges, and the railroads that handled the shipment for each leg of its journey (among many other descriptors). Origins and destinations are recorded using the Freight Station Accounting Code and Standard Point Location Code. Because it is a sample, and because it is gathered from only larger railroads, the waybill data may not show the complete picture of all freight movements in the United States, particularly shipments that are handled solely by Class 2/3 railroads. However, the STB waybill data is the best available measure of U.S. freight rail traffic.

[33] Surface Transportation Board. "Carload Waybill Sample" https://prod.stb.gov/reports-data/waybill/

To route the shipment, each waybill is separated into "legs" representing the portion of the journey handled by a single railroad. For example, a waybill representing a shipment that was handled by three railroads would be represented by three legs: the first leg representing the portion of the movement from the origin to the first interchange; the second leg representing the portion of the movement from the first interchange to the second interchange; and the third representing the portion of the movement from the second interchange to the destination.

### 3.3.3 Routing Waybill Records on the NARN

This analysis uses an algorithm that gives preference to routes with higher track class to assign carloads to the NARN. The routing algorithm used in this analysis is an all-or-nothing traffic assignment meaning that for each unique combination of origin, destination, and handling railroad, for a leg specified in the waybill record, a single best route is identified. The possible routings are confined to the network of the handling railroad specified in the waybill. Each railroad's network is defined by links in the NARN where the railroad is an owner or has trackage rights.

For the track class routing algorithm, Table 18 shows the factors used to adjust the relative length of each link to account for differences in track class among alternate potential routes. The factors are derived from the FRA maximum allowable speeds in miles per hour (MPH) for freight trains on each class of track.

**Table 18. Relative Length Adjustment Factors by Track Class**

| Track Classification | Maximum Speed | Relative length compared to Class 1 Track |
|---|---|---|
| Class 1 Track | 10 MPH | 1/1 |
| Class 2 Track | 25 MPH | 1/2.5 |
| Class 3 Track | 40 MPH | 1/4 |
| Class 4 Track | 60 MPH | 1/6 |
| Class 5 Track | 80 MPH | 1/8 |

Unfortunately, there is not publicly available carload routing information which can be used to identify if this routing algorithms produces results that closely resemble actual rail routings or to otherwise calibrate the routing algorithm. Further, actual railroad operations result in variability in traffic routing which can be observed in the variance of route distances in waybill records with the same origin, destination, and handling railroad.

Based on feedback from the railroad industry, a few modifications to the routing method described above are made. First, in Washington state, the routing algorithm was adjusted so that low priority traffic would be routed using the longer southern route, reserving the shorter east-west route in the center of the state for high priority intermodal traffic. This was done to approximate railroad routing practices in that area where a tunnel imposes a capacity constraint. Second, the Union Pacific railroad has two parallel routes running through east Texas and Arkansas. Before modification, the routing algorithm would have directed all relevant traffic to the shorter route, resulting traffic over expected capacity and leaving a great deal of excess capacity on the slightly longer parallel route. Feedback from railroad industry representatives indicated that in practice, traffic is split directionally on those two parallel routes such that northbound traffic uses one route and southbound traffic uses the other. The routing algorithm and modeling was adjusted to account for directionality of traffic flows and the impedances on the two routes were adjusted to direct traffic appropriately in that section of the rail network.

The results of the routing algorithm are displayed in Figure 5, below. Less than five percent of the unique waybill record legs could not be routed. These instances were usually due to less common origin, interchange, or destination points in the waybill not being found in the NARN. When evaluating waybill routing results by leg miles, only 1.9% could not be flowed.


**Figure 5. Annual Carloads Estimated Using Track Class Impedance**[34]

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[34] Categories are non-overlapping, e.g., the second category is greater than 150,000 and less than or equal to 450,000 carloads.

### 3.3.4 Rerouting Waybill Records on the NARN

The routings derived from the full network described in Section 3.3.3 are referred to as the baseline routing, i.e., the routings that would occur without an incident. To estimate the cost of rerouting for an incident in a certain location, the waybill data is flowed on a modified network *without* that location. The routings are identified for the same origin, destination, and handling railroad as specified in the original waybill data. Therefore, this analysis makes a simplifying assumption that railroads will not alter the interchange point for movement as a result of an incident. In actual practice, railroads may have additional flexibilities that may further reduce the cost of an alternate routing. As with the baseline routings, the alternate routings are confined to the network of the handling railroad specified in the waybill. The resulting alternate routings describe the routes that would be used if the location of the incident was closed. Appendix B contains maps describing the alternate routings for the locations explored as scenarios in this analysis. (The process of selecting the locations for analysis is described in Section 6.) The maps show the *change* in daily carloads for an alternate routing when a particular link is removed from the network, relative to the baseline. Track segments that experience increases in daily carloads compared to baseline are marked with yellow, orange, and red lines while track segments experiencing decreases in daily carloads are marked with various shades of blue lines. In some cases, no alternate routing is available. The maps showing these instances will only contain blue track segments because traffic volumes only go down since some waybill records cannot be flowed on the modified network with the specified link removed. This happens if the incident occurs on a spur of a particular railroad's network that has a connection to the rest of the railroad's network on only one side of the location of the incident. In the maps found in Appendix B, if one leg of a multi-leg waybill record cannot be routed, the entire movement for that waybill record will not be rerouted. Therefore, in some cases, the maps show network impacts far away from the location of interest. In some cases, some of the traffic can reroute while some cannot because routings are specific to the railroad specified for that leg in the waybill data. A certain location may have an alternate routing for one railroad but not for another railroad that runs traffic over that location.

### 3.3.5 Transforming Annual Carloads to TPD

Each waybill record and the carloads it describes is assigned to one of four commodity types based on the STB car type associated with the waybill record as shown in Table 19. The commodity types are derived from the *National Rail Freight Infrastructure Capacity and Investment Study*, a 2007 report authored by Cambridge Systematics and sponsored by the AAR (Cambridge Systematics, 2007). The commodity types are:

- Automotive: assembled automobiles, vans, and trucks moving in multilevel cars;
- Bulk: grain, coal, and similar bulk commodities moving in unit trains;
- Intermodal: commodities moving in truck trailers on flat cars (TOFC), containers on flat cars (COFC) or specialized intermodal cars; and

- General Merchandise: everything else, including commodities moved in box cars and tank cars.

**Table 19. Type of Train Car by Commodity Type**

| Commodity Type | Type of Train Car (STB Car Type) |
|---|---|
| Automotive | Flat Car – Multi-level |
| Bulk | Plain Gondolas, Equipped Gondolas, Covered Hopper, Open Top Hoppers |
| Intermodal | Flat Car TOFC/COFC |
| General Merchandise | Plain Box Cars, Equipped Box Cars, Refrigerator Cars, Flat Cars – General Service, Flat Cars – Other, Tank Cars, and All Other Freight Cars |

The annual carloads for each commodity type on each link in the network are factored to account for empty carloads that must be repositioned, as the waybill sample only provides records for revenue movements. The Uniform Rail Costing System supplies data on the number of empty car-miles and loaded car-miles for each Class 1 railroad.[35] In 2018, 41.8 percent of all Class 1 carload miles in 2018 are empty, and 58.2 percent are loaded. To represent movements of empty cars on the network, the waybill records are duplicated, the origin and destination stations for each leg of the movement are swapped, and the original carload count is factored by 0.718 (from 41.8/58.2) to estimate total carloads on each network link. Class 2/3 railroads do not have equivalent publicly available data on empty cars, and so the Class 1 factor is applied to Class 2/3 railroads' track segments.

Estimated daily carloads for each commodity type on each link are converted to average TPD by dividing by the average number of carloads per train for the commodity type. Table 20, below presents the information on average carloads per train by commodity type. These values are based on 2007 values but have been adjusted upwards by 10 percent to account for an industry shift towards precision scheduling and longer train lengths.[36] The commodity specific values in Table 20 are specific to Class 1 railroads.[37] Any link that has Class 1 ownership or Class 1 trackage rights in the NARN is assigned these Class 1 railroad train lengths. For Class 2/3 railroads, the analysis uses an average of 26 carloads per train regardless of commodity type.[38] The analysis assumes 1.5 intermodal containers per car for Class 2/3 railroads. Finally, average TPD is transformed into an hourly arrival rate for freight trains at each location on the network ($af_l$) by dividing by 24 hours.[39]

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[35] Surface Transportation Board. "Uniform Rail Costing System (URCS)." Surface Transportation Board. Last accessed: January 11, 2021. https://prod.stb.gov/reports-data/uniform-rail-costing-system/

[36] Dick, C. T., Zhao, J., Liu, X., & Kirkpatrick, S. W. (2021). Quantifying Recent Trends in Class 1 Freight Railroad Train Length and Weight by Train Type. Transportation Research Record, 2675(12), 890–903. https://doi.org/10.1177/03611981211031534
Barrow, N. (2019). Precision Scheduled Railroading—Evolution or revolution? *International Railway Journal.* Retrieved February 5, 2021, from https://www.railjournal.com/in_depth/precision-scheduled-railroading-evolution-revolution/

[37] Eastern Railroads: CN, CSX, NS. Western Railroads: BNSF, CP, KCS, UP

[38] The assumption of 26 carloads on a Class 2/3 train is based on several studies of railroad operations conducted for Kansas DOT (Babcock & Sanderson, 2004) and (Fitzsimmons et al., 2017), and for Texas DOT with FHWA (Qiao et al., 2016).

[39] This method implicitly makes an assumption of uniform traffic levels over the year, month, day of week, and time of day.

**Table 20. Average Number of Carloads per Train by Commodity Type**

| Commodity Type | Eastern Railroads | Western Railroads |
|---|---|---|
| Automotive | 62.7 | 70.3 |
| Bulk | 94.6 | 123.6 |
| General Merchandise | 90.2 | 88.8 |
| Intermodal (TOFC/COFC count) | 121.8 | 180.7 |
| All Class 2/3 | 26 | 26 |

*Source: Class 1 (Cambridge Systematics, 2007) (Dick, C. T., Zhao, J., Liu, X., & Kirkpatrick, S. W. 2021), Class 2/3 see footnote 38*

The results of transforming annual carloads to TPD are displayed in Figure 6, below.

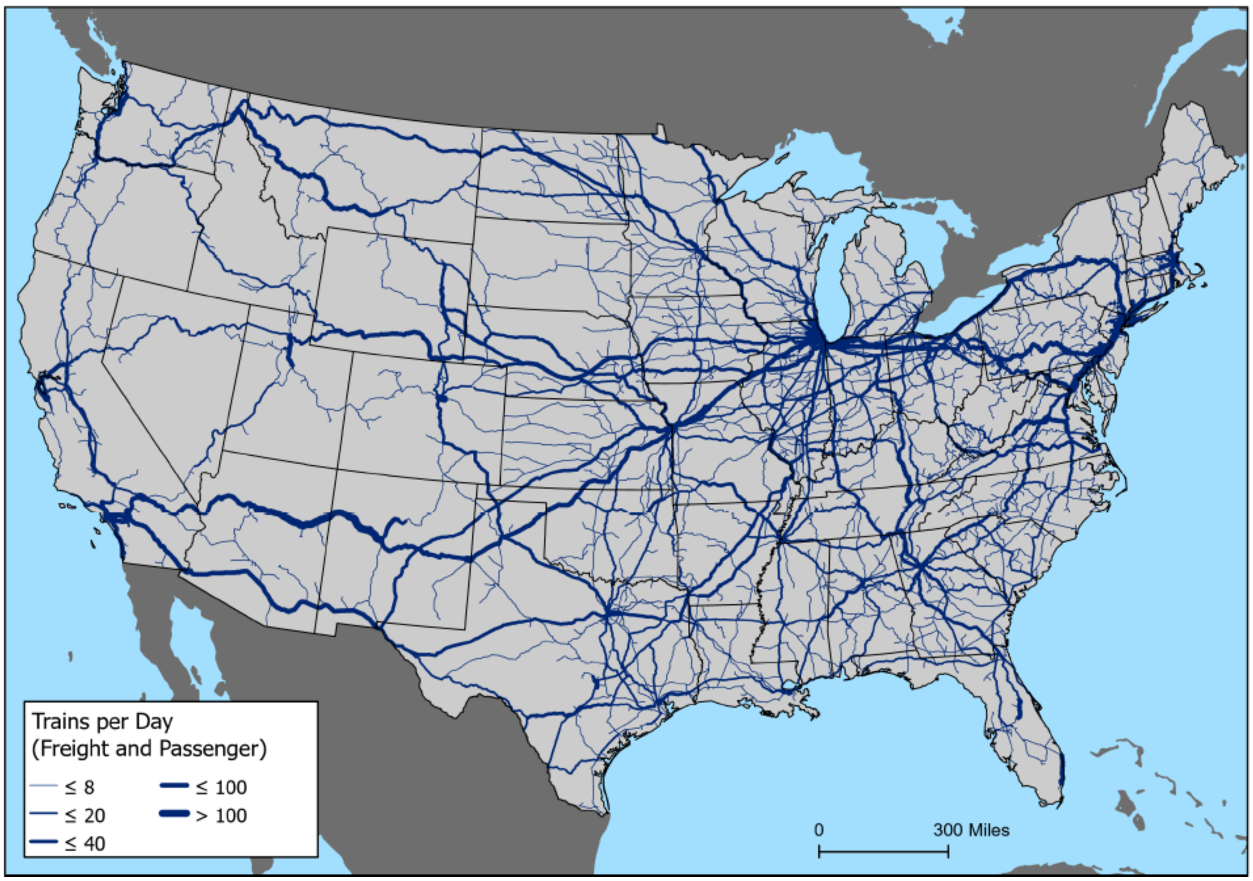


**Figure 6. Freight and Passenger TPD**[40]

### 3.3.6 Calculating Time to Traverse

The cost of rerouting requires information on the time required to traverse the links on the alternate routing compared to the baseline routing. Each link on the network includes its length in miles and its

[40] Categories are non-overlapping, e.g., the second category is greater than eight and less than or equal to 20 trains per day.

track class. To calculate the time, in hours, needed to traverse a link requires the distance traveled and the average or expected speed for trains traveling over that link. The data found in the Rail Service Data provided by STB (average of 2018 weekly speed values) contains information on average network speeds reported by the Class 1 railroads.[41] In addition, the portion of train-miles that occurred on each type of track class in the baseline routing for each Class 1 railroad was calculated. Then a sum of least squares methodology was used to identify 0.41 as a factor to transform maximum speed limits for a certain track class to an estimated train speed for each track class. The data used for the least squares analysis is provided in Table 21 and the resulting implied average speeds by track class are provided in Table 22.

**Table 21. Average Train Speeds and Share of Carload Miles on Each Track Class, By Class 1 Railroad**

| Class 1 Railroad | Track Class 1 Share | Track Class 2 Share | Track Class 3 Share | Track Class 4+ Share | Average Speed | Total Carload Miles |
|---|---|---|---|---|---|---|
| BNSF | 0% | 1% | 6% | 92% | 24.5 | 15,372,719,318 |
| CN | 2% | 4% | 13% | 81% | 21.9 | 1,251,380,663 |
| CPRS | 2% | 9% | 42% | 48% | 22.9 | 421,606,303 |
| CSXT | 1% | 3% | 17% | 80% | 22.5 | 3,855,158,285 |
| KCS | 1% | 4% | 35% | 60% | 26.5 | 320,113,866 |
| NS | 0% | 3% | 14% | 82% | 19.0 | 4,760,712,788 |
| UP | 0% | 2% | 6% | 91% | 24.5 | 11,192,675,570 |

**Table 22. Implied Average Train Speed by Track Class**

| Track Classification | Maximum Speed | Implied Average Speed |
|---|---|---|
| Class 1 Track | 10 MPH | 4.1 MPH |
| Class 2 Track | 25 MPH | 10.3 MPH |
| Class 3 Track | 40 MPH | 16.5 MPH |
| Class 4 Track | 60 MPH | 24.7 MPH |
| Class 5 Track | 80 MPH | 32.8 MPH |

## 3.4 Capacity Modeling

A review of the available literature (summarized in Appendix A) found that the capacity of a link in the network depends on many factors including, track class, number of sidings, spacing of sidings, length of sidings, track grade, track curvature, signal type, mix of traffic, locomotive power, etc. (Lovett et al., 2017), (Schlake et al., 2011), (Cambridge Systematics, 2007), (Krueger, 1999). In addition to these track characteristics, yard capacity, crew availability, and access to fuel also impact the capacity of a rail line. However, any modeling exercise must make some simplifying assumptions and this effort is influenced not only by the need to abstract real world conditions to an executable model, but also by the lack of

[41] Surface Transportation Board. "Rail Service Data." Surface Transportation Board. Last accessed: December 17, 2020. https://prod.stb.gov/reports-data/rail-service-data/.

publicly available information related to the many factors that influence rail capacity.

The starting point of assigning capacities to each link the rail network is the information provided in the *National Rail Freight Infrastructure Capacity and Investment Study* (Cambridge Systematics, 2007). That study provides a range of capacities of network segments based on number of tracks, signal types, and mix of traffic**.** In this analysis, all track is assumed to have the capacities associated with control type Centralized Traffic Control or Traffic Control System ("CTC or TCS"), as shown in Table 23.

In that report, for that signal type and for a specific number of tracks, the lowest capacity is associated with an equal mix of train priorities (33 percent bulk trains, 33 percent intermodal trains, and 33 percent passenger trains) and the highest capacity is associated with traffic of a single type (100 percent of a single train type). To estimate the capacity for corridors with intermediate mixes of traffic, the Cambridge Systematics (2007) report first calculates the standard deviation of the traffic shares on each link and compares it to the maximum possible standard deviation of 0.47 associated with completely uniform traffic of all one type (see text box below for derivation). That factor is then used interpolate practical capacity for corridors with traffic mixes between 100 percent of a single type and a completely evenly mixed train traffic. This analysis adopts that same method which is a simplification of the actual capacities of any given network segment, but necessary for developing a tractable model.

**Table 23. Capacity Ranges for Signal Type and Number of Tracks**

| Number of Tracks | Type of Control | Even Mix of Multiple Train Types (TPD) | Single Train Type (TPD) |
|---|---|---|---|
| 1 | CTC or TCS | 30 | 48 |
| 2 | CTC or TCS | 75 | 100 |
| 3 | CTC or TCS | 133 | 163 |
| 4 | CTC or TCS | 173 | 230 |
| 5 | CTC or TCS | 248 | 340 |
| 6 | CTC or TCS | 360 | 415 |

*Source: (Cambridge Systematics, 2007)*

### Capacity Calculations: Hypothetical Link

For an example of how capacity is calculated for an individual link, consider a double track link with 20 bulk TPD, 14 intermodal TPD, and two passenger TPD, for a total of 36 TPD. The traffic mix in percentage terms is 55.6 percent bulk trains, 38.9 percent intermodal trains, and 5.6 percent passenger trains. A link hosting only a single type of traffic would have shares of 100 percent, 0 percent, and 0 percent for an average share of 33 percent. The formula to derive the standard deviation of traffic shares is shown in Equation 5. By that formula, the standard deviation for the example link is 0.21 and the standard deviation for a link with just one type of traffic is 0.47 (the maximum possible standard deviation).

$$Standard\ Deviation = \sqrt{\frac{\sum(X - mean)^2}{n}}$$

**Equation 5. Standard Deviation**

Where $X$ is a train type's share of traffic on a link, $mean$ is the mean share for all three train types on a link, and $n$, the number of train types, is three.

This standard deviation of 0.21 is 44.1 percent of the maximum standard deviation of 0.47 for a completely uniform mix of traffic. The difference in capacities between an even mix of train types and a single train type for double track is 25 TPD (100 TPD minus 75 TPD). Therefore, the capacity of this example is 75 TPD plus 44.1% times 25 TPD or 86 TPD.

Figure 7, below, compares the estimated capacities to combined freight and passenger TPD. Links colored green show where TPD are well below assumed capacity, links colored yellow show where TPD are near assumed capacity, links colored orange show where TPD are at assumed capacity while links colored red show instances where TPD exceeds assumed capacity.

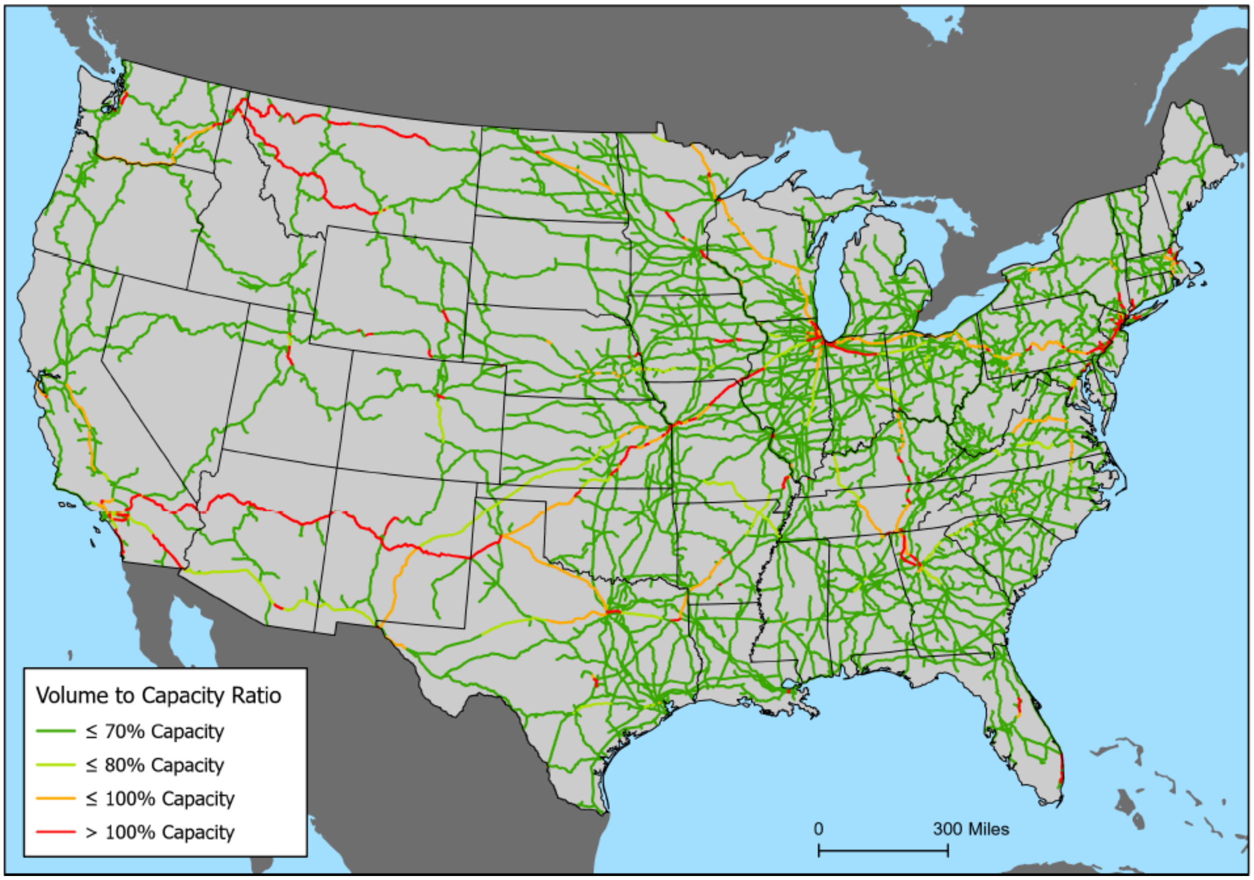


**Figure 7. Traffic Volume to Track Capacity Ratio**[42]

There are several possible explanations for the instances where volume exceeds capacity. First, the assumed capacity may be incorrect for any given link. This would not be surprising given the multitude of factors that impact capacity but that are not accounted for in the capacity estimates presented in Table 23. For instance, Figure 7 shows the BNSF Transcon line through Arizona to be running at above capacity. However, a study by Arizona DOT documents that volume on that route is 120 TPD which comports to the results of this analysis and well exceeds the maximum capacity of 100 TPD for a double track provided by the 2007 Cambridge Systematics study (Arizona Department of Transportation, 2010). In addition, 14 years have passed since those capacity estimates were developed and capacity expansion projects across the network may have altered what are considered prototypical capacities. Second, the information on traffic volumes is based on a sample of waybills and therefore is subject to sampling error. However, the waybill data used in this analysis is the best information publicly available, so no better alternative exists to estimate traffic volumes. Third, in some limited cases volumes on a link do actually exceed capacity resulting in longer travel times. The Cambridge Systematics study found that for less than one percent of the network in 2007, traffic exceeded capacity. However, Figure 7 shows much

[42] Categories are non-overlapping, e.g., the second category is greater than 70% capacity and less than or equal to 80% capacity.

more than one percent of the network experiencing traffic volumes above the practical capacity listed in Table 23.

Given the areas of uncertainty discussed above, this analysis adjusts the assumed capacity for any link that is near or above the capacity implied by Table 23. In making future projections on the need for capacity improvements the 2007 study by Cambridge Systematics assumed that railroads would invest in capacity enhancements when volume exceeded 70 percent of capacity. Based on that assumption from the Cambridge Systematics study, this analysis assumes that the traffic volumes used in the analysis are generally accurate and that railroads make appropriate investments so that there is always at least 30 percent spare capacity. For this analysis, the assumed capacity of any network link is the larger of either the relevant traffic mix adjusted capacity shown in Table 23 or the estimated traffic volume on that link resulting from flowing waybills divided by 70 percent (TPD/0.70). Figure 8 shows track capacities using the traffic mix adjusted capacity shown in Table 23, and Figure 9 shows track capacity after adjustments.


**Figure 8. Track Capacity *before* Adjustment**[43]

[43] Categories are non-overlapping, e.g., the second category is greater than 36 TPD and less than or equal to 44 TPD.


**Figure 9. Track Capacity *after* Adjustment[44]**

## 3.5 Monetization

The following section describes the monetization factors that are used to transform hours of train delay to the cost of train delay. The monetization factors are presented in 2021 dollars and primarily expressed in dollars per hour of train delay. The exception is non-idling fuel and emissions costs which are expressed as dollars per additional train-mile. Section 8 provides a suggested method for updating delay costs in the future to account for changes in these unit values.

### 3.5.1 Crew Costs

Crew costs per train hour of delay are derived from representative crew staffing levels for each freight train and the average hourly fully loaded wages for each crew position.

[44] Categories are non-overlapping, e.g., the second category is greater than 36 TPD and less than or equal to 44 TPD.

Crew wage data for Class 1 freight rail operators are from STB Form A and Form B quarterly data.[45] Labor wage rates are available for "train crews" (engineers and conductors).[46] These wages are computed from quarterly totals of wages paid and therefore represent a combination of straight time and overtime.[47] A December 2021 Bureau of Labor Statistics (BLS) "Employer Costs for Employee Compensation" shows that for unionized workers, wages comprise 60.1 percent of total compensation, excluding supplemental pay.[48] Thus, all wages are factored by 1.664 to account for the costs of employer provided benefits. The resulting hourly wage rates are presented in Table 24.

**Table 24. Crew Compensation and Employer Costs**

| Train Type | Employee Type | Hourly Wage (2021$) | Fully Loaded Hourly Wage Rate (2021$) |
|---|---|---|---|
| Freight | Engineers and Conductors | $36.79 | $61.22 |

Representative crew complements for each train type, developed in consultation with an FRA subject matter expert, are shown in Table 25. The composition of each crew is then multiplied by the hourly employment cost (wages plus benefits) of each crew member type to produce crew cost per train hour, as shown in Table 25.

**Table 25. Train Crew Complements and Total Crew Cost per Train Hour**

| Train Type | Crew Complement | Crew Cost per Train Hour |
|---|---|---|
| Freight | 1 engineer<br>1 conductor | $122.45 |

### 3.5.2 Equipment Costs

Train equipment costs capture the opportunity cost of locomotives and railcars that are delayed or rerouted. The equipment costs represent the capital costs associated with unproductive rail equipment.

#### *3.5.2.1 Train Characteristics*

Equipment costs are impacted by the total number of locomotives and railcars in use with each train. The number of locomotives per train can vary depending on several factors, including the size of the

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[45] Surface Transportation Board. "Quarterly Wage A&B Data" https://prod.stb.gov/reports-data/economic-data/quarterly-wage-ab-data/
[46] Engineer and conductor pay is reported together. As a result, the computed average hourly wage rate is effectively a weighted (by hours worked) average of all engineers and conductors.
[47] Supplemental pay was excluded as is it is largely comprised of overtime and similar pay. The wage base used for the fully loaded wage rate calculation includes overtime pay.
[48] Bureau of Labor Statistics. "Employer Costs for Employee Compensation – December 2021." News Release, Release Date: March 18, 2022, Bureau of Labor Statistics, Department of Labor. Last accessed June 15, 2022. https://www.bls.gov/news.release/archives/ecec_03192019.pdf

train, the grade of track being traversed, and priority of the goods being hauled. The analysis utilizes and average values of 2.6 locomotives for freight trains.[49] The number of carloads per train is provided in Table 20 in Section 3.3.5.

#### *3.5.2.2 Locomotive*

Hourly locomotive costs are the hourly depreciation costs of freight locomotives. Class 1 railroads report the purchase price of locomotives annually to the Surface Transportation Board.[50] The cost per locomotive for a six-year period (2015 to 2020) was calculated, converted to 2021 dollars, and averaged to find a mean locomotive purchase price of $2,809,485. No locomotive purchases for 2021 were available in the data. This mean purchase price was then converted to an annual payment that would be required for a 25-year loan with an interest rate of seven percent. That yearly cost was then divided by 8760 hours (365 days times 24 hours per day), resulting in a cost of $27.52 per locomotive-hour. Multiplying by 2.6 locomotives per train results in an estimated cost of $71.55 per train hour.

**Table 26. Locomotive Cost of Ownership**

| Locomotive Cost of Ownership | Value (2021$) |
|---|---|
| Locomotive Purchase Price | $2,809,485 |
| Lifespan (years) | 25 |
| Interest Rate | 7% |
| Locomotive Annual Cost | $241,083 |
| Cost per Locomotive Hour | $27.52 |
| **Cost per Train Hour** | **$71.55** |

#### *3.5.2.3 Railcar*

Railcar costs are based on a representative lease price of $692 per month.[51] Railcar lease rates can vary significantly based on the car type and commodity specific requirements, as well as due to demand for the railcar's commodity and lease terms. The $692 value represents the average lease rate from a large railcar leasing firm and is assumed to be representative of rates across the industry. Hourly railcar costs are calculated by dividing $692 per month by 720 hours (720 = 24 hours times 30 days), resulting in a railcar cost of $0.96 per hour per railcar.

### 3.5.3 Time Value of Freight

[49] Bureau of Transportation Statistics. "Rail Profile" U.S. Department of Transportation. Last accessed May 15, 2022. https://www.bts.gov/content/rail-profile Calculated by Class 1 Locomotive miles divided by train miles with most recent available data, 2004.
[50] Surface Transportation Board. "Annual Report Financial Data: R-1, Schd. 710-S." https://www.stb.gov/reports-data/economic-data/annual-report-financial-data/.
[51] S&P Global. "Trinity Rail Leasing 2021 LLC (Series 2021-1)." June 17, 2021. https://www.spglobal.com/_assets/documents/ratings/research/12001201.pdf

There is cost related to the value of freight itself being delayed which is referred to as the time value of freight. That inventory in transit represents capital laying idle and is valued using a private rate of return of seven percent annually, converted to an hourly rate of return as shown in Equation 6.

$$HourlyRateOfReturn = (1 + 0.07)^{\frac{1}{365\times24}} - 1$$

**Equation 6. Hourly Rate of Return**

The average value per ton of rail freight varies by commodity type and is given in Table 27.[52] It is multiplied by tons per carload which also varies by commodity type and is derived from information provided *National Cooperative Highway Research Program (NCHRP) Report 755: Comprehensive Costs of Highway-Rail Grade Crossing Crashes* (Brod et al., 2013). Finally, the value per carload is multiplied by the average number of carloads per train as given in Table 20 to provide the time value of freight per train hour as shown in Table 27. Initial cost estimates using 2018 freight movements were then adjusted to 2021 dollars using the GDP deflator.[53]

**Table 27. Time Value of Freight Per Train Hour, by Commodity Type for Class 1 Railroads**

| Commodity Type | Average Tons per Carload | Carloads per Train (East/West) | Value per Ton (2021$) | Time Value of Freight Per Train Hour (East/West) |
|---|---|---|---|---|
| Automotive | 21.32 | 62.7 / 70.3 | $6,727.85 | $69.47 / $77.89 |
| Bulk | 99.36 | 94.6 / 123.6 | $255.21 | $18.53 / $24.21 |
| General Merchandise | 82.76 | 90.2 / 88.8 | $719.93 | $41.51 / $40.87 |
| Intermodal (TOFC/COFC count) | 13.09 | 121.8 / 180.7 | $1,364.93 | $16.81 / $24.94 |
| Class 2/3 | 82.76 | 26 | $469.70 | $7.81 / $7.81 |

### 3.5.4 Fuel and Emissions

The average cost of diesel for 2021 (in 2021 dollars) was $3.287 per gallon.[54] This price includes excise taxes on diesel fuel, including $0.244 per gallon federal excise tax, and an average $0.327 per gallon State excise tax.[55] The social cost of fuel removes excise taxes as they are considered transfers with a resulting social cost of $2.716 per diesel gallon. The social cost of emissions for the year 2021 expressed

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[52] Bureau of Transportation Statistics. "Freight Analysis Framework Data Tabulation Tool (FAF4)". U.S. Department of Transportation. https://faf.ornl.gov/faf4/Extraction1.aspx

[53] The assumption of 26 carloads on a Class 2/3 train is based on several studies of railroad operations conducted for Kansas DOT (Babcock & Sanderson, 2004) and (Fitzsimmons et al., 2017), and for Texas DOT with FHWA (Qiao et al., 2016).

[54] "Weekly Retail Gasoline and Diesel Prices," U.S. Energy Information Administration, https://www.eia.gov/dnav/pet/pet_pri_gnd_dcus_nus_a.htm.

[55] "How much tax do we pay on a gallon of gasoline and on a gallon of diesel fuel?" U.S. Energy Information Administration, https://www.eia.gov/tools/faqs/faq.php?id=10&t=10

in 2020 dollars is provided by USDOT benefit cost guidance from 2022.[56] Table 28 provides the values expressed in 2020 dollars and those values factored by 1.04 to convert 2020 dollars to 2021 dollars using the GDP deflator.[57]

**Table 28. Unit Cost of Emissions per Metric Ton**

| Emission Type | Unit Cost of Emissions per Metric Ton in year 2021 (2020$) | Unit Cost of Emissions per Metric Ton in year 2021 (2021$) |
|---|---|---|
| Nitrogen Oxides (NOx) | $15,600 | $16,224 |
| Particulate Matter ($PM_{2.5}$)* | $748,600 | $778,544 |
| Carbon Dioxide ($CO_2$) | $52 | $54 |

*While locomotive emission standards are for $PM_{10}$, $PM_{2.5}$ comprises 97% of all $PM_{10}$, so $PM_{2.5}$ emission unit costs have been applied to 97% of the $PM_{10}$ locomotive inventories.[58]

The estimates of the fuel use and emissions for trains are developed for two modes of operation:

1. idling while waiting for the rail line to reopen, and
2. line-haul while rerouting around the closure to the original destination.

Graver and Frey (2013), provide data on emissions rates by notch position for passenger and freight locomotives and time spent in each notch position. That information is used to develop a rail emission inventory for each criteria pollutant, traffic type (freight or passenger), and operation mode (idling or line-haul) per train hour, as shown in Equation 7.[59] These criteria pollutants per train hour are then costed using the unit costs of emissions shown in Table 28.[60]

$$EI_{\alpha,\tau,\sigma} = \mu_\tau \times \sum_{\eta}^{\eta\epsilon N} \varepsilon_{\alpha,\eta,\tau} \times \rho_{\eta,\tau} \times \lambda_{\eta,\tau,\sigma}$$

**Equation 7. Rail Emission Inventories per Train Hour**

Where $EI_{\alpha,\tau,\sigma}$ is emission inventory by criteria pollutant $\alpha$, traffic type $\tau$ (passenger or freight), and

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[56] *Benefit-Cost Analysis Guidance for Discretionary Grant Programs.* "Table A-6: Damage Costs for Pollutant Emissions" (Revised March 2022). Office of the Secretary, U.S. Department of Transportation. https://www.transportation.gov/sites/dot.gov/files/2022-03/Benefit%20Cost%20Analysis%20Guidance%202022%20%28Revised%29.pdf

[57] USDOT BCA guidance also provides monetized values for SOx, but the emissions inventory modeling for locomotive (described below) does not include estimates for SOx.

[58] U.S. Environmental Protection Agency. (2009). *Technical Highlights: Emission Factors for Locomotives*. https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P100500B.TXT

[59] Modal locomotive emission rates have been pulled from dynamometer measurements in Table 3 from Graver and Frey (2013), NC 1869 is representative of passenger train data and NC 1792 is representative of freight train data.

[60] The Graver and Frey (2013) paper provides estimates of total hydrocarbons (THC), but because DOT Benefit-Cost guidance does not provide a monetization value for THC, those emissions are not included in the cost estimates developed here.

operation mode $\sigma$,

$\mu_{\tau}$ is number of locomotive engines per passenger or freight train respectively (see Section 3.5.2 Equipment Costs),

$\eta \epsilon N$ is notch position $\eta$ in the set of all notch positions $N$ [dynamic braking (DB)[61], idle, and 1 through 8],

$\varepsilon_{\alpha, \eta, \tau}$ is emission rate in grams per brake horsepower-hour (g/bhp-hr) for a given criteria pollutant, notch position, and traffic type,

$\rho_{\eta, \tau}$ is horsepower by notch position and by traffic type, and

$\lambda_{\eta, \tau, \sigma}$ is fraction of operating hours spent in a particular notch position by traffic type and operation mode.

Modal locomotive emission rates have been pulled from dynamometer measurements from Graver and Frey (2013), a General Motors Electro-Motive Division (EMD) F59PH prime mover tagged as NC 1869 is representative of a passenger train and an EMD GP40 prime mover tagged as NC 1792 is representative of a freight train. The EPA develops emissions standards for newly manufactured and rebuilt locomotives. The different tiers of emissions standards have changed over time resulting in various "tiers" of locomotive emissions standards. Tier 0 to Tier 2 standards apply to older locomotives and Tier 3 and Tier 4 standards apply to newer locomotives.[62] Both of these passenger and freight engines were rebuilt between 2008 and 2012, such that the real-world emission rates reflect deterioration and maintenance. Table 29 below provides the average dynamometer measured emission rate in g/bhp-hr from Graver and Frey (2013) for various criteria pollutants with the equivalent emissions tier that it would meet if applicable. In some cases, the measured emissions levels exceed Tier 0 levels.

**Table 29. Average Freight Locomotive Dynamometer Emission Rates (g/bhp-hr) and Equivalent Emission Standard Tiers[63]**

| Traffic Type ($\tau$) | Nitrogen Oxides (NOx) | Total Hydrocarbons (THC) | Carbon Monoxide (CO) | Fine Particulate Matter ($PM_{2.5}$) |
|---|---|---|---|---|
| Freight | 12.6 (> Tier 0) | 1.70 (> Tier 0) | 1.2 (Tier 2) | 1.01 (> Tier 0) |

Note: VOCs are components of total hydrocarbons (THC).

Even without a HAZMAT incident, both passenger and freight trains tested in Graver and Frey (2013) spent roughly between 20 and 30 percent of their duty cycles idling as shown in Table 30.[64] However,

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[61] Engine outputs and emission rates for dynamic braking was not readily available for all trains tested in Graver and Frey (2013), so DB engine output is assumed to be equal to idle output for any given locomotive. Likewise, this analysis has applied DB emission rates from NC 1859 to NC 1869 for all pollutants and to NC 1792 for PM only.

[62] DieselNet, "Emission Standards – United States: Locomotives," Accessed: 22 Jan 2021, https://dieselnet.com/standards/us/loco.php.

[63] Average emission rates taken directly from Table 4 in Graver and Frey (2013).

[64] The duty cycle for NC 1859 Train 74 on September 3, 2013 was chosen as representative passenger train behavior and NC 1792 Train 73 on May 1, 2010 was chosen as representative freight train behavior (https://pubs.acs.org/doi/suppl/10.1021/acs.est.5b02497/suppl_file/es5b02497_si_001.pdf).

based on feedback from reviewers, the model here uses the operating distribution for the EPA line-haul duty cycle by notch position.[65] All time spent in idling operation mode is assessed at emission rates for "idle."

**Table 30. Summary of Engine Output and Duty Cycle Distributions by Notch Position for Freight**

| Traffic Type ($\tau$) | Notch Position ($\eta$) | Engine Output (ρ) | Fraction of Operating Hours ($\lambda$) for $\sigma$ = line-haul from Graver and Frey (2013) | Fraction of Operating Hours (λ) from EPA Line-Haul Duty Cycle |
|---|---|---|---|---|
| Freight | Dynamic Braking | 20 | 0.148 | 0.125 |
| Freight | Idle | 20 | 0.258 | 0.380 |
| Freight | 1 | 183 | 0.017 | 0.065 |
| Freight | 2 | 419 | 0.037 | 0.065 |
| Freight | 3 | 827 | 0.026 | 0.052 |
| Freight | 4 | 1,119 | 0.023 | 0.044 |
| Freight | 5 | 1,514 | 0.036 | 0.038 |
| Freight | 6 | 1,938 | 0.026 | 0.039 |
| Freight | 7 | 2,710 | 0.016 | 0.030 |
| Freight | 8 | 3,160 | 0.412 | 0.162 |

Calculations of the fuel consumption are the same as the emission inventories in Equation 7, except fuel rates are in brake horsepower-hour per gallon of diesel. Therefore, the reciprocal of the fuel-specific engine output (FSEO) rate[66] must be used to compute the number of gallons consumed, such that the fuel consumption inventory $FI$ can be expressed as Equation 8.

$$FI_{\tau,\sigma} = \mu_\tau \times \sum_{\eta}^{\eta \epsilon N} (1/\omega_{\eta,\tau}) \times \rho_{\eta,\tau} \times \lambda_{\eta,\tau,\sigma}$$

**Equation 8. Fuel Consumption**

Where previously defined terms retain their meaning and $\omega_{\eta,\tau}$ is FSEO for a specific notch position and traffic type.

In estimating the number of train hours for calculating additional emissions and fuel and costs, this analysis assumes the presence of automatic engine start/stop (AESS) technology. This analysis assumes that approximately 50% of waiting train hours are spent idling, the rest of the time, engines are shut off and do not consume fuel or produce emissions.

[65] 40 CFR § 1033.530 - Duty cycles and calculations, https://www.law.cornell.edu/cfr/text/40/1033.530

[66] Graver and Frey (2013) does not report FSEO for dynamic braking, therefore fuel consumption is estimated as follows: $FSEO_{DB} = (CO_{2_{DB}}/CO_{2_{Idle}}) \cdot FSEO_{Idle}$ for the passenger and freight trains, respectively.

Table 31 presents combined costs per hour for a freight train with and without AESS for the waiting only and rerouting scenarios. The AESS estimates are used in this analysis. When idling, fuel costs comprise 8 percent of those costs and the social costs related to $PM_{2.5}$ comprise 83 percent. When in line-haul operation, fuel costs comprise 18 percent of those costs and the social costs related to $PM_{2.5}$ comprise 58 percent.

**Table 31. Combined Per Hour Freight Fuel and Emission Social Costs Equipped With and Without AESS**

| Cost Area | Qty per Locomotive Hour Freight Waiting | Qty per Locomotive Hour Freight Rerouting | Social Cost per Unit[67] | Cost per Hour Freight Waiting | Cost per Hour Freight Rerouting |
|---|---|---|---|---|---|
| **Diesel Fuel Use** | 6.33 gal | 46.87 gal | $2.72 | $17.19 | $127.30 |
| **NOx Emitted** | 0.94 kg | 8.37 kg | $16,224.00 | $15.19 | $135.72 |
| **VOC Emitted** | 0.69 kg | 1.43 kg | $0.00 | $0.00 | $0.00 |
| **CO Emitted** | 0.95 kg | 0.72 kg | $0.00 | $0.00 | $0.00 |
| **$PM_{10}$ Emitted** | 0.01 kg | 0.02 kg | $0.00 | $0.00 | $0.00 |
| **$PM_{2.5}$ Emitted** | 0.25 kg | 0.62 kg | $778,544.00 | $193.33 | $486.18 |
| **CO2 Emitted** | 38.72 kg | 387.29 kg | $54 | $2.09 | $20.94 |
| **Total per Locomotive Hour** | N/A | N/A | N/A | **$227.80** | **$770.14** |
| **Total per Train Hour** | N/A | N/A | N/A | **$596.83** | **$2,017.78** |
| **Total per Train Hour (w/ AESS)** | N/A | N/A | N/A | **$298.41** | **N/A** |

### 3.5.5 Sensitivity Analyses - Emissions

A number of locomotives currently in use for line haul operations may have specific emissions that differ from this analysis. Some freight train operators may be utilizing newer locomotives than those tested in Graver and Frey (2013) and would adhere to more recent emission standards than Tier 0. Therefore, Table 32 presents a sensitivity case for potential emission reductions when considering new locomotives compared to Tier 0 standards. The latest emission standards (Tier 4) would yield upwards of 80 percent reductions from Tier 0 for NOx and PM.[68] The EPA standards apply only to criteria pollutants, not to

[67] Under existing guidance, impacts from released VOCs, CO, and PM 10 are not monetized. This analysis includes them here, but they do not impact the estimate of social cost.
Source: USDOT "Benefit-Cost Analysis Guidance for Discretionary Grant Programs"
[68] The EPA regulations relate to $PM_{10}$ but this sensitivity analysis assumes the same percentage reduction would apply to $PM_{2.5}$.

carbon.

Table 32. Newer Standards Compared to Tier 0[69]

| Emissions Tier | Tier 1 | Tier 2/3 | Tier 4 |
|---|---|---|---|
| **Model Year** | 1993-2004 | 2005-2014 | 2015 or later |
| **THC Emission % Reduction** | 45% | 70% | 86% |
| **NOx Emission % Reduction** | 8% | 31% | 84% |
| **PM Emission % Reduction** | 0% | 55% | 86% |

Figure 10 highlights the social cost sensitivities for these newer freight locomotives and more stringent emission standards. Tier 4 locomotives would reduce emission social costs for the idling scenario by about three-quarters and for the rerouting scenario by more than one-half compared to the original Tier 0 locomotives tested.

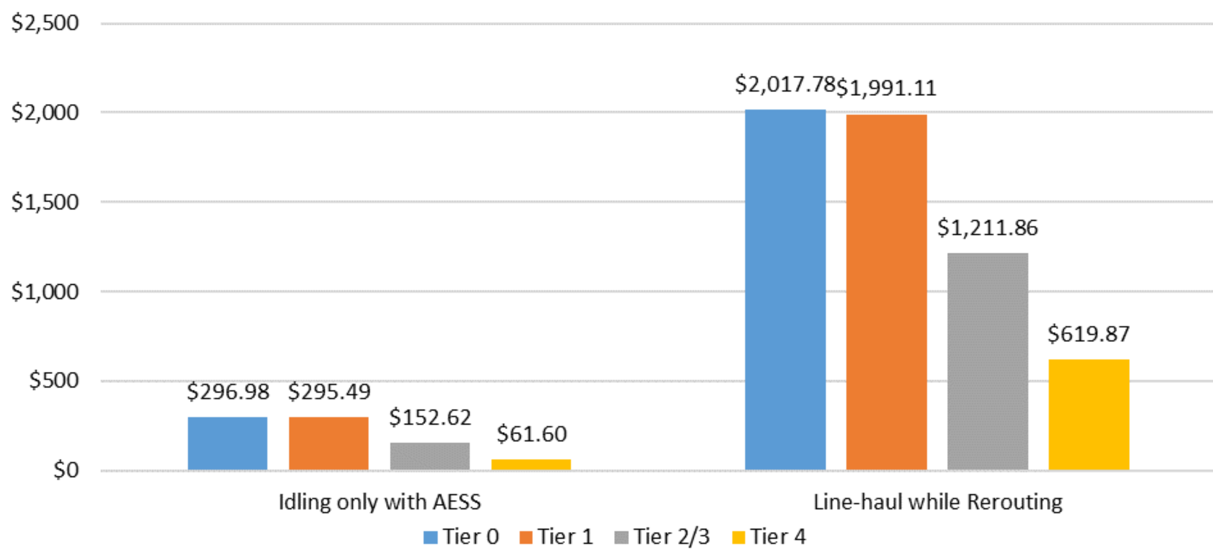


**Figure 10. Social Cost of Emission per Hour - Sensitivity Testing**

### 3.5.6 Summary of Freight Monetization Factors

Table 33 below summarizes the monetization factors described above and provides the total cost per train hour while waiting and Table 34 provides the total cost per train hour when rerouting. Each table presents the business cost and the social cost per train hour. Recall that when modeling the decisions of railroads whether to wait for an incident to clear, or to reroute traffic, this analysis assumes that

[69] Code of Federal Regulations, Title 40, Chpt. I, Subchapter U, Part 1033 – Control of Emissions from Locomotives, Last Updated: 30 June 2008, https://www.ecfr.gov/current/title-40/chapter-I/subchapter-U/part-1033.

railroads will choose the option with the lowest costs to their business. That is, they will not consider the social costs, just the costs the railroad will incur, not considering externalities. The business costs a railroad considers are:

- Crew costs;
- Equipment costs;
- Time value of freight; and
- Fuel costs, including taxes.

In some cases, a railroad may need to pay penalties to a shipper for late delivery. Lacking information on the magnitude and prevalence of such penalties, this analysis uses the time value of freight as a proxy. For some cost categories, the summary tables present ranges rather than a single value because the values differ by type of railroad (eastern Class 1, western Class 1, and Class 2/3).

**Table 33. Total Cost per Freight Train Hour, Waiting**

| Cost Type | Freight Business Cost Waiting (*FreightBizWaitCostPerTrainHour*) (2021$) | Freight Social Cost Waiting (*FreightSocialWaitCostPerTrainHour*) (2021$) |
|---|---|---|
| Crew Costs | $122.44 | $122.44 |
| Equipment | $97.06 to $245.57 | $97.06 to $245.57 |
| Time Value of Freight | $7.81 to $77.89 | $7.81 to $77.89 |
| Fuel | $54.51 | $45.04 |
| Emissions[70] | N/A | $548.92 |
| Total | $281.82 to $500.31 | $821.27 to $1039.86 |

**Table 34. Total Cost per Train Hour, Line-Haul**

| Cost Type | Freight Business Cost Line-Haul (*FreightBizRunCostPerTrainHour*) (2021$) | Freight Social Cost Line-Haul (*FreightSocialRunCostPerTrainHour*) (2021$) |
|---|---|---|
| Crew Costs | $122.44 | $122.44 |
| Equipment | $97.06 to $245.57 | $97.06 to $245.57 |
| Time Value of Freight | $7.81 to $77.89 | $7.81 to $77.89 |
| Fuel | $684.81 | $565.85 |
| Emissions | N/A | $2,568.27 |
| Total | $912.12 to $1130.71 | $3361.43 to $3580.02 |

[70] Due to AESS technology, the emissions and fuel costs per hour apply only for 50 percent of time spent waiting.

## 3.6 Cost of Freight Delay Model

The delay costs associated with a HAZMAT rail incident of a certain duration vary depending on the location of the incident. Therefore, this analysis explores the impacts of incidents occurring at several different possible locations. These costs for each location are averaged to develop a single expected cost of delay for ARs and NARs using a weighted average.

For each scenario (a specified closure duration and incident location), the railroad has the option to either wait for the track to be cleared and repaired or reroute traffic around the closure. During the period that the track is closed, trains will continue to arrive and a queue will form. Once the track is reopened, the queue of trains can pass through the site of the closure, but the departure rate will be constrained by the capacity of the rail line. Alternatively, a railroad may choose to route the traffic around the site of the closure. The alternate route will take longer and be more costly to the railroad in terms of crew time, fuel burn, etc. The analysis assumes a railroad will choose the option with the lowest cost incurred by the railroad, and that railroads are able to accurately estimate the duration of the closure and their expected costs based on the location and characteristics of the incident at the onset of the incident. Thus, this analysis first estimates the costs incurred by railroads for both waiting and rerouting around the delay. Then the analysis estimates the total *social* cost associated with the railroad's lower cost option. The methods to estimate the cost of waiting and the cost of rerouting for incidents of specified duration at a specific location are described the following sections.

### 3.6.1 Cost of Waiting for Freight Rail

When faced with a track closure, the railroads may choose to simply wait for the track to be cleared and repaired. This analysis uses a simple bottleneck model to estimate the total hours of train delay associated with waiting for the track to be repaired and put back into service.[71] The analysis assumes that all the tracks on the line segment are closed due to the incident, i.e., both tracks if the segment is double tracked, all three tracks if the segment is triple track, etc. During the period that the track is closed, additional trains beyond the one involved in the incident will arrive at the location of the closure and wait. Once the track is re-opened, the trains that have been waiting will pass through the point of the closure at a rate consistent with the capacity of the rail link. While the queue of trains begins to traverse the site of the closure, additional trains will continue to arrive. However, as long as the capacity of the rail link exceeds the arrival rate of traffic, the queue will eventually dissipate. The following "bottleneck" model accounts for the level of traffic and the capacity of the link to estimate the cost of waiting for an incident to be cleared. The queues will form on both sides of the closure when traffic arrives from both directions, but the total delay from both queues is depicted in the following discussion.

[71] Williams, M. K. (2011). Using simulation to understand bottlenecks, delay accumulation, and rail network flow. *In Proceedings of the Annual AREMA Conference.*

Figure 11, below, shows a graphical depiction of an illustrative example of the bottleneck model. The vertical axis measures the queue length measured in number of trains, for each hour subsequent from the beginning of a hypothetical six-hour closure. During hours one through six, the length of queue increases at the hourly train arrival rate of two trains per hour. After the link is reopened, trains continue to arrive at the same rate but the queue dissipates at the rate of the track capacity (three trains per hour) until there is no queue. The total delay measures train hours and is the sum of the queue length over each hour until the queue dissipates. The literature review in Appendix A: Review of Literature shows that this bottleneck model closely approximates the results derived from simulation modeling of rail line closures.

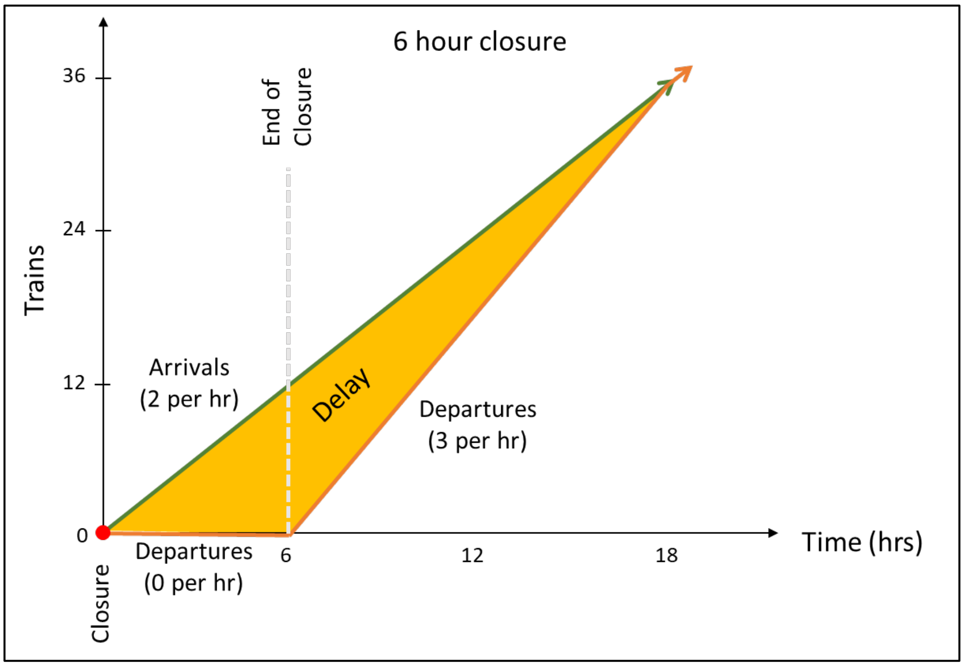


**Figure 11. Example of Bottleneck Model**

The method for estimating rail traffic at various locations on the network was described in Section 3.3 and the method for estimating capacity was described in Section 3.4. This analysis assumes that the rail operators will be able to accurately estimate the duration of the closure at its onset in order to make an informed decision on whether to wait or reroute.

Equation 9 provides the method for calculating the queue length for freight trains (measured in number of trains) at a given hour after the beginning of a closure, given arrival rates of all trains (including passenger trains) and the capacity of a link. $FL_{l,h}$ refers to the length of queue (in freight trains) at any hour $h$ and at location $l$. The formula is different depending whether the hour is *before* or *after* the time when freight trains can start moving out of the queue past the location of the closure (that hour is labeled $A_{l,d}$). In this analysis freight trains must wait until the link is reopened (which occurs at hour $d$) and until any waiting passenger trains have departed, because passenger trains have priority over freight trains. The formula to derive $A_{l,d}$ is provided in Equation 10. The hourly arrival rate of freight trains at location $l$ is $af_l$. Therefore, before hour $A_{l,d}$, in any given hour, the number of freight trains in the queue is simply $h$ times $af_l$.

At hour $A_{l,d}$, the queue of waiting freight trains is at its maximum length ($FL_{l,A}$). After hour $A_{l,d}$, the queue of waiting freight trains can begin to depart. However, because trains keep arriving, the queue can only dissipate at a rate consistent with the spare capacity of the link. That spare capacity is the capacity of the link measured in trains per hour ($c_l$) minus the arrival rate of all trains at location $l$ ($a_l$). Therefore, for each hour after $A_{l,d}$, the queue length of freight trains ($FL_{l,h}$) is the maximum queue length ($FL_{l,A}$) shortened by the hourly spare capacity of the track ($c_l$ minus $a_l$) multiplied by the number of hours that has passed since the queue of freight trains started to depart ($h$ minus $A_{l,d}$).

$$FL_{l,h} = \begin{cases} h \times af_l, & h \leq A_{l,d} \\ max\{0,\ FL_{l,A} - (h - A_{l,d}) \times (c_l - a_l)\}, & h > A_{l,d} \end{cases}$$

**Equation 9. Train Queue Length at Any Particular Hour**

The hour $A_{l,d}$ is specified by Equation 10, below. To determine the hour $A_{l,d}$ (the hour when freight trains will begin to be able to move past the location of the closure), one must identify the number of hours that will be required to dissipate the queue of any waiting passenger trains. In this analysis, depending on the duration of the closure, some types of passenger service will wait for the link to reopen while other types of passenger service will implement a "bus bridge" to transport passengers around the closure. However, once the link is reopened *all* passenger trains will traverse the site of the closure with priority. Similar to Equation 9, the queue of waiting passenger trains will dissipate at the rate of the spare capacity of the link. Therefore, spare capacity is the capacity ($c_l$) minus the arrival rate of all passenger trains – those that will wait ($apwait_l$) and those that will not wait ($apnowait_l$). The maximum length of the passenger train queue is at hour $d$, just when the closure location is reopened. Therefore, the maximum passenger train queue length is $d$ times $apwait_l$. The queue will dissipate at a rate of $c_l$ minus ($apnowait_l$ plus $apwait_l$) per hour.

$$A_{l,d} = d + \frac{d \times apwait_l}{c_l - (apnowait_l + apwait_l)}$$

**Equation 10. Determination of Hour $A_{l,d}$ When Freight Queue Begins to Dissipate**

Given the queue length in any particular hour as given in Equation 9, the calculation of total freight train hours of delay for waiting ($FreightTrainHoursDelay_{l,d}$) is given in Equation 11. The total number of train hours of delay is calculated by summing the queue length in terms of trains over each hour of the closure and continuing until queue has dissipated at hour $B_{l,d}$. The derivation of $B_{l,d}$ is similar to the derivation of $A_{l,d}$ and is provided in Equation 12. The maximum length of the freight train queue occurs at hour $A_{l,d}$ and is therefore $A_{l,d}$ times the freight train arrival rate, $af_l$. The queue will dissipate at a rate of $c_l$ minus $a_l$ per hour (the hourly spare capacity of the track).

$$FreightTrainHoursDelay_{l,d} = \sum_{h=1}^{B_{l,d}} FL_{l,h}$$

**Equation 11. Total Freight Train Hours of Delay from Waiting**

$$B_{l,d} = A_{l,d} + \frac{A_{l,d} \times af_l}{c_l - a_l}$$

**Equation 12. Total Hours of Closure and Queuing**

For each train that waits for a closure to clear, there is also an increase in travel time due to the additional time needed to accelerate from stopped to operating speed. While operating speeds vary by track class, and the time needed to accelerate to running speed is impacted by the mass of the train,[72] for modeling purposes each train is assumed to spend an additional 15 minutes of line-haul time accelerating to speed.[73] Each freight train stopped by the closure ($FreightTrains_{l,d}$), as shown in Equation 13, adds an additional cost for the additional quarter hour of line-haul travel time (as applied in Equation 14 and Equation 15).

$$FreightTrains_{l,d} = af_{l,d} \times B_{l,d}$$

**Equation 13. Freight Trains Stopped by Closure**

The estimate of freight train hours of delay for each scenario (a location $l$ and a duration $d$) is then converted to business costs and social costs using the monetization factors described in Section 3.5 and summarized in Table 33 as shown in Equation 14 and Equation 15.

$$\begin{aligned} BizFreightCostWaiting(l,d) \\ &= FreightTrainHoursDelay_{l,d} \times FreightBizWaitCostPerTrainHour \\ &+ FreightTrains_{l,d} \times 0.25 \times FreightBizRunCostPerTrainHour \end{aligned}$$

**Equation 14. Business Costs of Waiting Freight Trains**

$$\begin{aligned} SocialFreightCostWaiting(l,d) \\ &= FreightTrainHoursDelay_{l,d} \times FreightSocialWaitCostPerTrainHour \\ &+ FreightTrains_{l,d} \times 0.25 \times FreightSocialRunCostPerTrainHour \end{aligned}$$

**Equation 15. Social Costs of Waiting Freight Trains**

[72] Lai, Y.-C., & Barkan, C. (2009). Enhanced Parametric Railway Capacity Evaluation Tool. *Transportation Research Record*, 2117, 33–40. https://doi.org/10.3141/2117-05
[73] Lovett et al (2017) assumes that accelerating and decelerating into and out of a slow order requires 30 minutes. Therefore, this analysis assumes 15 minutes for just accelerating after an incident is cleared.

**Cost of Waiting for Freight Rail: Bottleneck Model**

To illustrate the calculations of the bottleneck model, consider a hypothetical link in the network with a capacity of 40 TPD that hosts 9.6 freight TPD and eight passenger TPD. The calculated hourly arrival rate of freight trains is 0.4 (9.6 divided by 24 hours), the hourly arrival rate of passenger trains is 0.33 (8 divided by 24 hours), and the maximum hourly departure rate is 1.67 (40 divided by 24). At the end of an 18 hour closure there are 7.2 (0.4 times 18) freight trains in the queue.

Because the duration is 18 hours, all the passenger trains will opt to institute a bus bridge, and none will wait in a queue. Therefore, the waiting freight trains in the queue can begin passing through the opened track segment after hour 18 ($A_{l,d}$) along with any newly arriving passenger trains. The queue of freight trains will dissipate at a rate of 0.94 trains per hour (1.67 minus 0.40 minus 0.33), so that 8 hours after the track is reopened, the queue will have dissipated. In total, 10.4 freight trains will have been impacted ({18 hours plus 8 hours} times 0.4 freight trains per hour) for a total of 92.5 hours of freight train delay.

### 3.6.2 Cost of Rerouting for Freight Rail

When railroads face long wait times at the site of closure, they may choose to reroute trains along an alternative route. Railroad industry representatives indicate that in practice, railroads tend to focus on considering whether to reroute high priority traffic such as intermodal and finished autos. Alternative routes represent higher cost options compared to the baseline route, either due to slower operational speeds, longer route length or a combination of the two. However, in some cases, no alternate route may be available or there may not be sufficient capacity on the alternate route to accommodate the additional traffic. Therefore, the cost of rerouting as discussed in this analysis has three components as shown in Figure 12 – the cost of waiting associated with non-rerouted traffic (i.e., traffic that is not able to reroute or low priority traffic that railroads do not consider rerouting), the cost from longer alternate routes, and the cost of congestion caused by additional traffic on the alternate route. The methods for estimating the cost of delay for each of those components are discussed below.

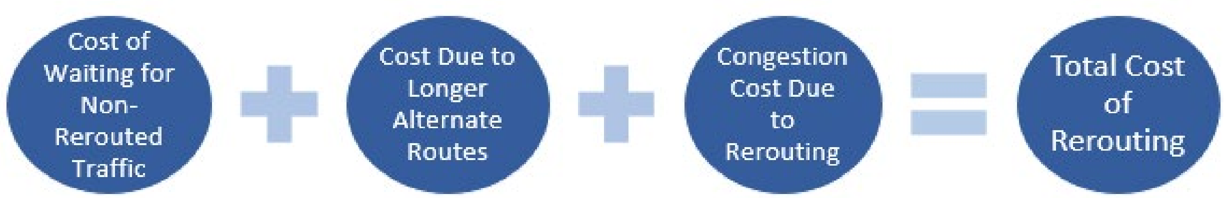


**Figure 12. Overview of Cost of Rerouting**

#### *3.6.2.1 Non-Rerouted Traffic*

The bottleneck model used to estimate the cost of waiting (described in Section 3.6.1) is used to estimate delay costs for traffic that is not rerouted. There are three situations where some traffic is not rerouted.

First, as mentioned above, railroads do not typically consider rerouting low priority traffic. In this model, all general merchandise and bulk traffic is assumed to wait and accrues the cost of waiting as estimated by the bottleneck model.

Second, in some cases, an alternative route for high priority traffic does not exist. To calculate the additional travel time involved in rerouting for a particular location, the network link representing that location was removed from the rail network and all waybill records were reflowed over the modified network, as discussed in Section 3.3.4. For some locations, some waybill records could not be rerouted since no alternative route was possible. That is, the network of the railroad handling the traffic could not provide an alternative route when a specific section of track was closed. This non-reroutable traffic is assumed to wait and accrues the cost of waiting as estimated by the bottleneck model.[74]

In other cases, the alternate route for high priority traffic may not have sufficient capacity to handle the additional traffic. To account for this possible limitation on the ability of traffic to reroute, this analysis assumes that if the traffic from rerouting high priority cargo would increase traffic volumes over estimated capacity for more than 100 track miles of alternate route, then rerouting is not possible for that incident location. This 100-mile cutoff was chosen based on review of the results of the rerouting analysis for the sampled locations. The cutoff being greater than zero allows for inclusion of rerouting as an option for instances where the amount of track over assumed capacity is relatively low. For these cases where no rerouting is possible because of network configuration or because of the lack of available capacity on alternate routes, the trains are assumed to wait and the cost of delay for those movements is estimated using the bottleneck model.

The resulting estimate of train hours of delay based on all three categories of non-rerouted traffic is referred to as $UnRerouteFreightTrainHoursDelay_{l,d}$ for an incident at location $l$ with duration $d$. The number of impacted trains is $UnRerouteFreightTrains_{l,d}$.

#### *3.6.2.2 Longer Alternate Routes for High Priority Traffic*

For high priority traffic that is reroutable, Equation 16 shows how the rerouted traffic flows are converted to additional trains on each link in the network for an incident at a certain location ($l$) and duration ($d$). Recall that waybill records represent a year's worth of traffic. Those annual traffic flows are prorated by the duration of the closure in hours to identify the amount of traffic (measured in carloads) that would be impacted by an incident at location $l$. Then the number of *additional* carloads on any link in the network ($k$) is calculated by subtracting a given link's baseline carloads ($AnnualBaselineCarloads_{l,k}$) from the sum of the carloads under the alternative routing for that link

[74] In a small number of cases, some high priority traffic was able to reroute, and some was not. For simplicity, the model treats all of the high priority traffic as not reroutable in those scenarios.

($AnnualAltRouteCarloads_{l,k}$) and any unrerouted carloads that will eventually traverse the route after the site of the closure has reopened ($AnnualUnreroutedCarloads_{l,k}$). The carloads are then converted to trains by dividing by the average number of carloads per train ($CarloadsPerTrain$) from Table 20. *Average Number of Carloads per Train by Commodity Type*.[75]

$$AdditionalTrains_{l,k,d} = \frac{AnnualAltRouteCarloads_{l,k} + AnnualUnreroutedCarloads_{l,k} - AnnualBaselineCarloads_k}{CarloadsPerTrain} \times \frac{1}{365 \times 24} \times d$$

**Equation 16. Additional Carloads due to Rerouting**

As shown in Equation 17, the net change in TPD for each link is then multiplied by the time to traverse the link ($Length_k$ divided by $AvgSpeed_k$) (discussed in Section 3.3.6), generating the net change in train travel time hours per link ($FreightAltRouteTime_{l,d}$).

$$FreightAltRouteTime_{l,d} = \sum_k AdditionalTrains_{l,k,d} \times {}^{Length_k}/_{AvgSpeed_k}$$

**Equation 17. Additional Time for Traversing Longer Route in Train Hours**

#### *3.6.2.3 Cost of Congestion on Alternate Route*

The decision of a freight railroad to reroute traffic around the site of a closure may result in additional congestion-related delay on the alternate routes and that delay may be experienced not only by the traffic that is rerouting but by the traffic that uses that route under baseline conditions. In order to estimate the additional delay from increased congestion, a review of relevant literature was performed (see Appendix A: Review of Literature). Given that explicit simulation modeling of the entire freight rail network in North America would be impractical, it was decided to apply estimates of delay from the available literature to the rail network, acknowledging that certain simplifying assumptions would be necessary. Ultimately, the analyses which were determined to be most applicable to this modeling effort were Sogin et al. (2016) and Dingler (2010). Sogin et al. (2016) uses Rail Traffic Controller (RTC), a simulation software to simulate operating conditions on single and double track configurations. Dingler (2010) which uses RTC to estimate train delay resulting from scenarios under different levels of traffic and traffic mix on single track.[76] The discussion below explains how the results from Sogin et al. (2016)

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[75] As shown in Table 18, the assumed number of carloads per train depends on the link's location on the network (Eastern Class 1, Western Class 1, or Class 2/3). In these calculations, the number of carloads per train for any increased traffic is determined by the location of the incident.

[76] Dingler characterizes his analysis as intended to provide a "consistent basis for relative comparison of different scenarios…under a reasonably realistic set of operating conditions," but not to "represent absolute predictive

and Dingler (2010) were applied to the entire network in order to make an estimate of congestion delay due to rerouting under a set of simplifying assumptions.

#### 3.6.2.3.1 Application Methods and Gaps

Sogin et al. (2016) examines train delay in the context of traffic mix and volume, as well as the percentage of double track. The traffic mix considered was a mix of freight and passenger traffic, where both the impact of passenger train priority and passenger train speed differential when compared to freight traffic were separated and examined by varying the speed of the passenger traffic. The analysis simulates different traffic levels, ranging from 8 to 64 trains per day, different track configurations (in terms of percentage double track), as well as different methods for transitioning from single to double track.[77] These simulations were used to estimate a single equation (Equation 18) which estimates delay as a function of the traffic level, percent double track ($x$),[78] traffic mix ($\iota$) and constant parameters estimated in Sogin et al. (2016); $S_\iota$, $T_\iota$, which are delay constants and $\kappa_\iota$, which is a congestion factor. Because values are only presented for the relationship between delay and TPD for TPD levels less than 64 TPD, the analysis applies the value of 64 TPD for any links that have greater than 64 TPD on single track ($TruncTPD_z$, where $z$ is single track). On double track, the equation is extrapolated for a maximum value of 100 TPD ($TruncTPD_z$, where $z$ is double track). Implementing a ceiling on TPD, although necessary due to lack of more relevant information, is likely to underestimate the cost of congestion used in this analysis.

$$CongDelayMinPer100TrainMiles_{x,\iota,\mathrm{TruncTPD_z}} = [(S_\iota - T_\iota \times x)e^{\kappa_\iota} \times TruncTPD_z] \div 2.4$$

**Equation 18. Congestion Delay in Minutes per 100 Train Miles (Adapted from Sogin et al. 2016)**

The mix of trains on a track affects the amount of delay because when the trains do not have the same priority, delay occurs when a higher priority train must pass a lower priority train. Sogin et al. (2016) examines the impact of homogenous all freight traffic versus a heterogeneous traffic mix of passenger and freight traffic to isolate the impact of train priority on delay. For the purpose of this analysis, the factors for a higher priority train with no speed differential were used, as they would most closely measure a relationship between delay and freight train priority differences, without the added component of a speed differential.

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measurements for a particular set of conditions." In applying his results, this analysis focuses on comparative differences in congestion – looking only at the difference in delay between baseline conditions and conditions with additional traffic due to some trains rerouting around a closure.

[77] Sogin et al. (2016) considers two methods for transitioning from single to double track. However, for the purposes of this report, the relevant information for a static (i.e., not in transition) rail network is only track which is single track or double track. Parameters provided in the report for traffic type scenarios were for the alternate method of track transition and therefore these were the values used in the application of results.

[78] For the purposes of the analysis, single track was considered to be 19% double track, due to the presence of sidings.

Sogin et al. (2016) estimate impacts of heterogeneity for passenger and freight trains, but rerouting in this model considers rerouting of freight trains only. Therefore**,** to apply the results to the entire network, a set of simplifying assumptions is required**.** In this analysis, bulk and general merchandise (general) trains are considered to behave similarly to lower priority freight trains in the Sogin et al. (2016) analysis, and all other traffic (intermodal, auto, and passenger) was considered to behave similarly to intermodal trains in the analysis because they have higher priority. Sogin et al. (2016) examines only heterogenous (25 percent passenger, 75 percent freight) and homogenous traffic. For the purpose of this analysis, traffic was assigned to the heterogenous or homogenous congestion formulas using the specifications shown in Table 35. However, assuming the same delay function for all heterogeneous traffic**,** although necessary due to lack of more relevant information, likely underestimates the cost of congestion delay for track where heterogeneity is greater than analyzed in Sogin et al. (2016), as demonstrated by Dingler (2010) which finds that delay due to heterogeneity increases as a function of degree of heterogeneity.

**Table 35. Components of Delay Estimates due to Congestion by Percent of Bulk Trains**

| Traffic Mix ($\iota$) | Traffic Mix (Sogin et al. 2016) | Range of Traffic Mix for Application | $S_\iota$ (Sogin et al. 2016) | $T_\iota$ (Sogin et al. 2016) | $\kappa_\iota$ (Sogin et al. 2016) |
|---|---|---|---|---|---|
| 1 (homogeneous) | *Freight only* | $PercentBulk <= 12.5$ OR $PercentBulk >= 87.5$ | 19.5206 | 19.149 | 0.0471 |
| 2 (heterogeneous) | *75 percent freight trains, 25 percent 50 MPH passenger trains* | $12.5 < PercentBulk < 87.5$ | 19.9317 | 19.3509 | 0.0547 |

Sogin et al. (2016) explored simulations involving freight train speeds of 50 MPH and passenger train speeds of up to 100 MPH, which most closely resembles track class five. However, those estimates of congestion were the only ones available in the literature. Therefore, this analysis adopts those congestion-related delay estimates for track class three and four as well and notes that they are likely to underestimate the magnitude of congestion-related delay for those lower track classes**.** There is very little rerouting of traffic on track class one and two. For segments with more than two tracks (triple track and above), it was assumed that the delay from additional traffic would be negligible and was estimated to be zero. Again, these assumptions likely underestimate the magnitude of congestion-related delay for alternate routes that involve triple track in cases where the additional traffic from rerouting pushes the traffic volume close to capacity.

Nonetheless, using the simplifying assumptions and specifications in Equation 18 and Table 35, the congestion-related delay under baseline and rerouting conditions in minutes per 100 train-miles was calculated for specified level of traffic measured in TPD for applicable links. The TPD on any link under rerouting conditions is the TPD from the rerouting traffic.[79] The estimate of minutes of delay per 100 train-miles is then multiplied by the number of affected trains and the length of the link in hundreds of miles to produce congestion-related delay in minutes for each link in the network. The number of affected trains is TPD for each link under baseline or rerouting scenarios divided by 24 hours to calculate trains per hour and multiplied by the duration of the closure in hours ($d$) and the length of the link in hundreds of miles to calculate train miles. That calculation for minutes of congestion-related delay on a certain link for an incident of a certain duration for baseline and rerouting scenarios is described in Equation 19.

$$
\begin{aligned}
&CongDelayMins_{l,link,Base\ or\ Reroute,d} \\
&= CongDelayMinPer100TrainMiles\left(PercentBulk_{l,link,Base\ or\ Reroute}, TruncTPD_{l,link,Base\ or\ Reroute}\right) \\
&\times \frac{TPD_{l,link,Base\ or\ Reroute}}{24} \times \frac{Length_{link}}{100} \times Duration
\end{aligned}
$$

**Equation 19. Calculation of Congestion Delay Minutes in Baseline and Rerouting Scenarios**

For each link in the network, the difference between the congestion under rerouting conditions and the congestion under baseline condition is calculated and then converted to hours by dividing by 60. The difference in congestion is summed across all the links in the network to estimate total hours of congestion-related delay due to rerouting as shown Equation 20.

$$
CongDelayHours_{l,d} = \sum_{link} \frac{\left(CongDelayMins_{l,link,Rerouted,d} - CongDelayMins_{l,link,Base,d}\right)}{60}
$$

**Equation 20. Calculation for Additional Congestion Delay Due to Rerouting in Hours**

#### 3.6.2.3.2 Monetization Methods

Congestion-related delay due to rerouting in hours is calculated in total for every link in the network under the above specification and limits and must be distributed to each commodity type in order to be monetized. Dinger (2010) finds that the most delay is experienced by the lower priority bulk trains because those trains spend relatively more time waiting in sidings during meets and passes with higher priority traffic. In this analysis, it is assumed passenger trains will experience no congestion-related delay because they are given highest priority**.** The intermodal and automotive trains are assumed to experience a relatively small share of delay, while the greatest share of congestion is experienced by the lowest priority bulk and general trains. Using estimates approximated from Dingler (2010), the total estimated congestion-related delay is allocated to bulk/general trains and intermodal/automotive trains

[79] This modeling assumes that for links where any portion of the traffic is not reroutable, the traffic will choose to wait instead of rerouting. This is due to the lack of temporal component in the model, where all rerouting occurs for the duration of the crash only.

using percentages of freight traffic reported in Table 36.[80]

**Table 36. Congestion Delay Experienced by Commodity Type**

| Range of Freight Traffic Mix | Percent of Delay Allocated to Bulk/General | Percent of Delay Allocated to Intermodal/Automotive |
|---|---|---|
| $PercentBulkFreight = 0$ | 0% | 100% |
| $0 < PercentBulkFreight \leq 12.5$ | 81% | 19% |
| $12.5 < PercentBulkFreight \leq 25$ | 78% | 22% |
| $25 < PercentBulkFreight \leq 50$ | 75% | 25% |
| $50 < PercentBulkFreight \leq 75$ | 72% | 28% |
| $75 < PercentBulkFreight < 100$ | 72% | 28% |
| $PercentBulkFreight = 100$ | 100% | 0% |

In order to apply costs for each commodity type, the proportion of traffic with each commodity type was applied to the distributed congestion delay. This further distributed the congestion delay to each individual commodity type; bulk, general, intermodal, and automotive. This way, if the majority of intermodal/automotive traffic is intermodal, intermodal traffic will experience the majority of the congestion-related delay distributed to intermodal/automotive traffic.

The resulting estimates of congestion-related delay measured in minutes per hundred train-miles are monetized using the appropriate line-haul cost per train hour from Table 34. This congestion-related cost of delay is included in the social cost of rerouting and in the business cost of rerouting. This analysis assumes that when deciding whether to wait or reroute, railroads will include not only the cost of additional congestion imposed on their own trains and but also trains operated by other railroads on shared trackage. This assumption is supported by the idea that trackage rights agreements will dictate operations on shared tracks and are likely include costs or other controls that will cause railroads to internalize costs imposed on others that share the tracks.

#### 3.6.2.3.3 Discussion of Results

For each link in the network, congestion can either increase or decrease as a result of a rerouting. On some links, traffic will go down because the impacted traffic will take an alternate route and the remaining traffic will experience less congestion. However, on other links the traffic will increase and so will congestion. In general, one would expect total congestion to increase as a result of rerouting. This is because the same amount of traffic must be served on a smaller network. However, in certain circumstances, the net amount of congestion-related delay between the baseline and the rerouting scenario *might* be negative. Consider an example where a major corridor that is highly congested and hosts traffic that will need to reroute because of the closure. The rerouting might push the rerouting traffic to another corridor that is not as congested while also reducing congestion on the main corridor.

[80] Percentages used are percentage of total freight traffic, excluding passenger traffic.

Since congestion delay is non-linear, it is possible that total congestion delay might fall due to the shift resulting from the track closure. Similarly, if traffic moves from single to double track in the rerouting, congestion would be lower as calculated in this analysis. However, in order for the baseline traffic assignment to be logical, the *total* business costs (congestion delay costs plus the non-congestion related costs of traversing the route at an average speed) would be expected to be lower in the baseline than in the alternate routing. One would not expect that any railroads would have negative total business cost of rerouting in any scenario because they would then always choose the rerouting and never use the baseline route. Feedback from railroad industry stakeholders indicated, however, that due to the nature of the model, which may not necessarily capture all factors in business decision making, that it is reasonable to see reduced business costs for rerouting. Among sampled links where rerouting is possible, there are several results where congestion business costs are negative. However, among links where the choice to wait or reroute is modelled eight out of a total of 95 links which have the choice to wait or reroute have total business costs of rerouting which are negative for a six-hour closure. Generally, these reductions in business costs overall when rerouting occur when less congested routes are available, and traffic is dispersed on these routes under rerouting.

It should be noted that the routing algorithm does not consider congestion, which could potentially result in a negative total business cost for a rerouting with substantially reduced total congestion and a minimal increase in rerouting distance. It should also be noted that this method applies the limited information available in the literature which assumes zero congestion delay on triple track and above and on track class one or two. If a substantial amount of traffic is being rerouted onto these track types, the information gaps in the literature would result in a substantial underestimate of the costs of congestion. Finally, the application of Sogin's results to track class three and four and truncating TPD at when estimating minutes of delay per 100 train-miles is again a likely underestimate of the congestion delay for those track classes. The main analysis does also consider congestion in a more limited way, by not permitting a railroad to reroute if more than 100 miles of the network would be above practical capacity when rerouting.

### Congestion Calculations and Monetization: Hypothetical Link

Take the example of a rerouting scenario with an incident duration of 18.5 hours. Consider a link representing a 20-mile-long track segment that is track class four and single track. Suppose this link has a baseline volume of 25 TPD, and 10 percent of traffic is bulk or general. To calculate the baseline delay in minutes per 100 train-miles, apply coefficients for $\iota=1$ and volume of 25 to Equation 18 and produce an estimate of 21.5 minutes per 100 train-miles. Suppose the volume on link increases to 35 TPD in the rerouting scenario and 10 percent of the rerouting traffic is bulk or general. To calculate the delay in minutes per 100 train-miles, apply coefficients for $\iota=1$ and increase the volume to 35 TPD to produce an estimate of 34.4 minutes per 100 train-miles.

To convert these delay estimates from minutes per 100 train-miles to total minutes for an incident of a certain duration, the values must be multiplied by the number of affected trains and the length of the link in hundreds of miles and the duration of the closure as described in Equation 19. The number of affected trains is TPD (25 for baseline and 35 for rerouting) divided by 24 and the length of the link in hundreds of miles is 0.2. Thus, the minutes for an 18.5-hour closure of delay are approximately 82.9 minutes in the baseline scenario, and 185.6 minutes in the rerouting scenario. Subtracting the baseline from the rerouting and dividing by 60 to convert to hours gives the additional delay due to rerouting, which is approximately 102.7 minutes or 1.71 hours of delay for this link.

To monetize the congestion delay, it must be distributed to different commodity types. Suppose the rerouted traffic has the following mix of traffic; 10 percent of the traffic is bulk, 45 percent is intermodal, and 45 percent is automotive (there are not passenger trains in this example). Using the groupings of train types developed for applying Dingler's estimates, this train mix is equivalently, 10 percent bulk/general and 90 percent auto/intermodal. To allocate the share of delay experienced by bulk/general versus intermodal/automotive trains, the values from Table 36 are used. Given that 10 percent of trains are bulk/general, one can estimate that 81 percent of the delay is experienced by bulk/general trains, and the remaining 19 percent by intermodal/automotive trains.

The delay must be further allocated to the specific commodity types. Since all of the bulk/general is bulk, all of 81 percent of delay hours is assigned to bulk trains. Similarly, half of the auto/intermodal delay is experienced by intermodal trains, so half of the 19 percent of delay is allocated to intermodal trains, and the other half to automotive trains. As an example, the hours of delay experience by intermodal traffic in this example is 0.5 times 0.19 times 1.71 hours or 0.16 hours. The resulting amounts of delay in hours for each train type are multiplied by the social and business costs for each train type and summed across train type to calculate the congestion delay cost for that link. To find the total congestion delay social or business cost, the link level results are summed to calculate the total congestion delay cost for an incident location.

#### *3.6.2.4 Summary of Cost of Rerouting*

The costs of rerouting for freight are the costs of waiting for traffic that is not rerouted plus the cost of longer time need to traverse the alternate route compared to the baseline route ($FreightAltRouteTime_{l,d}$) plus the congestion costs associated with rerouted traffic. The total business costs of rerouting which are monetized using business costs per train hour and the total social costs of rerouting which are monetized using the social costs per train hours are illustrated in Equation 21 and Equation 22, respectively.[81]

$$
\begin{aligned}
BizFreightCostReroute(l,d) &= UnRouteFreightTrainHoursDelay_{l,d} \times FreightBizWaitCostPerTrainHour \\
&+ UnRouteFreightTrains_{l,d} \times 0.25 \times FreightBizRunCostPerTrainHour \\
&+ FreightAltRouteTime_{l,d} \times FreightBizRunCostPerTrainHour \\
&+ CongDelayHours_{l,d} \times FreightBizRunCostPerTrainHour
\end{aligned}
$$

**Equation 21. Business Costs of Rerouting Freight Trains**

$$
\begin{aligned}
SocialFreightCostReroute(l,d) &= UnRouteFreightTrainHoursDelay_{l,d} \times FreightSocialWaitCostPerTrainHour \\
&+ UnRouteFreightTrains_{l,d} \times 0.25 \times FreightSocialRunCostPerTrainHour \\
&+ FreightAltRouteTime_{l,d} \times FreightSocialRunCostPerTrainHour \\
&+ CongDelayHours_{l,d} \times FreightSocialRunCostPerTrainHour
\end{aligned}
$$

**Equation 22. Social Costs of Rerouting Freight Trains**

## 3.7 Comparison of Costs of Waiting to Costs of Rerouting for Freight Rail

When faced with a rail line closure, a freight railroad has two different methods of responding: the railroad can choose to have all traffic wait for the track to be cleared and repaired, or the railroad can reroute high priority traffic around the closure while the other traffic waits. To determine which method a freight railroad would most likely choose, this modeling effort compares the costs incurred by the railroad under both strategies. The analysis assumes that railroads are able to accurately estimate the duration of the closure and their expected costs based on the location and characteristics of the incident at the onset of the incident. In practice, a rail crash would involve uncertainty during the initial response period, and operators are unlikely to have a complete picture of the scenario. It is likely that all crashes would involve some initial period where all trains wait until information indicating the duration of closure is available. Further, rerouting trains likely requires greater resources from a railroad to manage logistics and potentially coordinate with other rail operators on alternative routes. For both these

---

[81] Please note that the term $UnRouteFreightTrains l,d$ times $0.25$ times $FreightBizRunCostPerTrainHour$ is the additional delay costs caused by freight trains decelerating into and accelerating away from the closure.

reasons, this analysis may overestimate the number of trains rerouting in response to closures, and consequently may underestimate costs.

The social costs that would occur as a result of the decision of the railroad are different than the costs the railroad itself experiences. A comparison of the costs incurred by railroads with the total social costs is provided in Table 2. *Components of Business Costs and Social Costs*. As the final step in the model of *Freight Rail Cost of Delay*, Equation 23 describes how the social costs of an incident are influenced by the business costs incurred by the railroad. The social costs for freight traffic will be the social costs associated with strategy that results in the lower business costs: waiting or rerouting.

$$FreightSocialCost(l,d) = \begin{cases} FreightSocialCostWait(l,d) \ \ for \ \ BizFreightCostWait(l,d) \leq BizFreightCostReroute(l,d) \\ FreightSocialCostReroute(l,d) \ for \ BizFreightCostWait(l,d) > BizFreightCostReroute(l,d) \end{cases}$$

**Equation 23. Determination of Decision to Wait or Reroute**

# 4. Passenger Rail Cost of Delay

This section provides detail concerning passenger rail costs from delay due to a HAZMAT incident. Costs are estimated both for the passengers themselves along with the operating railroads. For closures of short duration, passenger trains will simply wait for track to be cleared. For closures of longer durations, passenger rail operators will use buses to help passengers complete their journeys ("bus bridge"). Passenger costs are limited to their VOT while the railroad costs include crew costs, equipment costs, and in some cases costs of providing alternate bus transportation. This section describes the overall framework of estimating the cost of delays to the passenger network including inputs, monetization factors, and the models used to calculate the cost of passenger rail delays from waiting or using buses.

## 4.1 Passenger TPD

Data on TPD for commuter rail and intercity Amtrak operations that share right of way with freight traffic operations were collected from the GTFS feed for each system for Wednesday, October 17, 2018. This date is a typical travel day in the fall, not impacted by summer travel patterns or holidays. GTFS is a common format that allows public transportation agencies to publish their transit data and users to consume it in a consistent manner.[82]

Two primary classifications of passenger rail indicated in the GTFS data are intercity Amtrak service and commuter railroads operated in metropolitan areas around the country. For intercity Amtrak service, the GTFS data indicates the name of each route, its origin and destination, and TPD. Using the route name from the GTFS, Amtrak routes are grouped into three separate service categories, each of which have their own characteristics:

- Northeast Corridor (NEC) Routes: The Amtrak-owned and operated NEC between Boston, Massachusetts and Washington, D.C. hosts multiple Amtrak routes (along with several commuter railroads) characterized by high frequency service and minimal freight interaction.
- Long Distance Routes: Amtrak's long distance routes operate almost exclusively on freight owned and operated networks with a high interaction with freight trains. The routes are over 750 miles in length and largely provide once-daily service.
- State-Supported Routes: These routes less than 750 miles in length operate on a variety of service frequencies including once-daily and multiple roundtrips per day. These routes operate largely on freight owned and operated networks but may also operate partly on Amtrak-owned infrastructure including on the NEC.

Distinct from Amtrak in the GTFS data, commuter rail service is a high frequency service between a central city and adjacent suburbs. Commuter service may operate on a variety of infrastructure types including tracks owned by the commuter railroad itself, a freight railroad, or Amtrak. This analysis does

[82] https://developers.google.com/transit/gtfs

not differentiate between different commuter rail agencies or routes.

The GTFS data gives the passenger TPD, which is divided by 24 hours per day to produce trains per hour or the hourly arrival rate at a certain location for each route and service type.[83]

## 4.2 Monetization

The following section describes the monetization factors that are used to transform hours of train delay to the cost of train delay. The monetization factors are presented in 2021 dollars and primarily expressed in dollars per hour of train delay. The exception is non-idling fuel and emissions costs which are expressed as dollars per additional train-mile.

### 4.2.1 Crew Costs

Crew costs per train hour of delay are derived from representative crew staffing levels for each train type and the average hourly fully loaded wages for each crew position.

Commuter rail operator average wage values were constructed from 2020 National Transit Database (NTD) employee data from six directly operated commuter rail systems and one hybrid system that share track with freight operations.[84] Specifically, the vehicle operator average hourly wage was weighted by the rail system's share of annual vehicle operations hours as shown in Table 37. The 2020 commuter rail crew wage rate was then multiplied by 1.04 (GDP deflator) to convert it to 2021 dollars, for a value of $43.75 (from $42.07) as shown in Table 38.

---

[83] While long-distance and NEC Amtrak service tend to operate over the full 24-hour period, state-supported Amtrak and commuter services have somewhat shorter operating windows. The assumption of a 24-hour operating window for all passenger service types is a simplifying assumption.

[84] National Transit Database. "2020 Employees" https://www.transit.dot.gov/ntd/data-product/2020-employees. The San Francisco BART operates a hybrid system which shares some characteristics with commuter rail and shares some track with freight rail.

Table 37. Commuter Rail Average Hourly Wage

| Commuter Rail Agency | Vehicle Operations Hours | Vehicle Operator Average Hourly Wage (2020$) |
|---|---|---|
| New Jersey Transit Corporation | 4,666,031 | $43.19 |
| Southeastern Pennsylvania Transportation Authority | 1,986,206 | $35.72 |
| Metro-North Commuter Railroad Company, dba: MTA Metro-North Railroad | 3,500,610 | $47.65 |
| Utah Transit Authority | 196,329 | $29.36 |
| Northeast Illinois Regional Commuter Railroad Corporation, dba: Metra | 1,906,521 | $38.06 |
| Northern Indiana Commuter Transportation District | 242,055 | $29.67 |
| San Francisco Bay Area Rapid Transit District | 66,774 | $57.25 |
| **Total** | **12,564,526** | **$42.07** |

Crew wage data for Amtrak rail operators are from STB Form A and Form B quarterly data.[85] Labor wage rates are available for "train crews" (engineers and conductors) as well as "transportation other than train crew" (including café, dining, and sleep car attendants).

These average hourly wages are computed from quarterly totals of wages paid and therefore represent a combination of straight time and overtime. A December 2021 BLS "Employer Costs for Employee Compensation" shows that for unionized workers, wages comprise 60.1 percent of total compensation, excluding supplemental pay. [86] Thus, all wages listed below are factored by 1.664 to account for the costs of employer provided benefits. Straight and fully loaded hourly wage rates are presented in Table 38.

Table 38. Passenger Crew Compensation and Employer Costs

| Train Type | Employee Type | Hourly Wage (2021$) | Fully Loaded Hourly Wage Rate (2021$) |
|---|---|---|---|
| Intercity Amtrak | Engineers and Conductors | $45.53 | $75.77 |
| Intercity Amtrak | Café, dining, coach, and sleeper attendants | $31.90 | $53.09 |
| Commuter | All on-board crew | $43.75 | $72.81 |

Representative crew complements for each train type, developed in consultation with an FRA subject matter expert, are shown in Table 39. The composition of each crew is then multiplied by the fully

[85] Surface Transportation Board. "Quarterly Wage A&B Data" https://prod.stb.gov/reports-data/economic-data/quarterly-wage-ab-data/

[86] Bureau of Labor Statistics. "Employer Costs for Employee Compensation – December 2011." News Release, Bureau of Labor Statistics, Department of Labor. Last accessed June 23, 2022. https://www.bls.gov/news.release/pdf/ecec.pdf.

loaded hourly employment cost (wages plus benefits) of each crew member type to produce crew cost per train hour, as shown in Table 39.

**Table 39. Passenger Train Crew Complements and Total Crew Cost per Train Hour**

| Train Type | Crew Complement | Crew Cost per Train Hour (2021$) |
|---|---|---|
| Amtrak NEC | 1 engineer<br>1 conductor<br>2 assistant conductors<br>1 cafe car attendant | $356.17 |
| Amtrak Long-Distance | 1 engineer<br>1 conductor<br>2 assistant conductors<br>3 cafe/dining car attendants<br>2 coach attendants<br>2 sleeping car attendants | $674.71 |
| Amtrak State-Supported | 1 engineer<br>1 conductor<br>1 assistant conductor<br>1 cafe car attendant | $280.40 |
| Commuter | 1 engineer<br>2 conductors | $218.43 |

### 4.2.2 Equipment Costs

Train equipment costs capture the opportunity cost of locomotives that are delayed. The equipment costs represent the capital costs associated with unproductive rail equipment. Locomotive costs for passenger train locomotives are assumed to be the same as freight locomotive costs.

The analysis utilizes an average value of 1.25 locomotives for Amtrak trains.[87] The Amtrak value was also utilized for commuter rail trains, reflecting their similar operating characteristics. Thus, the hourly locomotive equipment cost for passenger trains is $27.52 per locomotive, or $34.40 per train. Additional information concerning the calculation of locomotive costs can be found in Section 3.5.2.2.

### 4.2.3 Passenger VOT

USDOT benefit cost guidance offers recommended hourly values of travel time based on the trip

[87] While BTS data from 1995 suggests 1.5 locomotives per train (Bureau of Transportation Statistics. "Rail Profile" U.S. Department of Transportation. Last accessed January 21, 2021. https://www.bts.gov/content/rail-profile), reviewer feedback suggested that an assumption of 1.25 locomotives per train would be more appropriate for this analysis.

purpose (business or personal) and trip length (local or intercity).[88] In this analysis passenger VOT for intercity Amtrak services is the personal, intercity travel VOT, and passenger VOT for commuter service is the personal, local VOT. The values provided in USDOT Benefit-Cost Analysis Guidance (2022) are expressed in 2020 dollars and transformed to 2021 dollars using a factor of 1.04 based on the GDP deflator. The resulting VOT estimates are shown in Table 40. DOT guidance also suggests doubling the in-vehicle VOT for time spent waiting or transferring between routes.

**Table 40. Passenger VOT**

| Type of Passenger | In-vehicle VOT (2021$) | Waiting or Transferring VOT (2021$) |
|---|---|---|
| Intercity Amtrak | $24.43[89] | $48.86 |
| Commuter | $18.51 | $37.02 |

Number of passengers per train for intercity Amtrak services are derived from train operational data available from the FRA Office of Safety.[90] FRA captures total train-miles, yard switching miles, and passenger miles (the movement of a passenger for a distance of one mile). Dividing passenger miles by total train-miles less yard switching miles yields the number of passengers per train.

Using this calculation and figures for 2018, the system wide Amtrak average passengers per train is 166.5.[91] A similar estimate was constructed for 16 commuter railroads that have operations that share track with freight using data from the NTD. Dividing passenger-miles by train-miles for those commuter rail systems, it was estimated that the average commuter rail train operates with 199.5 passengers per train, as seen in Table 41.

**Table 41. Passengers per Train**

| Passenger Service | Passengers per Train |
|---|---|
| Intercity Amtrak | 166.5 |
| Commuter | 199.5 |

[88] *Benefit-Cost Analysis Guidance for Discretionary Grant Programs.* "Table A-3: Value of Travel Time Savings." (March 2022(Revised)). Office of the Secretary, U.S. Department of Transportation. https://www.transportation.gov/sites/dot.gov/files/2022-03/Benefit%20Cost%20Analysis%20Guidance%202022%20%28Revised%29.pdf

[89] A mix of business ($29.40 per hour comprising 11.8% of the total hourly value of time) and intercity personal travel ($22.70 per hour comprising 88.2% of the total hourly value of time), multiplied by 1.04 to calculate the 2021-dollar value.

[90] FRA Office of Safety. "Operational Data, By Month." Federal Railroad Administration https://safetydata.fra.dot.gov/OfficeofSafety/publicsite/Query/rrstab.aspx

[91] More recently available passenger counts reflect pandemic related decreases in ridership and may not be reasonable to assume for future years of passenger rail operation.

### 4.2.4 Fuel and Emissions

The complete fuel and emissions modeling information can be found in Section 3.5.4. In summary, the estimates of the fuel use and emissions for trains are developed for two modes of operation:

1. Idling while waiting for the rail line to reopen, and
2. Line-haul while rerouting around the closure to the original destination.

Graver and Frey (2013), provide data on emissions rates by notch position for passenger freight locomotives and time spent in each notch position. That information is used to develop a rail emission inventory for each criteria pollutant, traffic type (freight or passenger), and operation mode (idling or line-haul) per train hour.

Modal locomotive emissions rates have been pulled from dynamometer measurements from Graver and Frey (2013), and a General Motors EMD F59PH prime mover tagged as NC 1869 is representative of a passenger train. The passenger engine was rebuilt between 2008 and 2012, such that the real-world emission rates reflect deterioration and maintenance and therefore do not directly correspond to line-haul locomotive exhaust emission standard tiers.[92] Table 42 provides the average dynamometer measured emission rates for the passenger locomotive in g/bhp-hr from Graver and Frey (2013) for various criteria pollutants with the equivalent emissions tier that it would meet if applicable. In some cases, the measured emissions levels exceed Tier 0 levels.

**Table 42. Average Locomotive Dynamometer Emission Rates (g/bhp-hr) and Equivalent Emission Standard Tiers**

| Traffic Type ($\tau$) | NOx | THC | CO | $PM_{2.5}$ |
|---|---|---|---|---|
| Passenger | 11.9 (> Tier 0) | 0.63 (Tier 0) | 2.5 (Tier 0) | 0.21 (Tier 1) |

Note: VOCs are components of THC.

The passenger train tested in Graver and Frey (2013) spent almost 30 percent of its duty cycle idling while en-route. The representative duty cycle distributions and engine output (in terms of horsepower) by notch position for passenger line-haul operations is shown in Table 43.[93]

[92] DieselNet, "Emission Standards – United States: Locomotives," Accessed: 22 Jan 2021, https://dieselnet.com/standards/us/loco.php.

[93] The duty cycle for NC 1859 Train 74 on September 2, 2013 was chosen as representative passenger train behavior and NC 1792 Train 73 on May 1, 2010 was chosen as representative freight train behavior (https://pubs.acs.org/doi/suppl/10.1021/acs.est.5b02497/suppl_file/es5b02497_si_001.pdf).

**Table 43. Summary of Engine Output and Duty Cycle Distributions by Notch Position for Passenger**

| Traffic Type ($\tau$) | Notch Position ($\eta$) | Engine Output ($\rho$) | Fraction of Operating Hours ($\lambda$) for $\sigma$ = line-haul |
|---|---|---|---|
| Passenger | Dynamic Braking | 11 | 0.134 |
| Passenger | Idle | 11 | 0.285 |
| Passenger | 1 | 184 | 0.033 |
| Passenger | 2 | 425 | 0.028 |
| Passenger | 3 | 830 | 0.016 |
| Passenger | 4 | 1,120 | 0.016 |
| Passenger | 5 | 1,521 | 0.009 |
| Passenger | 6 | 1,947 | 0.007 |
| Passenger | 7 | 2,724 | 0.001 |
| Passenger | 8 | 3,225 | 0.470 |

Table 44 presents combined costs per hour for a passenger train for the waiting only and rerouting scenarios. When idling, fuel costs comprise 15 percent of those costs and the social costs related to $PM_{2.5}$ comprise 57 percent. When in line-haul operation, fuel costs comprise 32 percent of those costs and the social costs related to $PM_{2.5}$ comprise 34 percent. Note that passenger locomotives are unlikely to utilize automatic engine start/stop (AESS) technology during extended waiting periods due to thermal constraints. Industry experts suggested that most AESS systems cannot provide enough power to adequately regulate cabin temperatures or continue food service. Instead, passenger rail operators more frequently rely on head-end engines for auxiliary power while waiting. These head-end engines also produce emissions but categorically much less than if the passenger train was to idle for the same amount of time, except for particulate matter (PM). Although PM emissions are fairly comparable for passenger trains and head-end engines, this should not affect the decision of whether to wait for the incident to clear or to reroute passengers via alternative transportation such as buses.

**Table 44. Combined Per-Hour Passenger Fuel and Emission Social Costs**

| Scenario | Value (2021$) |
|---|---|
| Idling only | $93.24 |
| Line-haul while rerouting | $848.94 |

### 4.2.5 Sensitivity Analyses - Emissions

Amtrak or other passenger train operators may be utilizing newer locomotives than those tested in Graver and Frey (2013) and would adhere to more recent emission standards. Sensitivity testing of potential emission reductions when considering new locomotives compared to Tier 0 standards has been summarized in Table 32. The latest emission standards (Tier 4) would yield upwards of 80 percent reductions from Tier 0 for NOx and $PM_{2.5}$.

Figure 13 highlights the social cost sensitivities for these newer passenger locomotives and more stringent emission standards. Tier 4 locomotives would reduce emission social costs for the idling scenario by roughly two-thirds and for the rerouting scenario by nearly one-half compared to the original, older locomotives tested.

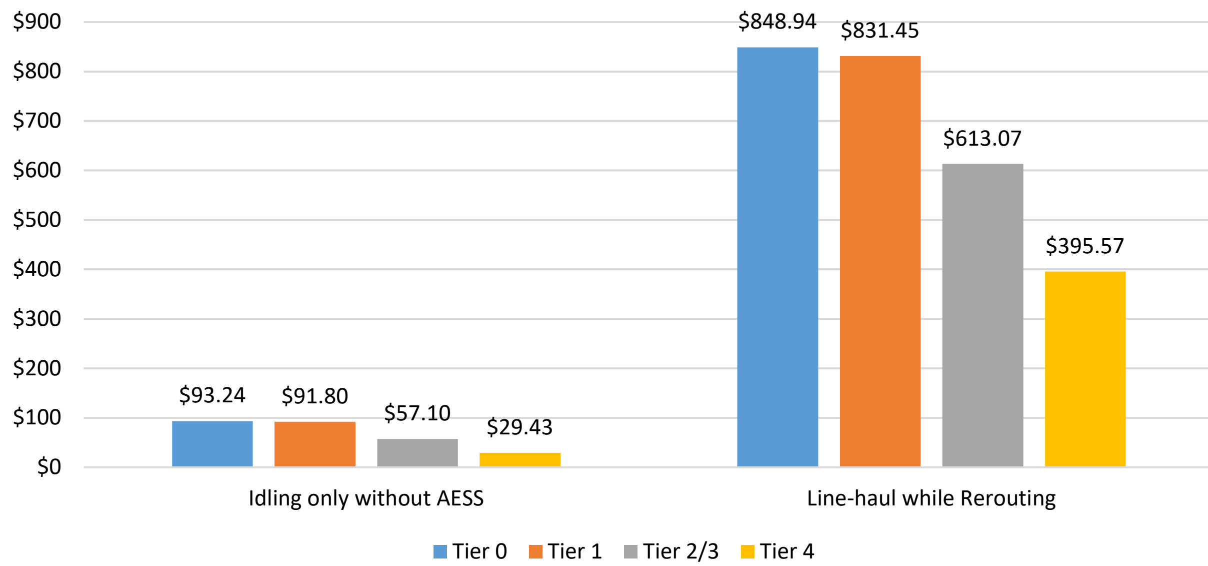


**Figure 13. Sensitivity Testing with Reduced Passenger Locomotive Emissions and Social Costs**

### 4.2.6 Summary of Passenger Monetization Factors

Table 45 below summarizes the monetization factors described above and provides the total cost per passenger train hour while waiting and Table 46 provides the total cost per passenger train hour when rerouting.

**Table 45. Total Social Cost per Passenger Train Hour, Waiting**

| Cost Type | Amtrak NEC (*PaxWaitCostPerTrainHour*) (2021$) | Amtrak Long Distance (*PaxWaitCostPerTrainHour*) (2021$) | Amtrak State-Supported (*PaxWaitCostPerTrainHour*) (2021$) | Commuter (*PaxWaitCostPerTrainHour*) (2021$) |
|---|---|---|---|---|
| Crew Costs | $356.17 | $674.71 | $280.40 | $218.43 |
| Passenger VOT | $4,067.60 | $4,067.60 | $4,067.60 | $3,692.75 |
| Fuel & Emissions | $93.24 | $93.24 | $93.24 | $93.24 |
| **Total** | $4,517.01 | $4,835.55 | $4,441.24 | $4,004.42 |

Table 46. Total Social Cost per Passenger Train Hour, Line-Haul

| Cost Type | Amtrak NEC (*PaxRunCostPerTrainHour*) (2021$) | Amtrak Long Distance (*PaxRunCostPerTrainHour*) (2021$) | Amtrak State-Supported (*PaxRunCostPerTrainHour*) (2021$) | Commuter (*PaxRunCostPerTrainHour*) (2021$) |
|---|---|---|---|---|
| Crew Costs | $356.17 | $674.71 | $280.40 | $218.43 |
| Passenger VOT | $4,067.60 | $4,067.60 | $4,067.60 | $3,692.75 |
| Fuel & Emissions | $848.94 | $848.94 | $848.94 | $848.94 |
| **Total** | $5,272.71 | $5,591.25 | $5,196.94 | $4,760.12 |

## 4.3 Cost of Passenger Delay Model

Passenger rail network costs are estimated under two general scenarios. First, in shorter duration incidents, the model will estimate the costs to passengers and operating railroads for waiting for the incident to clear using the same bottleneck model used to estimate the cost of waiting for freight rail. After the incident is cleared and service resumes, the passenger trains will proceed on their normal route and the cost of delay includes the passenger VOT and railroad operating costs for the duration of that closure. For incidents of a longer duration, a discussion with an Amtrak executive indicated that in situations where a rail incident has disrupted service, the passenger rail operator will often implement a substitute bus service for some portion of the intended rail journey. For Amtrak services, a “bus bridge” is implemented where passengers move by bus around the closure to a train on the other side that will complete the journey. For commuter rail service, it is assumed that the bus will replace the rail service for the remainder of the journey. For all service types, the costs of busing increases the operating costs to railroads for the duration of the incident. A description of the bus bridge concept is outlined below.

## Overview of Bus Bridge Concept for Intercity Passenger Service

Figure 14 below depicts the steps required to deploy the bus bridge for intercity Amtrak services.

Train X is traveling east with eastbound passengers (colored in blue). As Train X approaches the location of the closure (Step 1), it will stop at the station preceding the closure, Station A. The eastbound passengers will remain on Train X while the railroad sets up the busing operation (Step 2). Once the buses have arrived, the eastbound passengers will transfer from Train X to the buses (Step 3) and travel by bus around the closure before disembarking at Station B (Step 4). Eastbound passengers will then wait at Station B until the train approaching from the opposite direction, Train Y, arrives. Train Y is traveling west with westbound passengers (colored in green). As Train Y approaches the location of the closure, it will stop at the station preceding the closure, Station B (Step 5). The westbound passengers will transfer from Train Y to the buses and travel around the closure (Step 6). The eastbound passengers will then board the now-empty Train Y (Step 7). Train Y will then return to its origin, carrying the eastbound passengers to their destination (Step 8). After the westbound passengers are bused around the closure, they will board the waiting Train X (Step 9) which will then return to its origin, carrying the westbound passengers to their destination (Step 10).

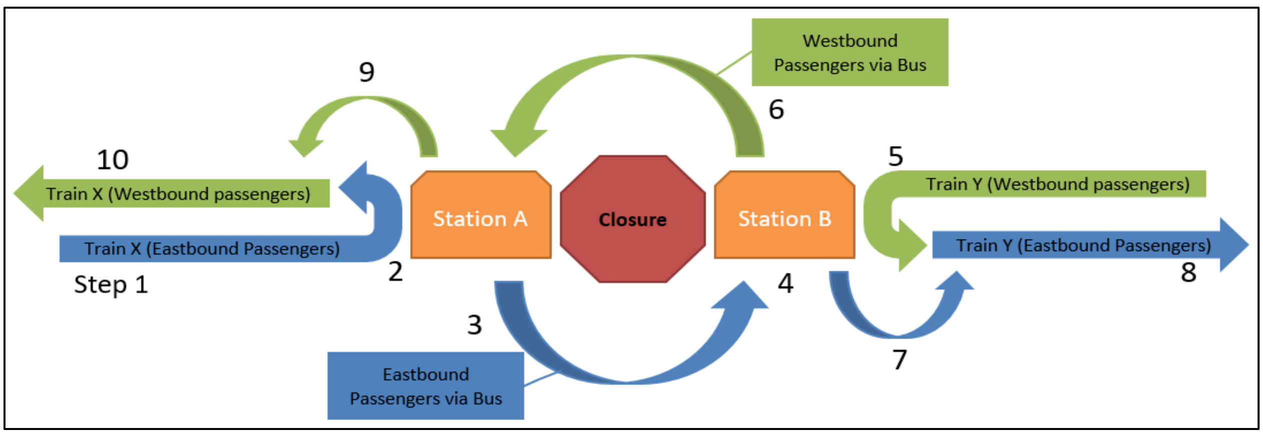


**Figure 14. Overview of Bus Bridge Concept for Intercity Passenger Service**

The methods to estimate the cost of passenger delay depend on the length of the closure and the passenger rail service type and are summarized in Table 47. The analysis assumes that faced with a closure of one hour or longer, commuter rail operators will always use buses for the remainder of the trip. NEC intercity Amtrak service will only wait for closures of four hours or less. For durations longer than four hours, NEC service will use a bus bridge. Intercity Amtrak long distance and state-supported passenger trains will wait for durations up to six hours and will use a bus bridge for longer durations. The long distance and state-supported services will wait for longer duration closures because their longer headways mean that passengers will likely have to wait for a significant period of time for another train to arrive from the opposite direction. Therefore waiting, even up to six hours, may be the preferred strategy.

Table 47. Waiting or Busing Strategy by Passenger Service Type

| Duration Category | Waiting | Busing |
|---|---|---|
| 1 hour ≤ Duration ≤ 4 hours | NEC<br>Long Distance<br>State-Supported | Commuter |
| 4 hours < Duration ≤ 6 hours | Long Distance<br>State-Supported | Commuter<br>NEC |
| Duration > 6 hours | N/A | Commuter<br>NEC<br>Long Distance<br>State-Supported |

The bus bridge concept presented in Figure 14 assumes passenger trains are capable of reversing direction without significant additional delay. In this scenario, an Amtrak train can either operate in a push-pull fashion or the train crew will utilize setup and busing time to "change ends" and move the locomotive from one end of the train to the other. In actuality, changing ends relies on local track characteristics (e.g., position of wyes, sidings, double track, etc.) that varies by station. Commuter service is assumed to operate in a push-pull fashion.

### 4.3.1 Cost of Waiting for Passenger Trains

As described in Section 3.6.1, this analysis uses a simple bottleneck model to estimate the total hours of train delay associated with waiting for the track to be repaired and put back into service. [94] During the period that the track is closed, additional trains beyond the one involved in the incident will arrive at the site of the closure and wait. Once the track is re-opened the trains that have been waiting will pass through the point of the closure at a rate consistent with the capacity of the rail link. While the queue of trains begins to traverse the site of the closure, additional trains will continue to arrive. However, as long as the capacity of the rail link exceeds the arrival rate of traffic, the queue will eventually dissipate. The following "bottleneck" model accounts for the level of traffic and the capacity of the rail link to estimate the cost of waiting for an incident to be cleared.

Equation 24, below, provides the method for calculating the queue length for passenger trains (measured in trains) at a given hour after the beginning of a closure given arrival rates of all passenger trains and the capacity of a rail link. Given a specific duration $d$, two expected arrival rates are calculated using the GTFS data for each location ($l$) on the network: $apwait_{l,d}$ is the arrival rate of trains that will wait for the track to be returned to service and $apnowait_l$ is the arrival rate of trains that will not wait and instead will implement the bus bridge.

$PL_{l,h}$ refers to the length of queue (in passengers trains) at any hour ($h$) at a location $l$. The formula is

[94] Williams, M. K. (2011). Using simulation to understand bottlenecks, delay accumulation, and rail network flow. *In Proceedings of the Annual AREMA Conference.*

different depending on whether the hour is *before* or *after* the time when track is reopened (that hour is $d$, the duration of the closure). Before hour $d$, in any given hour, the number of passenger trains in the queue is simply $h$ times $apwait_{l,d}$. After the track is put back into service, waiting passenger trains are given priority over any waiting freight trains and begin to proceed past the site of the closure.[95] However, any newly arriving passenger trains are given priority and decrease the capacity available to dissipate the queue. Therefore, for each hour after hour $d$, the queue length of passenger trains is the maximum queue lengths from hour $d$ ($PL_{l,d}$) shortened by the hourly spare capacity of the track multiplied by the number of hours that has passed since the queue of passenger trains started to depart ($h$ minus $d$).

$$PL_{l,h} = \begin{cases} h \times apwait_l, & h \leq d \\ max\ \{0,\ PL_{l,d} + (h-d) \times (apwait_l + apnowait_l - c_l)\}, & h > d \end{cases}$$

**Equation 24. Passenger Train Queue Length at Any Particular Hour**

Equation 25 describes the calculation for passenger train hours of delay ($PaxTrainHoursDelay_{l,d,s}$) for each service type ($s$) that will wait at a location ($l$) for a closure duration ($d$).[96] The total number of passenger train hours of delay is calculated by summing the queue length in terms of trains over each hour of the closure and continuing until the passenger train queue has dissipated in hour $A_{l,d}$. The derivation of hour $A_{l,d}$ can be found in Equation 10 in Section 3.6.1. It is not only the hour that the passenger train queue is dissipated but also the hour when the queue of waiting freight trains can begin to proceed on the reopened track since waiting passenger trains have priority over freight trains in this analysis. The passenger train hours of delay are then attributed to each passenger rail service type ($s$) in proportion to the number of passenger trains of that service type in the queue compared to the total number of passenger trains.

$$PaxTrainHoursDelay_{l,d,s} = \frac{apwait_{l,s}}{apwait_l} \times \sum_{h=1}^{A_{l,d}} PL_{l,h}$$

**Equation 25. Passenger Train Hours of Delay from Waiting, by Service Type and Route**

As with freight trains, every passenger train that waits incurs an additional cost related to additional line-haul time needed to accelerate to operating speed. As each train that waits for a closure to clear, there is also an increase in travel time due to the additional time needed to accelerate from stopped to operating speed. While operating speeds will vary by track class, and the time needed to accelerate to running speed is impacted by the mass of the train, for modeling purposes each train is assumed to

[95] Passenger train priority assumes that dispatching is able to honor passenger priority and that there are sufficient sidings to allow passenger trains to pass all queued freight trains and that crew and dispatcher communications allow for this level of coordination.

[96] Service type refers to type of intercity Amtrak service – NEC, state-supported, and long distance – and commuter rail.

spend an additional 15 minutes of line-haul time accelerating to speed.[97] Each passenger train stopped by the closure ($PaxTrains_{l,d,,s}$), as shown in Equation 26, adds an additional cost for the additional quarter hour of line-haul travel time (as applied in Equation 27).

$$PaxTrains_{l,d,s} = apwait_{l,s} \times A_{l,d}$$

**Equation 26. Passenger Trains Stopped by Closure**

Those passenger train hours of delay and number of passenger trains stopped by the closure for each service type ($s$) are converted to costs using the hourly passenger train cost of waiting per hour for each service type described in Section 4.2 using Equation 27 below.

$$\begin{aligned} PaxCostWait(l,d,s) \\ &= PaxTrainHoursDelay_{l,d,s} \times PaxTrainWaitCostPerTrainHour_s \\ &+ PaxTrains_{l,d,s} \times 0.25 \times PaxTrainRunCostPerTrainHour_s \end{aligned}$$

**Equation 27. Cost of Waiting for Passenger Trains**

### 4.3.2 Cost of Busing for Passenger Trains

For longer duration closures (over six hours for Amtrak long distance and state-supported services, over four hours for Amtrak NEC service, and over one hour for commuter rail service), the analysis assumes that operators will institute a “bus bridge” to transport passengers around the site of the closure, as described above and depicted above in Figure 14. For intercity Amtrak service, it is assumed that the passengers will be transferred to another train on the opposite side of the closure to transport the passengers to their ultimate destinations.[98] For commuter rail service it is assumed that bus service replaces the train service for the rest of the journey. Thus, the passengers incur time delay costs resulting from waiting for such bus service to be deployed, transferring to and from a bus, and longer line-haul time. The passenger rail operator also incurs costs related to providing the bus service and the crew costs for trains that are waiting to pick up passengers on either side of the closure.

The social costs related to these busing operations are estimated for each impacted train ($t$) on each impacted route ($r$) for each service type ($s$) that is present at the location $l$ and summed to produce an estimated cost for each service type ($s$) as shown in Equation 28.

The cost of busing includes:

- The costs of operating the buses ($BusCostPerTrain$);
- The value of the increased travel time experienced by passengers relative to the time it would

[97] Lai, Y.-C., & Barkan, C. (2009). Enhanced Parametric Railway Capacity Evaluation Tool. *Transportation Research Record*, 2117, 33–40. https://doi.org/10.3141/2117-05
[98] This method makes a simplifying assumption that a train is available on the other side of the closure, which may not always be in the case under actual conditions.

have taken to travel by rail ($PaxBusNetVOT$) where the travel time experienced under the busing operations includes:
    - time spent waiting for the bus operations to be set up,
    - time spent transferring from train to bus and back again,
    - time spent on the bus, and
    - time spent waiting for a train to arrive on the opposite side of the closure;
- The crew costs of the trains waiting for passengers to arrive from the opposite side of the closure ($PaxCrewCostWait$); and
- Fuel and emissions costs related to the train idling while waiting for passengers to arrive from the opposite side of the closure ($PaxFuelEmissionCostWait$).

Each of those cost components are described in turn below. The busing operations are in place only for passenger trains that arrive during the closure period. After the closure has ended, all passenger trains will be able to proceed through the site of the closure due to passenger trains having priority over freight operations.

$$PaxCostBus(l,d,s) = \sum_{r,t} BusCostPerTrain_s + PaxBusNetVOT_{l,s,r,t} + PaxCrewCostWait_{l,s,r,t} + PaxFuelEmissionCostWait_{l,s,r,t}$$

**Equation 28. Cost of Busing for Passenger Trains**

#### *4.3.2.1 Cost of Operating Buses*

The busing cost per impacted train ($BusCostPerTrain$) is determined by the operating cost per hour of a bus and the length of time the bus is required, itself a function of the distance the bus needs to travel along with its speed. Motorcoach-style buses are the assumed substitute option and using an estimated 50 passenger capacity per bus with the passengers per train estimate discussed in Table 41 above, each impacted Amtrak train is assumed to need four coaches and each commuter train is assumed to need five coaches ($Coaches_s$).

The *2018 NTD National Transit Summaries and Trends* report shows that the commuter bus mode (which uses motorcoach-style buses) has an operating cost per vehicle revenue hour of $206.63 ($HourlyCostPerCoach_s$) in 2018 ($221.10 in 2021 dollars).[99] This estimated hourly cost may underestimate the cost of operating a motorcoach in an unplanned situation; however, it seems to be the best information available. Motorcoaches operated to replace commuter service have an assumed 25% premium added to the hourly cost per coach ($HourlyCostPerCoach_s$) to reflect higher demand and operating costs in urban areas. The distance the buses need to travel varies by the service type.

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[99] Office of Budget and Policy. (December 2019). *2018 National Transit Summaries and Trends*. "Exhibit 3: Cost per Vehicle Revenue Hour". Federal Transit Administration. https://www.transit.dot.gov/sites/fta.dot.gov/files/docs/ntd/data-product/134401/2018-ntst_1.pdf

Amtrak's long distance routes often traverse rural areas with stations further apart, while the NEC and state-supported services operate closer to cities with station stops closer together. Using milepost data available in Amtrak's published timetables, the average distance between stations that the buses would need to traverse was estimated for each service type ($Distance_s$) and estimated values are provided in Table 48. This represents the distance between rail stations via rail, however, a bus would use a less direct path using the road network and so an assumed circuity factor of 1.5 was applied to the milepost distances to capture this additional driving circuity. The distance is transformed to travel time by assuming average bus speeds of 50 MPH for intercity Amtrak services. Values for bus costs per impacted train by service type are estimated by Equation 29 and results are shown in Table 48.

$$BusCostPerTrain_s = \frac{(Distance_s \times Circuity)}{BusSpeed_s} \times Coaches_s \times HourlyCostPerCoach_s$$

**Equation 29. Bus Costs for Passenger Railroads**

**Table 48. Bus Costs by Service Type**

| Service Type | Passengers per Train | Coaches | Average mileage between stations | Mileage with 1.5 Circuity Factor | Bus Speed (MPH) | Time to Traverse Gap (hours) | Hourly Cost Per Coach (2021$) | Bus Costs per Train ($BusCostPerTrain_s$) (2021$) |
|---|---|---|---|---|---|---|---|---|
| Long Distance | 166.5 | 4 | 53.78 | 80.67 | 50 | 1.61 | $221.10 | $1,423.88 |
| State-Supported | 166.5 | 4 | 21.55 | 32.33 | 50 | 0.65 | $221.10 | $574.86 |
| NEC | 166.5 | 4 | 20.77 | 31.16 | 50 | 0.62 | $221.10 | $548.33 |
| Commuter | 199.5 | 5 | 11.8 | 17.7 | 25 | 0.71 | $276.37 | $981.11 |

The method to estimate the cost of busing for commuter services is somewhat different than for intercity Amtrak service. First, commuter rail agencies will bus passengers for shorter duration closures than Amtrak because commuter passengers have different expectations regarding delay and because, as transit agencies, they will likely have ready access to the needed coaches. Therefore, commuter rail operations will bus for any closure of one hour or longer. Second, busing for commuter rail services will replace the entire remainder of the journey with the bus, rather than simply transporting rail passengers to the next station. According to the 2018 American Public Transportation Association Fact Book, the average distance traveled by commuter rail passengers is 23.6 miles.[100] Assuming that an incident could happen at any time during that trip with equal probability, the average remaining mileage used in this

[100] American Public Transportation Association. (2018). *2018 Public Transportation Fact Book*. https://www.apta.com/wp-content/uploads/Resources/resources/statistics/Documents/FactBook/2018-APTA-Fact-Book.pdf

analysis is half that total trip distance, or 11.8 miles by rail, increased to 17.7 miles with the circuity factor 1.5 to account for the idea that road travel between rail stations is likely to be more circuitous than the original rail trip. Commuter passengers also travel in more congested urban settings and the average speed of the bus is assumed to be 25 MPH, half that of intercity Amtrak passengers, with a resulting busing time of 43 minutes (0.71 hours). Results are shown in Table 48.

#### *4.3.2.2 Net Travel Time Costs for Passengers*

The value of the increased travel time travel experienced by passengers relative to the time it would have taken to travel by rail ($PaxBusNetVOT$) is calculated by estimating the VOT for the bus journey and subtracting the VOT for the rail journey that would have taken place without the incident. Bus travel time costs to passengers are calculated by determining the amount of time spent on different portions of the bus trip and assigning the appropriate VOT to that time. Travel time experienced under the busing operations includes time spent waiting for the bus operations to be set up, time spent transferring from train to bus and back again, time spent on the bus, and time spent waiting for a train to arrive on the opposite side of the closure. Rail travel time costs are simply the VOT multiplied by the time it would take for the train to traverse the same distance. For the bus trip, time spent transferring between bus and train and time spent waiting outside a vehicle is valued at twice the in-vehicle VOT as specified in USDOT guidance.[101]

The analysis assumes that it will take four hours to set up the bus operations for Amtrak service and one hour to set up the bus operations for commuter service, starting from the time the incident occurs. As passenger trains arrive to the site of the closure, they experience wait time corresponding to the remaining portion of that set up period until the busing is operational. Any passenger trains arriving after the bus bridge has been set up experience no delay related set up. The formula to derive this bridge set up wait time for a particular train ($t$) of service type ($s$) at location ($l$) is given in Equation 30. Each train for a certain service type and route that arrives at the location of a closure is assigned a sequential index, $t$. The first train to arrive is $t$=1, the second $t$= 2, etc. The calculation considers the total set up time required for each type of service $SetupTime_s$ (four hours for intercity Amtrak services and one hour for commuter trains). If the hourly arrival rate is two trains per hour for a certain route $r$, the first train to arrive will have $Setup_{l,s,r,t=1}$ equal to 3.5 hours (4 hours minus 1 times (1/2)). The second train to arrive will have $Setup_{l,s,r,t=2}$ equal to 3.0 hours (4 hours minus 2 times (1/2)) and so on until the calculation reaches its floor of zero hours. In this analysis time spent waiting for the bus bridge to be set up is valued at the in-vehicle VOT (see Table 40) since passengers are likely waiting inside the train.

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[101] *Benefit-Cost Analysis Guidance for Discretionary Grant Programs.* "Table A-3: Value of Travel Time Savings" (March 2022 (Revised)). Office of the Secretary, U.S. Department of Transportation. https://www.transportation.gov/sites/dot.gov/files/2022-03/Benefit%20Cost%20Analysis%20Guidance%202022%20%28Revised%29.pdf

$$Setup_{l,s,r,t} = Max\left\{0, \left(SetupTime_s - t \times \frac{1}{arrivalrate_{l,s,r}}\right)\right\}$$

**Equation 30. Time Waiting While Busing Set Up**

Total transfer time between bus and train is assumed to be 90 minutes for intercity Amtrak passengers. These passengers experience two transfers of 45 minutes each. Commuter passengers experience just one transfer which is assumed to require 15 minutes. Transfer time is valued at double the in-vehicle VOT.

The bus journey is dependent on the length of the journey by rail and adjusted by a circuity factor, as shown in Table 48. For intercity Amtrak passengers, rail travel time depends on distance between two rail stations. For commuter rail passengers, it depends on the distance of the remainder of their journey. The expected passenger travel time costs without a rail line closure (travelled by rail) are then subtracted from the bus travel time and the difference in the two line-haul travel times is valued at the in-vehicle VOT. The baseline rail travel time is shown in Table 49. In estimating the travel time by rail for baseline conditions (without the closure), average speeds of 46 MPH, 49 MPH and 60 MPH for Amtrak long distance, state-supported, and Amtrak NEC service, respectively, were selected to reflect average intercity Amtrak passenger train speeds.[102] The NTD shows average speeds of 32.2 MPH for the 16 commuter rail agencies that share track with freight operations.

**Table 49. Rail Baseline Costs and Net Travel Time, by Service Type**

| Service Type ($s$) | Average mileage between stations | Rail Speed (MPH) | Time to Traverse Gap by Rail in Hours ($RailTime_s$) | Time to Traverse Gap in Hours ($BusTime_s$) | Net Travel Time in Hours | Passenger VOT (2021$) | Net Travel Time times VOT (2021$) |
|---|---|---|---|---|---|---|---|
| Long Distance | 53.78 | 46 | 1.17 | 1.61 | 0.44 | $24.43 | $10.75 |
| State-Supported | 21.55 | 49 | 0.44 | 0.65 | 0.21 | $24.43 | $5.13 |
| NEC | 20.77 | 60 | 0.35 | 0.62 | 0.27 | $24.43 | $6.60 |
| Commuter | 11.8 | 32.2 | 0.37 | 0.71 | 0.34 | $18.51 | $6.29 |

Intercity Amtrak passengers must wait for the train arriving in the opposite direction that they will board and then proceed on to the rest of their journey after the train reverses direction. This wait time is valued at double the in-vehicle VOT. The time spent waiting for a specific type of passenger rail service

[102] Average Amtrak actual train speeds for October 2018 as available from Amtrak's website and captured by asm.transitdocs.com.

($s$) and route ($r$), at location ($l$), denoted by $Wait_{s,r,l}$, depends on the headway in each direction shown in Equation 31. TPD as it is used in this report refers to total trains in both directions. Factoring TPD by 0.5 produces the TPD in a single direction which is relevant to headway calculations.

$$Headway_{l,s,r} = \frac{24\ hours}{(0.5 \times PaxTPD_{l,s,r})}$$

**Equation 31. Passenger Train Headway**

At any given point on a passenger's journey, the expected arrival time for an oncoming train is one-half of the headway away. But that time is shortened by the time the passengers have already spent waiting (the set-up time, the time spent transferring to and from buses and the time spent travelling between stations by bus) as shown in Equation 32. The wait time is subject to a minimum wait time of zero. If the passenger's transfer and bus journey time is more than one-half the headway time, the train arriving from the opposite direction would arrive and be waiting for passengers when their bus arrives and no additional wait time would be incurred. The wait time is valued at twice the in-vehicle VOT as specified in USDOT guidance.

$$Wait_{l,s,r,t} = Max\ \{\left(\frac{1}{2}Headway_{s,r,l}\right) - \left(Transfer_s + BusTime_s + Setup_{l,s,r,t}\right), 0\}$$

**Equation 32. Time Waiting for Approaching Train**

Each of the travel time components discussed above are summed together as specified in Equation 33.

$$\begin{aligned} PaxBusNetVOT_{l,s,r,t} &\\ &= PassengersPerTrain_s \\ &\times \left[PaxVOTInVeh_s \times Setup_{l,s,r,t} + 2 \times PaxVOTInVeh_s \times Transfer_s \right.\\ &\left. + PaxVOTInVeh_s \times (BusTime_s - RailTime_s) + 2 \times PaxVOTInVeh_s \times Wait_{s,r}\right] \end{aligned}$$

**Equation 33. Net Travel Time Costs for Passengers**

### Busing Costs for Passenger Trains: Net Travel Time Costs for Passengers

A hypothetical track segment is experiencing an 18.5-hour closure and runs eight state-supported TPD. During the closure, six passenger trains (0.33 times 18.5) will encounter this track segment and will experience a "bus bridge".

The first step is set up the busing operations. It will take four hours for Amtrak to set up the busing from the start of the closure. The first passenger train to arrive at the closure is assumed to arrive three hours after the closure began (1 divided by 0.33). Therefore, the first passenger train will wait for the remaining one hour ($Setup_{l,s,r,t}$) for the busing to be set up. Because the following trains are estimated to arrive every three hours, they will have zero set up time upon arrival at the closed track segment.

For this example, all eight passenger trains are on the same route, so the headway is six hours (24 hours divided by (0.5 times 8 TPD)). Headway is estimated for each specific Amtrak route because even if there were multiple state-supported Amtrak routes along the same segment of track, passengers from one route could not transfer to the train of another route. Each train load of passengers must wait for a train of their specific Amtrak route to arrive on the other side of the closure.

The next step is to estimate the time passengers will wait for the approaching train on opposite side of the closure. The passengers on the first train will have no extra wait time ( $Wait_{l,s,r,t}$) because the calculated time waiting for the approaching train is less than zero (0.5 times 6 hours minus (90 mins plus 0.65 hours plus 1 hour)). However, the following trains will have an estimated extra wait time of 0.85 hours (0.5 times 6 hours minus (90 mins plus 0.65 hours plus 0 hours)). The difference here is the first train has one hour of setup time where the following trains do not.

Applying this to the Equation 33 we would find that passengers on the first train experience delay at a cost of $176 in lost time per passenger, or $29,304 for the whole 166.5 passengers on the first passenger train impacted. The five subsequent passenger train passengers experience a loss of time at a cost of $218 (higher due to an increased wait for the next passenger train on their side of the closure). This equals $36,297 for the whole 166.5 passengers impacted per subsequent train, or $210,789 in total value of lost passenger time due to a closure.

### *4.3.2.3 Passenger Train Crew Costs and Fuel and Emissions Costs*

For intercity Amtrak service, the train and the train crew experience the same delay as the individual passengers. The hours of delay are monetized using the crew cost per hour from Table 39 as shown in Equation 34 and fuel and emissions costs for idling from Table 45 as shown in Equation 35.

$$PaxCrewCostWait_{l,s,r,t} = PaxCrewCostPerTrainHour_s \times \left[Setup_{l,s,r,t} + Transfer_s + BusTime_s + Wait_{s,r}\right]$$

**Equation 34. Passenger Crew Costs from Waiting While Busing for Intercity Amtrak Service**

$$PaxFuelEmissionCostWait_{l,s,r,t} = PaxFuelEmissionCostWaiting \times [Setup_{l,s,r,t} + Transfer_s + BusTime_s + Wait_{s,r}]$$

**Equation 35. Passenger Train Fuel and Emissions Costs from Waiting While Busing for Intercity Amtrak Service**

For commuter services, since the passengers are transported by bus for the remainder of their journeys, the only additional delay experienced by the trains and crew is related to the time needed to set up the busing operations as shown in Equation 36 and Equation 37.

$$PaxCrewCostWait_{l,s,r,t} = PaxCrewCostPerTrainHour_s \times [Setup_{l,s,r,t}]$$

**Equation 36. Passenger Crew Costs from Waiting While Busing for Commuter Service**

$$PaxFuelEmissionCostWait_{l,s,r,t} = PaxFuelEmissionCostWaiting \times [Setup_{l,s,r,t}]$$

**Equation 37. Passenger Train Fuel and Emissions Costs from Waiting While Busing for Commuter Service**

### 4.3.3 Limitations of the Passenger Rail Delay Costs Model

The passenger rail cost delay cost analysis presented here is a simplified model to provide a generalizable approach to be used across the rail network. As the model assumes that passenger trains will continue to depart and does not estimate cancellations for upcoming service, as presented it is expected to provide an upper bound of the delay costs to the passenger rail network. There are potential mitigations that could be taken by both railroads and passengers that might lower the social cost of delay including the cancelling of future service, rebooking on future service or alternative modes, or potentially busing a full route's distance. All such mitigations would lower the social cost of delay compared to what is estimated here. This model does not attempt to estimate these behaviors as the prices and quantities of these actions are unknown and unverifiable. Based on the literature review, there is no readily available method to value a cancelled or postponed trip that would result if the passenger rail operator cancelled trains before their departure in response to a rail accident. Additionally, in some cases multiple routes overlap and the assumption for time waiting for an oncoming train (1/2 times the train headway) may be an overestimate.

# 5. Roadway Users Cost of Delay

In the cases where a nearby roadway is closed due to an incident, there's an additional cost experienced by the vehicles on that portion of the roadway network. The nearby roadway might be closed because the incident blocks a grade crossing, because debris from the accident is blocking the roadway, because the possibility of a HAZMAT release resulted in an evacuation, or because the roadway is used to stage equipment used in the accident response. This section discusses the characteristics of incidents road closures, the factors used to monetize the costs of delay for these impacts, and the model used to estimate delay for roadway users.

## 5.1 Characteristics of Incidents with Roadway Closure

NRC initial incident reporting, media reporting, and other document review was performed for the purpose of manually locating incidents in the PHMSA data in terms of latitude and longitude (geolocation).[103] Incidents reported to PHMSA using Form 5800.1 that involved a major artery closure were manually reviewed to determine if incidents resulted in the closure of a nearby roadway or an evacuation of the public. Evacuation information was used because an evacuation of the public would necessarily affect highways and roads in the area. FRA Safety Map data on milepost locations and grade crossings were used in addition to ArcGIS Online and/or Google Maps to find approximate geolocations from narrative locations and milepost information.[104] In general, as many sources as possible were used together in order to logically verify locations of incidents.

### 5.1.1 National Response Center Initial Incident Report Review

Where possible, PHMSA data were supplemented by associating PHMSA reported incidents with reporting to the NRC initial incident reports. Through associating with NRC reports, more detailed location information, evacuation information, and road closure information were obtained. NRC initial incident reports contain narrative locations in the form of addresses, mileposts and subdivisions, or grade crossings. Road closure information from NRC incident reports included a binary field for road closure, as well as a field for the name of the road closed if applicable. Evacuation information from NRC incident reports included a binary field for evacuation, evacuation type, evacuation radius, and number of people evacuated. However, all fields were not available for every incident, and some incidents did not have a corresponding NRC initial incident report.

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[103] United States Coast Guard (USCG) National Response Center (NRC) https://nrc.uscg.mil/
[104] Federal Railroad Administration. "FRA – Safety Map" https://fragis.fra.dot.gov/GISFRASafety/

### 5.1.2 Media Review

Where possible, PHMSA data were also supplemented by associating PHMSA reported incidents with media reporting. This included local news reporting archives from newspapers and television news, social media posts of responding agencies, and press releases made by responding agencies. Through media review, location, evacuation and road closure information were obtained. Location information contained description of the site of the release, often through road or intersection names, landmarks, or geographic information. Road closure information varied from descriptions of segments of closed highway to general statements that roads were closed in the area of the incident. Evacuation information often included some combination of evacuation type, duration, radius, and number of people affected.

### 5.1.3 Other Document Review

The narrative incident descriptions in the Form 5800.1 data were manually reviewed for location, road closure, and evacuation information. Location information included milepost information, names of rail yards where incidents occurred, and general descriptions of incidents. In the case where a PHMSA reported incident resulted in a release into a waterway or otherwise sensitive environmental area, Environmental Protection Agency (EPA) information was used for precise geolocation information. EPA Pollution/Situation reports contain latitude and longitude coordinates, which were manually associated with the respective PHMSA reported incident. In the case where a PHMSA reported incident resulted in a NTSB investigation, information from the report was used for location, road closure, and evacuation information.[105] NTSB Accident Reports, Factual Reports, and Railroad Accident Briefs include location information in the form of mileposts, as well as descriptions of incidents which in some cases include evacuations or road closures.[106] Through manual review of all sources, it was found that approximately 52 percent of incidents resulting in a major artery closure also resulted in the closure of a road or an evacuation of the public, as seen in Table 50.

**Table 50. Incidents Resulting in a Major Artery Closure with Road Closures and/or Evacuation of the Public**

| Incident Type ( $j$ ) | Incidents with Road Closure or Evacuation | Incidents without Road Closure or Evacuation, or Unknown | Total Number of Incidents | Percent with Road Closure or Evacuation ($m_j$) |
|---|---|---|---|---|
| AR | 78 | 32 | 110 | 71% |
| NAR | 25 | 62 | 87 | 29% |
| **Total** | **103** | **94** | **197** | **52%** |

[105] National Transportation Safety Board. "Major Investigations" https://www.ntsb.gov/investigations/Pages/default.aspx
[106] National Transportation Safety Board. "Railroad Accident Reports" https://www.ntsb.gov/investigations/AccidentReports/Pages/railroad.aspx

The information sources listed above resulted in the determination of geolocations for 172 incidents with a major artery closure out of a total of 201 reviewed, as seen in Table 51.

**Table 51. Geolocation Coverage of Incidents Resulting In a Major Artery Closure**

| Incident Type ( $j$ ) | Geolocation Found | No Geolocation Found | Total Number of Incidents |
|---|---|---|---|
| AR | 112 | 1 | 113 |
| NAR | 66 | 22 | 88 |
| **Total** | **178** | **23** | **201** |

In order to apply the cost of a roadway closure, incidents were given a rural or urban designation. This was determined using the county and state of the incident, matched with county population data from the 2010 Census.[107] If the county population is at least 50 percent rural, the county is determined to be rural. Otherwise, the county is determined to be urban. The Federal Information Processing Standards (FIPS) county information was not available for six percent of incidents. Based on records where FIPS county information is available, the percent of ARs and NARs which are urban or rural can be seen in Table 52. These percentages were calculated for all ARs and all NARs, regardless of whether or not they resulted in a closure and are used to calculate the cost of a roadway closure.

**Table 52. Percent of Incidents which are Urban or Rural**

| Incident Type ( $j$ ) | Percent in Urban Area | Percent in Rural Area |
|---|---|---|
| AR | 65.2% | 34.8% |
| NAR | 91.0% | 9.0% |

## 5.2 Monetization

The following section describes the monetization factors that are used to transform hours of vehicle delay to the cost of a roadway closure. Hours of vehicle delay as well as cost per vehicle delay hour are presented for urban incidents and rural incidents to reflect the differences between urban and rural roadways. The monetization factors are presented in 2021 dollars.

### 5.2.1 Occupant VOT

A proportion of travel on each roadway type that is by passenger vehicle (as opposed to truck) is applied to separate the delay to passengers and the delay to truck drivers. A value of 1.67 occupants per vehicle as provided by USDOT benefit cost guidance is applied to passenger vehicles and the resulting estimates

[107] U.S. Census Bureau, (December 2019) "Percent Urban and Rural In 2010 by State and County," The United States Census Bureau https://www.census.gov/programs-surveys/geography/guidance/geo-areas/urban-rural/2010-urban-rural.html.

of hours of passenger delay and truck delay are multiplied by local travel passenger VOT ($PassVOT$) and truck driver VOT ($TruckVOT$) to estimate the cost of delay to roadway users. The VOT for delay for passenger vehicle traffic impacted by roadway closures is the all purposes (mix of business and personal) local VOT, and VOT for truck traffic is the truck driver VOT. Table 53 presents the car and truck driver VOT used in this analysis.

**Table 53. In-Vehicle VOT**

| Type | In-vehicle VOT (2021$) |
|---|---|
| Passenger Vehicle | $17.80 |
| Truck Driver | $32.00 |

*Source: Benefit-Cost Analysis Guidance for Discretionary Grant Programs*

### 5.2.2 Fuel and Emissions

The rate at which emissions are released per vehicle delay hour for an urban roadway and rural roadway are taken from Hagemann et al (2013) and is presented in Table 54. The social cost of emissions shown in Table 54 is provided by USDOT benefit cost guidance.[108] Combining that information results in an estimated total social cost of emissions per vehicle hour delay of $2.29 for urban roadway closures and $4.46 for rural roadway closures.

**Table 54. Emissions per Vehicle Hour of Delay**

| Emission Type | Emission Rate per Vehicle Hour of Delay (metric tons) Urban | Emission Rate per Vehicle Hour of Delay (metric tons) Rural | Cost per metric ton (2021$) |
|---|---|---|---|
| Carbon Dioxide | 0.0155129 | 0.0192323 | $54 |
| VOCs | 0.0000064 | 0.0000073 | $0 |
| NOx | 0.0000277 | 0.0000619 | $16,224 |
| $PM_{2.5}$ | 0.0000013 | 0.0000031 | $778,544 |
| Sulfur Dioxide | 0.0000003 | 0.0000003 | $43,160 |
| **Total Emissions Cost Per Vehicle Hour of Delay** | **$2.29** | **$4.46** | N/A |

*Source:* (Hagemann et al., 2013) *and Benefit-Cost Analysis Guidance for Discretionary Grant Programs. Values converted from short tons to metric tons.*

Gallons of diesel and gasoline per vehicle delay hour is determined by the fuel burn rate, diesel and gasoline consumption factors, the energy content for diesel and gasoline (see Table 55). Fuel burn rate multiplied by the respective consumption factor for diesel and gasoline divided by the energy content respective for diesel and gasoline results in the amount, in gallons, consumed per vehicle delay hour.

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[108] *Benefit-Cost Analysis Guidance for Discretionary Grant Programs.* "Table A-6: Damage Costs for Pollutant Emissions" (March 2022 (Revised)). Office of the Secretary, U.S. Department of Transportation. https://www.transportation.gov/sites/dot.gov/files/2022-03/Benefit%20Cost%20Analysis%20Guidance%202022%20%28Revised%29.pdf

Gallons of diesel and gasoline per vehicle delay hour for an urban and rural roadway are also presented in Table 55.

**Table 55. Gallons of Fuel (Diesel and Gasoline) per Vehicle Delay Hour**

| Roadway Type ($u$) / Fuel Type | Fuel Burn Rate (MMBtu per Vehicle Delay Hour) | Consumption Factor (%) | Energy Content (MMBtu/gallon) | Gallons per Vehicle Delay Hour |
|---|---|---|---|---|
| Urban / Diesel | 0.196 | 0.5 | 0.1387 | 0.707 |
| Urban / Gasoline | 0.196 | 0.5 | 0.125 | 0.784 |
| Rural / Diesel | 0.269 | 0.6 | 0.1387 | 1.164 |
| Rural / Gasoline | 0.269 | 0.4 | 0.125 | 0.861 |

The social cost of diesel is $2.716 per gallon and the social cost of gasoline is $2.606 per gallon in 2021 dollars. The unit social cost for diesel and gasoline applied to gallons per vehicle delay results in the total social cost for fuel by roadway type as shown in Table 56.

**Table 56. Social Cost of Fuel per Vehicle Delay Hour**

| Roadway Type ($u$) | Social Cost of Fuel (2021$) |
|---|---|
| Urban | $3.96 |
| Rural | $5.41 |

## 5.3 Costs of Roadway Closure Model

The model to estimate expected vehicle delay ($VehicleHoursDelay$) is taken from a study used to estimate the social costs of truck crashes developed on behalf Federal Motor Carrier Safety Administration (Hagemann et al., 2013). That study provides a model that estimates total vehicle delay as a function of parameters specific to a certain roadway type, volume, and duration of the closure as shown in Equation 38. This analysis assumes that roadway closure is of the same duration of the accompanying rail line closure.

This equation is based on the result of traffic modeling that used simulations to measure the delay resulting from closures of various durations on a variety of roadway types. The simulations used a representation of a roadway network that included the site of the closure and alternate routes around the closure (detours). In some scenarios, due to the capacity and volumes of the alternate routes, congestion on the alternate routes contributes to the total vehicle delay resulting from a roadway closure. The parameters $a, b, c, d, e, f$ in Equation 38 are specific to a certain roadway type and are provided in Table 57. $Volume$ is total number of vehicles on the roadway in both directions per hour and $duration$ is length of closure in minutes.

$$VehicleHoursDelay = a + b \times \frac{1}{1 + e^{-\left(\frac{volume - c}{d}\right)}} \times \frac{1}{1 + e^{-\left(\frac{duration - e}{f}\right)}}$$

**Equation 38. Total Vehicle Hours Delay in Roadway Closure (Hagemann et al., 2013)[109]**

In Hagemann et al (2013) the parameters $a, b, c, d, e, f$ are estimated individually for five groupings of roadway type: Urban Interstate/Expressway, Urban Principal Arterial, Urban Other, Rural Interstate/Arterial, and Rural Other. The set of parameters related to the Urban Principal Arterial was chosen to represent the roadway impacts from an incident in an urban area and the set of parameters related to Rural Other was chosen to represent the impacts from a rural incident.[110]

Using hourly traffic volumes for 2019 from Federal Highway Administration's (FHWA) Traffic Monitoring Analysis System (TMAS), the average hourly traffic volume for three portions of the day – peak, off-peak, and shoulder – was calculated for the collections of roadways categorized as Urban Principal Arterial and Rural Other.[111] Equation 38 was then applied to each volume of traffic and for the closure duration of interest to produce an estimate of the resulting vehicle delay. An expected amount of vehicle delay is calculated for each roadway by multiplying the delay estimate for each time of day by the share of hours in each time of day category (peak, off-peak, and shoulder). Table 57 below presents the parameters and traffic volumes used to apply the model for rail incidents that occur in urban and rural settings.

**Table 57. Parameters and Traffic Volumes in Roadway Closure Model**

| Parameters | Urban | Rural |
|---|---|---|
| $a$ | -54.0935 | -4.8833 |
| $b$ | 15215.42 | 654.6301 |
| $c$ | 4479.63 | 185.057 |
| $d$ | 1785.987 | 84.79895 |
| $e$ | 417.3425 | 365.8839 |
| $f$ | 133.7807 | 123.8583 |
| Volume peak (vehicles per hour) | 2,046.74 | 393.61 |
| Volume shoulder (vehicles per hour) | 1,461.51 | 277.43 |
| Volume off-peak (vehicles per hour) | 362.42 | 73.38 |
| Proportion peak | 0.292 | 0.292 |
| Proportion shoulder | 0.333 | 0.333 |
| Proportion off-peak | 0.375 | 0.375 |
| Proportion passenger vehicles ($car_u$) | 0.95 | 0.91 |
| Proportion trucks (1-$car_u$) | 0.05 | 0.09 |

[109] The equation is reproduced from the cited source. There is a lack of clarity as written, as "*e*" is used as Euler's number, and when is subtracted from duration in the exponent, is a model parameter.
[110] The Urban Principal Arterial group includes urban principal arterials (other) and urban minor arterials. The Rural Other group includes rural minor arterials, rural major collectors, rural minor collectors, and rural local roads.
[111] Federal Highway Administration. "Traffic Volume Data – FHWA's TMAS Data Program" https://explore.dot.gov/views/2017-19TMASDashboard_20200414_v10_5/TMAS17-19Dashboard?:iid=1&:isGuestRedirectFromVizportal=y&:embed=y

The estimate of vehicle hours of delay is transformed to the expected cost of a closure (*RoadwayCostj*) using Equation 39. The estimate is general in that it is not specific to a certain location. Rather it uses a probabilistic approach that incorporates the probability of the incident impacting an urban roadway or a rural roadway. In that equation $m_j$ is probability of a roadway closure for incident type *j* (AR or NAR). As shown in Table 50 of Section 5.1, $m_{j=NAR}$ is 29 percent and $m_{j=AR}$ is 71 percent. The term $z_{j,u}$ is the probability of incident type *j* (AR or NAR) occurring in area type *u* (urban or rural). Those probabilities are presented in Table 52 which shows that 65.2 percent of ARs and 91.0 percent of NARs are in urban areas with the remainder being in rural areas. The passenger and truck operator VOTs are provided in Table 53. The *VehicleDelayHours(d,u)* is estimated using Equation 38. The vehicle occupancy (*Occ)* is assumed to be 1.67 and the passenger vehicle and truck VOT (*PassVOT* and *TruckVOT*) are $17.80 and $32.00 respectively, as shown in Table 53. Finally, $car_u$ is proportion of travel for area type *u* that is by passenger vehicle, as opposed to by truck.

$$
\begin{aligned}
&RoadwayCost_j(d) \\
&\quad = m_j \sum_u z_{j,u} \{car_u \times VehicleDelayHours(d,u) \times Occ \times PassVOT \\
&\quad + (1 - car_u) \times VehicleHoursDelay(d,u) \times TruckVOT \\
&\quad + VehicleHoursDelay(d,u) \times SocialCostEmissionsRoadway_u \\
&\quad + VehicleHoursDelay(d,u) \times SocialCostFuelRoadway_u\}
\end{aligned}
$$

**Equation 39. Cost of Roadway Closure**

### 5.3.1 Results

Table 58 below provides the results of the cost of roadway closure model for various durations explored in this analysis as estimated using Equation 39. The values increase with duration, though after approximately 12 hours, the increase in costs reduces significantly. This is a result of the functional form of the model developed by Hagemann et al (2013) shown in Equation 38.

**Table 58. Roadway Cost Results**

| Duration/Accident Type | Highway Costs (2021$) |
|---|---|
| 4 Hours NAR | $3,744 |
| 6 Hours AR | $14,646 |
| 12.4 Hours AR | $34,750 |
| 13.4 Hours AR | $35,774 |
| 18.5 Hours AR | $37,520 |
| 22.2 Hours AR | $37,686 |
| 27.5 Hours AR | $37,722 |
| 41.1 Hours AR | $37,726 |
| 45.7 Hours AR | $37,726 |
| 68.3 Hours AR | $37,726 |

# 6. Scenario Development

Because the delay costs associated with a HAZMAT rail incident vary depending on the location of the closure, this analysis takes a scenario-based approach that explores a variety of randomly selected potential incident locations from the freight rail network in the United States. Those different locations display a variety of different freight and passenger rail traffic volumes and capacities. This section discusses the method for creating a random sample of locations to use in this analysis.

After flowing waybill data on the NARN, as described in Section 3.3, the U.S. portion of the network that hosted freight traffic was identified as the universe of possible HAZMAT incident locations. The cost of waiting for all of those locations can be estimated readily using the information available from the waybill data and the NARN. However, estimating the cost of rerouting for a particular location requires rerouting the waybill records on a version of the rail network modified to remove the location of interest in order to observe the “second best” alternative routings for a situation in which the location of interest is closed. That rerouting analysis, described in Section 3.3.4, is computationally intensive and therefore this analysis considers only a sample of locations as the site of a potential HAZMAT incident.

The majority of freight traffic flows on Class 1 railroad network (i.e., track that a Class 1 railroad owns).[112] For that Class 1 railroad network, the primary sampling unit (PSU) is the subdivision as reported in the NARN. It is assumed that the relative attractiveness of an alternate routing will likely be similar across all the locations within a subdivision. Therefore, sampling multiple locations within the same subdivision will likely not produce new information. For the Class 2/3 network, each individual railroad is used as the PSU, again under the assumption that sampling multiple locations within the same railroad network for these smaller railroads is unlikely to produce new information. Within each subdivision or railroad, an individual segment displaying the most common amount of traffic for the subdivision (the mode) was randomly selected to represent that PSU.

For the stratified sampling plan, Class 1 railroad subdivisions greater than or equal to 25 miles in length were split into eastern and western groups.[113] Class 1 railroads were further split. First, they were divided into east and west railroads and subdivisions with or without passenger rail. Each of these four sample groups was then further divided into high and low traffic samples with the high traffic subdivisions defined as the highest volume subdivision (as measured by car-miles) which collectively account for 50 percent of traffic in the grouping.

Shorter Class 1 subdivisions, and Class 1 rail segments without a subdivision identified were grouped together into track with and without passenger rail, and individual links were sampled for this group. Class 2/3 railroads were further divided by size, with a cutoff of 35 miles in length.[114] Each network group was then further divided into groups depending on whether the PSU did or did not host passenger

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[112] In this analysis, the track is classified according to the first owner as listed in the NARN.
[113] Eastern Railroads: CN, CSX, NS. Western Railroads: BNSF, CP, KCS, UP
[114] The median length of Class 2/3 railroads in the freight network is approximately 35 miles.

rail service. The final groups and various measures of their relative sizes are shown in Table 59.

**Table 59. U.S. Freight Rail Network PSUs**

| Sample Group | Passenger Rail | High Traffic or Low Traffic? | Subdivisions | Share of Track Miles | Share of Freight Train-Miles |
|---|---|---|---|---|---|
| Eastern Class 1 | No | High | 25 | 3.0% | 7.6% |
| Eastern Class 1 | No | Low | 229 | 16.2% | 7.8% |
| Western Class 1 | No | High | 21 | 3.5% | 13.8% |
| Western Class 1 | No | Low | 270 | 24.4% | 16.4% |
| Class 1 < 25miles | No | N/A | 726 | 4.2% | 1.2% |
| Big Class 2/3 | No | N/A | 165 | 19.3% | 7.0% |
| Small Class 2/3 | No | N/A | 198 | 2.2% | 0.3% |
| Eastern Class 1 | Yes | High | 11 | 1.5% | 5.9% |
| Eastern Class 1 | Yes | Low | 61 | 5.4% | 6.1% |
| Western Class 1 | Yes | High | 11 | 2.1% | 13.9% |
| Western Class 1 | Yes | Low | 99 | 12.4% | 16.6% |
| Class 1 < 25miles | Yes | N/A | 69 | 1.5% | 0.8% |
| Big Class 2/3 | Yes | N/A | 24 | 4.1% | 2.5% |
| Small Class 2/3 | Yes | N/A | 13 | 0.2% | 0.2% |
| **Total** | **N/A** | **N/A** | **1922** | **100.0%** | **100.0%** |

A total of 89.9 percent of network freight train-miles were on track owned by Class 1 railroads. However, analysis of the 10-year history of PHMSA 5800.1 data finds that, historically, 84.3 percent of ARs occurred on Class 1 track. This discrepancy may arise because the waybill data that form the basis for the estimate of freight train-miles is collected only from Class 1 railroads and therefore is likely to under-represent Class 2/3 railroad traffic. To account for this discrepancy, the share of freight train-miles in each network group was adjusted so that Class 1 network groups comprised 84.3 percent of all sample units, as shown in Table 60.

A random sample of 229 PSUs was drawn according to the sampling plan show in Table 60.[115]

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[115] Initially a 15 percent sample was drawn using a sampling plan that did not differentiate between high and low volume Class 1 railroad groups. Based on reviewer feedback, the sample was later expanded to draw more sample from the high volume Class 1 sample groups and from the Big Class 2/3 sample groups so that the resulting sample would be more representative of the full network.

Table 60. Network Group with Sample Sizes

| Network Group | Passenger Rail | High Traffic or Low Traffic? | Share of Freight Train-Miles | Adjusted Share | Sample Size |
|---|---|---|---|---|---|
| Eastern Class 1 | No | High | 7.6% | 7.1% | 13 |
| Eastern Class 1 | No | Low | 7.8% | 7.3% | 22 |
| Western Class 1 | No | High | 13.8% | 13.0% | 19 |
| Western Class 1 | No | Low | 16.4% | 15.4% | 43 |
| Class 1 < 25miles | No | N/A | 1.2% | 1.1% | 6 |
| Big Class 2/3 | No | N/A | 7.0% | 10.7% | 21 |
| Small Class 2/3 | No | N/A | 0.3% | 0.5% | 5 |
| Eastern Class 1 | Yes | High | 5.9% | 5.6% | 10 |
| Eastern Class 1 | Yes | Low | 6.1% | 5.7% | 19 |
| Western Class 1 | Yes | High | 13.9% | 13.0% | 11 |
| Western Class 1 | Yes | Low | 16.6% | 15.6% | 38 |
| Class 1 < 25miles | Yes | N/A | 0.8% | 0.8% | 6 |
| Big Class 2/3 | Yes | N/A | 2.5% | 3.9% | 13 |
| Small Class 2/3 | Yes | N/A | 0.2% | 0.3% | 3 |
| **Total** | **N/A** | **N/A** | **100.0%** | **100.0%** | **229** |

For each sampled PSU (a subdivision or Class 2/3 railroad), a representative network link was selected. To capture the typical level of traffic along the PSU, the model generated a list of links for each PSU with modal (most common) amount of freight traffic. A randomly selected link from that collection represents the PSU. For the network group containing Class 1 links from subdivisions of less than 25 miles or links with no subdivision listed in the NARN, links were randomly sampled from the collective group.[116] Figure 15 presents the subdivisions and Class 2/3 railroads that were selected for the sample and illustrates with a star the individual links that were chosen to represent the sampled PSU.

[116] A review of the sampled links found five instances where rerouting over the network with the link removed would not produce realistic results. Those links were so close in proximity to the alternate route that a rail incident would be expected to close both the original route and the alternate route. For the four on longer Class 1 subdivisions, a link within the same subdivision was chosen to represent the subdivision. For the track segment on a short Class 1 subdivision, a new randomly selected link was chosen to represent the network group.

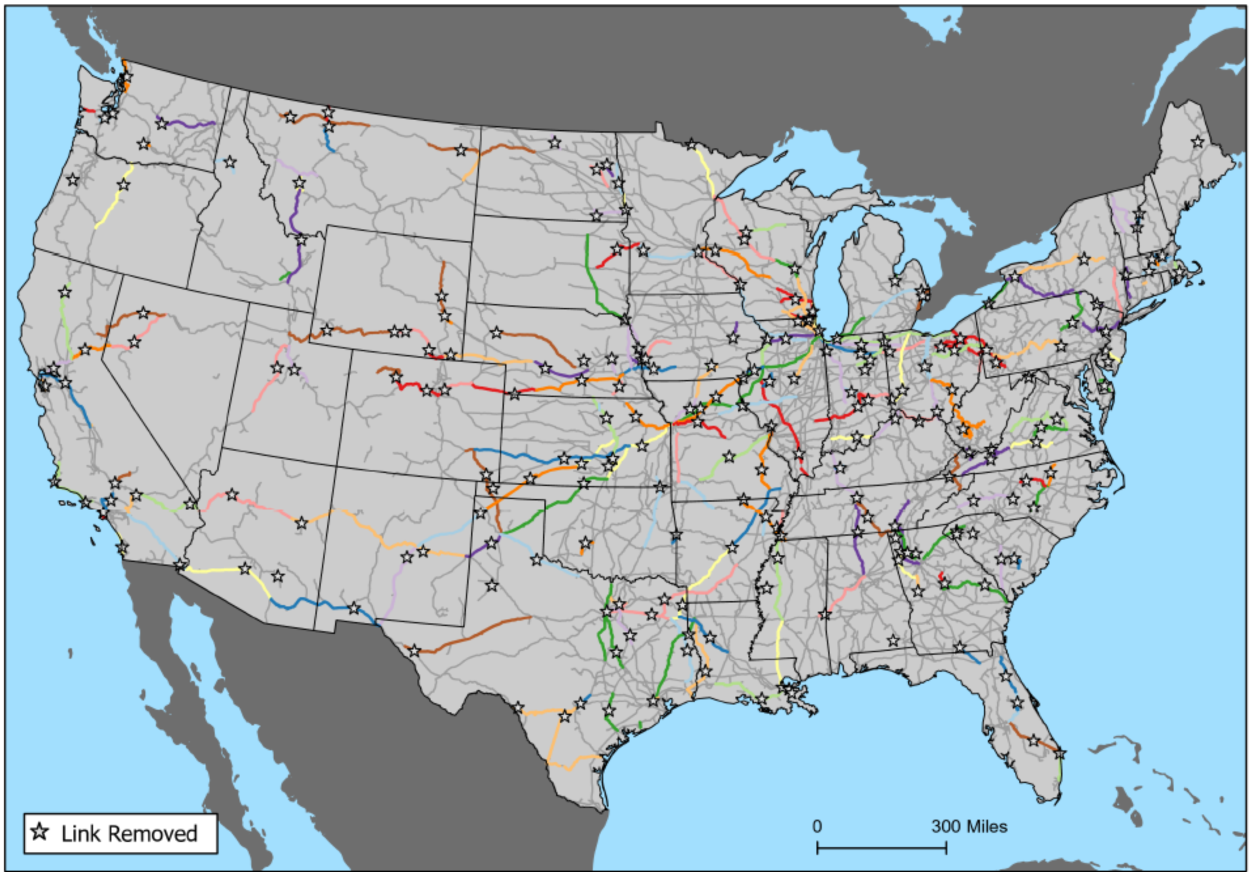


**Figure 15. Rail network sample of 229 locations**

# 7. Results

This section presents two sets of results. The first is the expected social cost of delay related to freight rail traffic waiting for an incident to clear and the train queue to dissipate. The second is the expected cost of delay related to freight rail traffic choosing to either have all traffic wait or reroute high priority traffic, depending on which option results in lower business costs.

Recall from Figure 1. *Components of Total Cost of Delay* that the total cost of an incident is the sum of the social cost from freight rail, the cost of passenger rail for each service type ($s$), and the cost to roadway users, as shown in Equation 40.

$$TotalSocialCost(l,d) = SocialFreightCost(l,d) + \sum_{s} PaxCost(l,d,s) + RoadwayCost(d)$$

**Equation 40. Total Social Cost of Incident**

For both sets of results, the cost of delay was estimated for all 229 sample locations on the U.S. freight rail network using the freight, passenger and roadway models described above. Results are presented separately for NAR and AR incidents. For each, the weighted average social costs of delay to freight rail, passenger rail, and roadway users impacted by rail and adjacent road closures are calculated for each network group described in Table 60. *Network Group with Sample Sizes*.

Within network group weights are calculated using each track segment's freight train-miles, divided by the total network group freight train-miles (i.e., calculating the track segment's share of network group train-miles). Each track segment's social cost of waiting is then multiplied by its within network group weight and these are summed to calculate the network group's average social cost of waiting. These network group averages are then weighted by the adjusted traffic shares for each network group shown in Table 60 to produce the full network average.

## 7.1 Cost of Delay When Freight Railroads Wait for Track to Reopen

### 7.1.1 Non-Accident Releases

The average social cost of NARs was estimated using median closure duration of four hours since the entire duration of the closure is attributed to the release of HAZMAT. This analysis assumes that for a short duration of four hours, freight railroads will always wait for the track to clear.

The weighted average across all locations ($l$) of $TotalSocialCost(l,d=4)$ in accordance with Equation 40 resulted in an average social cost for NARs of $28,027, or between $21,651 and $34,403 with a 95%

percent confidence interval. This estimate includes the social costs derived from freight traffic, passenger traffic, and roadway traffic. With a duration of four hours, the social cost derived from freight traffic comprise 86 percent of the social costs, the social cost derived from passenger traffic comprise 0.7 percent and the cost derived from roadway traffic comprise 13.4 percent. Table 61 shows that, given the relative infrequency of NARs resulting in closure of principle arteries (9.2 per year on average), the expected annual social cost of delay due to NARs is $257,846 per year.

**Table 61. Social Cost of NAR**

| Incident Type | Average Social Cost of Delay for a NAR (2021$) | NARs with Closures per Year (2010-2019) | Average Annual Social Cost of Delay for NARs (2021$) |
|---|---|---|---|
| NAR | $28,027 | 9.2 | $257,846 |

### 7.1.2 Accident Releases

The social cost of delay related to an incident of a specific duration is one of the components in Equation 1. *Expected Social Cost of Delay due to HAZMAT in an AR.* in Section 3.2*, Duration of Closure Analysis*. This social cost is estimated for each sample location for all the durations listed in Table 11. *Predicted Duration of Closure given a Closure by Incident Type and Facility Type (Hours) (for Non-Fatal ARs).* Table 62 shows the total social cost of delay when railroads wait, weighted by sample group and averaged across all sampled locations. Figure 16 charts the average total social cost of waiting by duration as well as the individual cost components of freight rail social cost, passenger rail cost, and roadway cost. Figure 17 focuses on the passenger rail cost and roadway cost by duration to provide more detail.[117]

**Table 62. Average Total Social Cost Delay When Freight Railroads Choose to Wait, by Duration of Incident**

| Duration ($d$) in hours | Average Total Social Cost of Delay When Railroads Wait (2021$) |
|---|---|
| 6 | $61,689 |
| 12.4 | $214,525 |
| 13.4 | $242,210 |
| 18.5 | $408,170 |
| 22.2 | $557,029 |
| 27.5 | $813,355 |
| 41.1 | $1,704,335 |
| 45.7 | $2,081,691 |
| 68.3 | $4,493,666 |

As shown in Figure 16 and Figure 17, the freight delay costs increase at an increasing rate with duration.

[117] In contrast to the adjusted network group shares, the unadjusted network group shares refer to shares of freight train-miles with no adjustments for the relative frequency of HAZMAT incidents between Class 1 and Class 2/3 railroads as shown in Table 55. *Network Group with Sample Sizes*.

Passenger delay costs increase at a linear rate with duration aside from a kink near the 8-hour point where all passenger service shifts to using bus bridges rather than waiting. Roadway delay costs have a more complex relationship with duration of closure, with costs increasing at an increasing rate for shorter closure durations, but increasing at a a much slower rate for most closure durations relevant to ARs. Those dynamics are the result of the functional form used by Hagemann et al (2013).

A curve was fit to provide an estimate of the average total social cost of delay as a function of duration (Equation 41). The formula suggests that a closure of one day (24 hours) results in a social cost of approximately $638,000 when the freight railroads choose to wait for the incident to clear rather than reroute.

$$TotalSocialCost_{Waiting} = 5409.6 \times Duration + 882.7 \times Duration^2$$

**Equation 41. Estimate of Average Total Social Cost of Delay When Freight Railroads Wait**

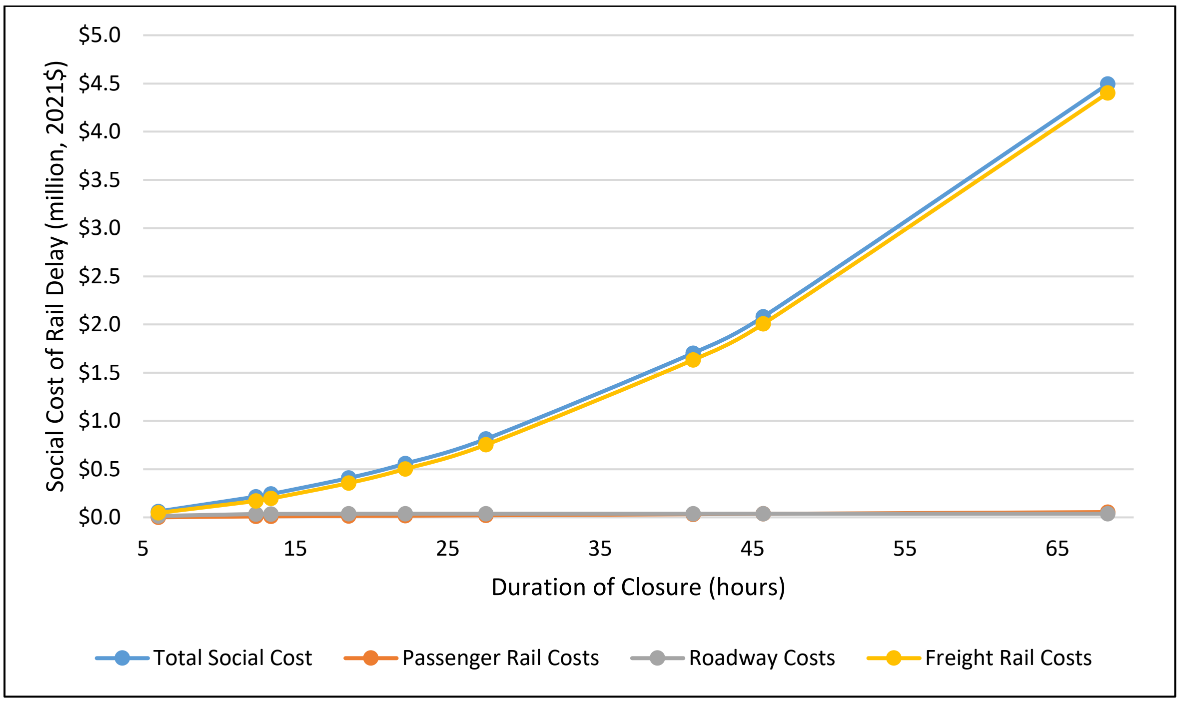


**Figure 16. Total Social Cost of Delay When Freight Railroads Wait, By Duration and Cost Component**

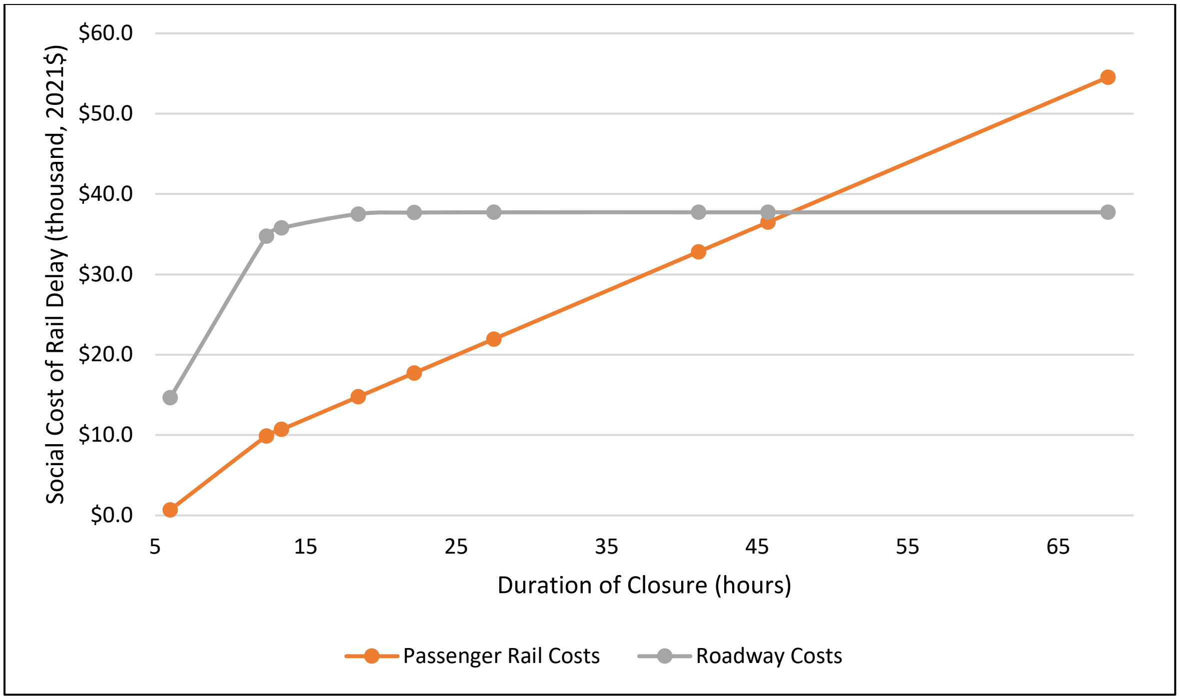


**Figure 17. Passenger Rail and Roadway Social Cost of Delay When Freight Railroads Wait, By Duration**

The total social costs of delay for each duration are inserted into Equation 1. *Expected Social Cost of Delay due to HAZMAT in an AR* (reproduced below) to estimate the expected social cost *attributable to HAZMAT* for an AR incident at each sample location ($l$).

$$
\begin{aligned}
&ExpectedSocialCost_{j=AR,l} \\
&\quad = 0.985 \times \sum_f p(f) \sum_i p(i|f) \times [q(i,f) \times SocialCost(l, d_{i,f}) - q(i=0,f) \\
&\quad \times SocialCost(l, d_{i=0})] + 0.015 \times \$0
\end{aligned}
$$

**Equation 1. Expected Social Cost of Delay due to HAZMAT in an AR**

Equation 1 considers the relative frequency of incident types (*no fire or evacuation*, *fire only*, *evacuation only*, *fire and evacuation*) and the relative frequency of incidents on a particular facility type (mainline, siding, or unknown) and then assesses the impact of changing all fire and/or evacuation incidents to be incidents without fire or evacuations to estimate the incremental social cost of delay related to presence of HAZMAT compared to a rail incident without HAZMAT. Table 63 shows the average social cost of delay related to presence of HAZMAT in a rail incident when freight railroads wait for the track to be reopened. The estimated values are presented for each network group and across the whole sample. The social cost of delay attributable to HAZMAT, when freight railroads will wait for the track to reopen, is estimated to be $156,815 per AR, or between $116,885 and $196,745 with a 95% percent confidence interval.

Table 63. Social Cost of Delay Due to HAZMAT in ARs When Freight Railroads Wait for Track to Reopen

| Network Group | Passenger Rail | Traffic Volume | Adjusted Share | Social Cost of Delay Due to HAZMAT (2021$) |
|---|---|---|---|---|
| Eastern Class 1 | No | High | 7.1% | $156,750 |
| Eastern Class 1 | No | Low | 7.3% | $39,808 |
| Western Class 1 | No | High | 13.0% | $274,904 |
| Western Class 1 | No | Low | 15.4% | $66,440 |
| Class 1 < 25miles | No | N/A | 1.1% | $228,877 |
| Big Class 2/3 | No | N/A | 10.7% | $4,914 |
| Small Class 2/3 | No | N/A | 0.5% | $2,643 |
| Eastern Class 1 | Yes | High | 5.6% | $252,252 |
| Eastern Class 1 | Yes | Low | 5.7% | $68,493 |
| Western Class 1 | Yes | High | 13.0% | $453,939 |
| Western Class 1 | Yes | Low | 15.6% | $72,514 |
| Class 1 < 25miles | Yes | N/A | 0.8% | $133,497 |
| Big Class 2/3 | Yes | N/A | 3.9% | $104,995 |
| Small Class 2/3 | Yes | N/A | 0.3% | $55,990 |
| **Total** | **N/A** | **N/A** | **100%** | **$156,815** |

### 7.1.3 Summary

Table 64 shows the estimated expected annual social cost of delay due to presence of HAZMAT in NARs and ARs. These values represent the expected social cost of delay due to HAZMAT under the assumption no freight trains reroute around the closure. Section 7.2 considers these results for ARs when freight railroads have the option to reroute.

Table 64. Summary of Social Cost of Delay due to HAZMAT Incidents When Freight Railroads Wait for Track to Reopen

| Incident Type | Social Cost of Delay per Incident (2021$) | Incidents per Year | Expected Annual Social Cost of Delay Due to HAZMAT (2021$) |
|---|---|---|---|
| NAR with closure | $28,027 | 9.2 | $257,846 |
| AR | $156,815 | 26.8 | $4,202,647 |
| **Total** | **N/A** | **N/A** | **$4,460,493** |

## 7.2 Cost of Delay When Freight Railroads May Choose to Reroute High Priority Cargo

The previous section provided results of the analysis of the costs delay of HAZMAT rail incidents assuming that railroads had only one option, to wait for the track segment to reopen. However, railroads in some instances would have the option to reroute high priority freight around an incident. This section discusses the results of additional analysis that considers the possibility of rerouting in estimating the cost of delay due to HAZMAT incidents.

The decision to wait or reroute trains was modeled using a comparison of expected business costs of having all traffic wait or rerouting high priority traffic while lower priority traffic waits. This framework emulates the decision-making process of freight railroads facing a closure by comparing the costs faced when waiting for the closure to be cleared with the cost of routing high priority trains on the next best alternative routes.

Roadway and passenger rail costs remain the same and do not depend upon the decision of the freight trains to wait or reroute. For passenger vehicles and trucks on adjacent roadways, their wait time is due to the roadway closure, which is separate from the freight rerouting decision. For passenger trains, the decision to wait or establish a bus bridge is based on the duration of the closure. Further, due to passenger train priority, the model used to estimate the train delay for passengers from waiting assumes that passenger trains will clear the queue first. Thus, passenger operations are not impacted by the decisions of the freight railroads to either wait or reroute in this analysis.

For freight rail, the analysis assumes that railroads will only choose to reroute high priority rail cars, comprised of automotive and intermodal cars. Lower priority trains, general and bulk, are assumed to wait regardless of the availability of alternative routes.

### 7.2.1 Rerouting Results

In conducting the rerouting analysis for the sample, some sampled network links were found to have no traffic that could be rerouted onto alternative routes. Freight rail traffic was considered un-reroutable for three possible reasons.

First, if no alternative route was found for any traffic that traverses sample location, the traffic is considered un-reroutable. This could be due to the location's position on a spur, or a lack of feasible trackage rights on alternative routes.

The second reason is if there is no high priority (automotive and intermodal) traffic on the sample location.

The third reason relates to available capacity on alternate routes. If, as a result of rerouting traffic, the alternative route would exceed its capacity for a significant portion of the detour, the modeling does not consider rerouting as a possible option, and all traffic will wait for the closure to be cleared. The model only assumes that rerouting is not possible due to overcapacity when 100 miles or more of rail are estimated to be over capacity. This 100-mile cutoff allows for the possibility that relatively short sections of rail can accommodate additional traffic over its practical capacity for a short amount of time.

In total, there was no high priority freight traffic on 89 sample locations. For an additional 21 sample locations, there was no alternate route for the high priority traffic. Another 24 sample locations were not reroutable due to traffic on alternative routes exceeding capacity along greater than 100 miles of track. For the remaining 95 sample locations, rerouting high priority traffic was a possibility. Table 65 shows that a large share of locations with no high priority freight are low volume Class 1 subdivisions with no passenger service and Class 2/3 railroads. A larger share of locations with no alternate route is on low volume Class 1 subdivisions. The alternate route being over capacity appears to be most common on high volume western Class 1 subdivisions.

**Table 65. Reasons Rerouting is not Possible in Model, by Sample Group**

| Network Group | Passenger Rail | Traffic Volume | No High Priority Freight | No Alternate Route | More than 100 Miles Over Capacity | Total |
|---|---|---|---|---|---|---|
| Eastern Class 1 | No | High | 0 | 1 | 1 | 2 |
| Eastern Class 1 | No | Low | 11 | 0 | 0 | 11 |
| Western Class 1 | No | High | 0 | 0 | 10 | 10 |
| Western Class 1 | No | Low | 29 | 3 | 0 | 32 |
| Class 1 < 25miles | No | N/A | 4 | 0 | 0 | 4 |
| Big Class 2/3 | No | N/A | 17 | 4 | 0 | 21 |
| Small Class 2/3 | No | N/A | 4 | 1 | 0 | 5 |
| Eastern Class 1 | Yes | High | 0 | 0 | 4 | 4 |
| Eastern Class 1 | Yes | Low | 3 | 4 | 1 | 8 |
| Western Class 1 | Yes | High | 1 | 1 | 7 | 9 |
| Western Class 1 | Yes | Low | 7 | 4 | 1 | 12 |
| Class 1 < 25miles | Yes | N/A | 3 | 1 | 0 | 4 |
| Big Class 2/3 | Yes | N/A | 8 | 2 | 0 | 10 |
| Small Class 2/3 | Yes | N/A | 2 | 0 | 0 | 2 |
| **Total** | **N/A** | **N/A** | **89** | **21** | **24** | **134** |

### 7.2.2 Deciding to Wait or Reroute for High Priority Traffic

For each sampled rail location and each closure duration, the freight railroads make a decision to reroute high priority freight, or have it wait with the low priority freight, based on comparing the business costs associated with each option. Table 66 shows for each duration of interest, the share of sampled locations where the freight railroads choose to reroute given a closure duration. As noted previously, rerouting is not an option for 134 sample segments because either they had no high priority freight, there was no alternative route for the high priority traffic on the closed link, or the alternative route exceeded capacity, and by necessity traffic on these links must wait.[118] The share of the 95 potentially reroutable segments where railroads would choose to reroute increases as the duration of closure increases, rising from 56% (n=53) choosing to reroute with a six hour duration, rising to 97% (n=92) choosing to reroute at 68.3 hours. This appears to be a reasonable approximation of railroad

[118] In a small number of cases some high priority traffic could reroute and some could not. For simplicity, this analysis assumes none of the traffic could reroute.

behavior, where some would choose to reroute for very short closures, but nearly all choosing to reroute high priority traffic during lengthy closures when the option to reroute is available.

In some cases, the business costs experienced by the railroad from rerouting are lower than the costs of the baseline routing with no incident. For the six-hour duration, eight such sample locations exist. The magnitude of the costs savings is relatively minor and railroad industry representatives indicated that such a finding was consistent with railroad experience. From a modeling perspective, the reason for such occurrences is that the baseline routing does not consider congestion. In some cases, dispersing the rerouting traffic to multiple, less congested alternate routes will result in lower total congestion, lowering costs relative to the baseline routing.

**Table 66. Number of Sampled Locations for Which Railroads Choose to Wait or Reroute for ARs, by Duration of Closure**

| Duration (*d*) in hours | Number Choosing to Wait | Number Choosing to Reroute | Share Choosing to Reroute |
|---|---|---|---|
| 6 | 42 | 53 | 56% |
| 12.4 | 29 | 66 | 69% |
| 13.4 | 29 | 66 | 69% |
| 18.5 | 24 | 71 | 75% |
| 22.2 | 18 | 77 | 81% |
| 27.5 | 12 | 83 | 87% |
| 41.1 | 6 | 89 | 94% |
| 45.7 | 5 | 90 | 95% |
| 68.3 | 3 | 92 | 97% |

The social cost of delay related to an incident of a specific duration is one of the components Equation 1. *Expected Social Cost of Delay due to HAZMAT in an AR* in Section 3.2*, Duration of Closure Analysis*. This social cost is estimated for each sample location for all the durations listed in Table 11. *Predicted Duration of Closure given a Closure by Incident Type and Facility Type (Hours) (for Non-Fatal ARs).* Table 67 below, provides the average social cost of either waiting or rerouting across the sampled locations for each of the closure durations of interest for this analysis. These estimates include the social costs derived from freight traffic, passenger traffic, and roadway traffic.

**Table 67. Average Social Cost of Delay When Freight Railroads Choose to Wait or Reroute for ARs, by Duration of Incident**

| Duration ($d$) in hours | Social Cost of Delay (2021$) |
|---|---|
| 6 | $54,370 |
| 12.4 | $185,336 |
| 13.4 | $208,342 |
| 18.5 | $344,650 |
| 22.2 | $463,716 |
| 27.5 | $667,026 |
| 41.1 | $1,364,372 |
| 45.7 | $1,657,494 |
| 68.3 | $3,522,934 |

A curve was fit to provide an estimate of the average total social cost of delay as a function of duration (Equation 42). The formula suggests that a closure of one day (24 hours) results in a social cost of approximately $527,000 when the freight railroads may either wait or reroute high priority traffic.

$$TotalSocialCost_{Reroute} = 5982.4 \times Duration + 666.5 \times Duration^2$$

**Equation 42. Estimate of Average Total Social Cost of Delay When Freight Railroads May Reroute High Priority Traffic**

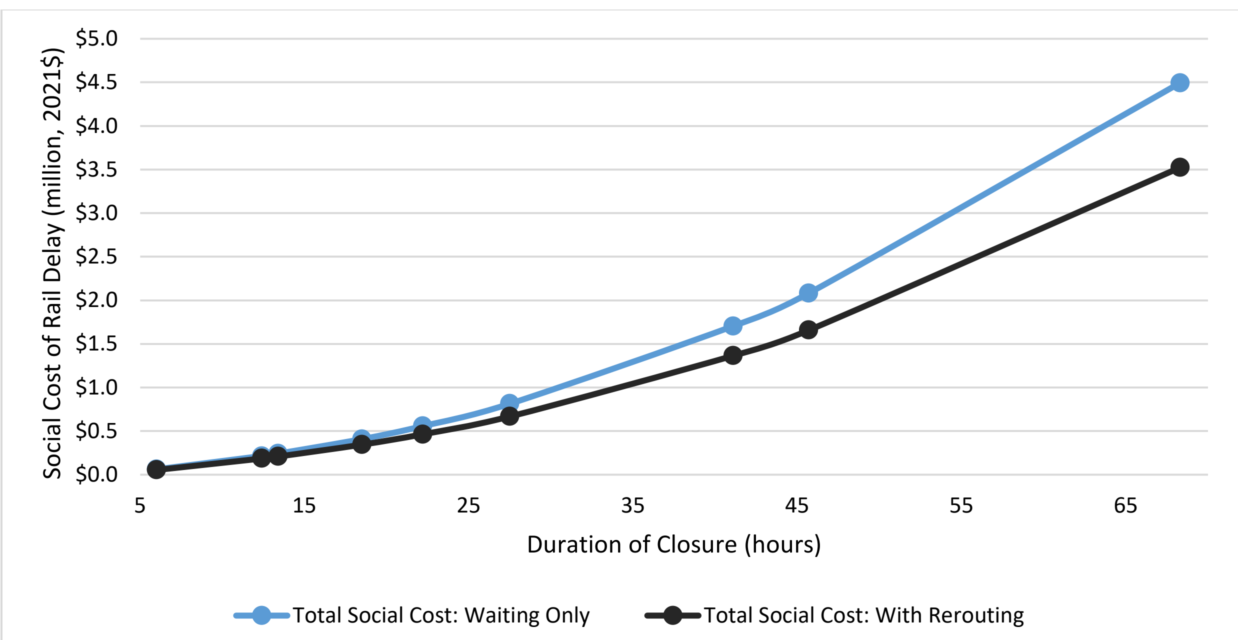


**Figure 18. Comparison of Total Social Cost of Delay by Duration, Waiting Only and With Rerouting**

### 7.2.3 Summary

The social costs for each duration from Table 67 are inserted into Equation 1. *Expected Social Cost of Delay due to HAZMAT in an AR* to estimate the expected social cost *attributable to HAZMAT* for an AR incident for each sample location. Recall that Equation 1 considers the relative frequency of incident types (*no fire or evacuation, fire only, evacuation only, fire and evacuation*) and the relative frequency of incidents on a particular facility type (mainline, siding, or unknown) and then assesses the impact of changing all fire or evacuation incidents to be incidents without fire or evacuations to estimate the incremental social cost of delay related to presence of HAZMAT compared to a rail incident without HAZMAT. Table 68 shows the average social cost of delay related to presence of HAZMAT in a rail incident when freight railroads have the option to either wait for the track to reopen or reroute high priority traffic around the site of the closure depending on which option produces the lower business costs. The estimated values are presented for each network group and the average across the whole network. The social cost of delay attributable to HAZMAT per AR, is estimated to be approximately $124,172, or between $82,672 and $165,672 with a 95% percent confidence interval. The point estimate is 79% of the cost when freight railroads can only wait for the track to open. This suggests that an average rerouting reduces delays costs by approximately one-fifth.

As shown in Table 68 we see the greatest cost savings from rerouting for Class 1 Eastern railroads and for the sample group containing short or unnamed subdivisions of Class 1 railroads. Eastern Class 1 railroads generally have denser rail networks with more redundancy for rerouting than Western Class 1 railroads. With Western Class 1 corridors, alternate routes often require substantial additional distance to access, and additional traffic often causes the alternate route to exceed capacity, even when rerouting is limited to high priority traffic.

Table 68. Social Cost of Delay Due to HAZMAT in ARs When Freight Railroads Choose to Wait or Reroute

| Network Group | Passenger Rail | Traffic Volume | Adjusted Share | Social Cost of Delay Due to HAZMAT (Waiting Only) (2021$) | Social Cost of Delay (Rerouting or Waiting) (2021$) |
|---|---|---|---|---|---|
| Eastern Class 1 | No | High | 7.1% | $156,750 | $49,343 |
| Eastern Class 1 | No | Low | 7.3% | $39,808 | $15,112 |
| Western Class 1 | No | High | 13.0% | $274,904 | $252,081 |
| Western Class 1 | No | Low | 15.4% | $66,440 | $60,920 |
| Class 1 < 25miles | No | N/A | 1.1% | $228,877 | $51,330 |
| Big Class 2-3 | No | N/A | 10.7% | $4,914 | $4,914 |
| Small Class 2-3 | No | N/A | 0.5% | $2,643 | $2,643 |
| Eastern Class 1 | Yes | High | 5.6% | $252,252 | $175,324 |
| Eastern Class 1 | Yes | Low | 5.7% | $68,493 | $61,659 |
| Western Class 1 | Yes | High | 13.0% | $453,939 | $401,764 |
| Western Class 1 | Yes | Low | 15.6% | $72,514 | $37,654 |
| Class 1 < 25miles | Yes | N/A | 0.8% | $133,497 | $77,778 |
| Big Class 2-3 | Yes | N/A | 3.9% | $104,995 | $103,227 |
| Small Class 2-3 | Yes | N/A | 0.3% | $55,990 | $53,245 |
| **Total** | **N/A** | **N/A** | **100.0%** | **$156,815** | **$124,172** |

## 7.3 Summary

Table 69 shows the expected annual social cost of delay attributable to HAZMAT. The estimate for a four-hour NAR is taken from analysis assuming freight railroads will wait for the track to reopen since this analysis assumes that for a closure of four hours, freight railroads will always wait. The estimate for an AR is taken from the analysis that accounts for freight railroads choosing to either wait or reroute depending on which option produces the lower business costs. NAR and AR rail incidents combined cost an estimated $3,532,271 in delay costs per year attributable to HAZMAT.

Table 69. Summary of Social Cost of Delay due to HAZMAT Incidents When Freight Railroads Choose to Wait or Reroute (2021$)

| Incident Type | Social Cost per Incident (2021$) | Incidents per Year | Average Annual Social Cost of Delay (2021$) |
|---|---|---|---|
| NAR with Closure | $28,027 | 9.2 | $257,846 |
| AR (Rerouting High Priority Freight) | $124,172 | 26.8 | $3,327,811 |
| **Total** | N/A | N/A | $3,585,658 |

# 8. Suggested Method for Updating Estimates for Future Changes in Unit Costs

For these estimates to be used in analysis in future years, the monetary values may need to be updated to reflect future social costs and prices. A simple approach would be to update the reported values using a GDP deflator, increasing the reported values in 2021 dollars to the relevant future year value. However, individual cost categories may be subject to dynamics that differ from the economy as a whole. For instance, fuel prices show considerably more fluctuations year to year than more general measures of inflation, such as the consumer price index. Equation 43 presents a method to update the social costs of delay expressed in 2021 dollars as presented in Section 7 to future years. In Equation 43, $z$ indexes all cost categories listed in Table 70; $CostPct_z$ refers to the percent of total costs that each cost category represents; and $SocialCost_{z,\ futureyear}$ divided by $SocialCost_{z,2021}$ is the percentage increase in a particular cost category from 2021 to a certain future year. The method basically computes an overall adjustment factor as the weighted average of the adjustment factors specific to different cost categories such as labor, fuel, emissions, etc.

$$SocialCost_{futureyear} = SocialCost_{2021} \sum_{z} CostPct_z \times \frac{SocialCost_{z,futureyear}}{SocialCost_{z,2021}}$$

**Equation 43. Cost Update**

Table 70 shows several key cost components, as well as their approximate percentage of total costs, unit value in 2021, and the source of the 2021 unit value.

Table 70. Value for Updating Estimates in Future Years

| Cost Category ($z$) | Approximate Percentage of Total Costs ($CostPct_z$) | Unit Value in 2021$ ($SocialCost_{z,2021}$) | Source of Unit Value in 2021 |
|---|---|---|---|
| Train Crew (Freight & Pax) | 15.7% | Freight: $61.22 per person-hour | Freight and Amtrak: Surface Transportation Board – Annual Wage A&B Data |
| Carbon ($CO_2$) emissions | 0.8% | $54 per metric ton | USDOT "Benefit-Cost Analysis Guidance for Discretionary Grant Programs" |
| $PM_{2.5}$ emissions | 38.1% | $778,544 per metric ton | USDOT "Benefit-Cost Analysis Guidance for Discretionary Grant Programs" |
| NOx emissions | 4.5% | $16,244 per metric ton | USDOT "Benefit-Cost Analysis Guidance for Discretionary Grant Programs" |
| Diesel Price | 4.6% | $2.72 per gallon | U.S. Energy Information Administration - Gasoline and Diesel Fuel Update |
| Other | 36.2% | $23,315.1 billion | U.S. Bureau of Economic Analysis, Gross Domestic Product [GDP], retrieved from FRED, Federal Reserve Bank of St. Louis; https://fred.stlouisfed.org/series/GDP |

Note that roughly 36 percent of the costs relate to items other than train crew, emissions or fuel. These other cost categories include the cost of railroad equipment (locomotives and rail cars), the cost of motorcoaches used in bus bridges, and value of time for highway users. Individually, each of these cost categories is a small percent of the total and their dynamics are likely to track will the general economy. Therefore, this methodology suggests using an overall measure of inflation such as the GDP deflator to adjust for future years.

# 9. Sensitivity Analyses

In the central analysis discussed above, data related to certain key issues was not available and therefore the modeling used either incomplete data or made informed assumptions. In the following discussion, the impact of alternative means of addressing two of those key issues is explored. The assumptions related to the impact of the presence of HAZMAT on probability and duration of closure in ARs is discussed first, followed by an investigation of alternative estimates of the emissions from locomotives.

## 9.1 Duration Attributable to HAZMAT

A key uncertainty in the central analysis is how much the presence of HAZMAT in an AR impacts the probability of a closure due to an AR and the amount of time that the rail segment is closed if there is a closure. The regression analysis described in Section 3.2.2 finds that incidents with fires and/or evacuations tended to have higher probability of closures and/or longer durations than other ARs. All of that differential is ascribed to the presence of HAZMAT given that HAZMAT is almost certainly the cause of the fires and evacuations. However, even without a fire or evacuation, the presence of HAZMAT could potentially cause either higher probability of closure or longer durations of closure than rail incidents that do not involve any HAZMAT. There is no data describing the closure probabilities or durations for rail incidents that do not involve HAZMAT, so estimates of the incremental costs imposed by the presence of HAZMAT could not be developed. Therefore, in the central analysis, unless there is a fire or evacuation, the delay costs caused by the presence HAZMAT is assumed to be zero. This sensitivity analysis relaxes that assumption.

This sensitivity analysis considers two alternative assumptions. One is an extreme case where all of the delay as a result of the AR is ascribed to the presence of HAZMAT. The other is a middle case where half of the probability of closure and half of the duration of a closure is ascribed to the presence of HAZMAT. Those two sensitivities, combined with the central case where none of the delay for incidents without fires or evacuations is ascribed to HAZMAT, explore the full range of possibilities of the social cost of delay due to HAZMAT in ARs related to this issue (NARs are not impacted by this sensitivity analysis because it is a straightforward conclusion that all the delay from an NAR is ascribable to the presence of HAZMAT). The technical details of how these sensitivities are implemented are provided in Section 3.2.5.

The results of these sensitives are shown below in Table 71. As would be expected, assuming that half of the duration and probability of closures for HAZMAT ARs without fire or evacuation is attributable to the presence of HAZMAT (i.e., $A$ = 50% in Equation 2 and Equation 3) results in substantially higher expected social costs of delay than in the central case with an increase in annual expected costs of approximately 60 percent.

Assuming that the entire duration of closures for HAZMAT ARs without fire or evacuation is attributable to the presence of HAZMAT (i.e., $A$ = 0% in Equation 2 and Equation 3) results in substantially higher expected social costs of delay than in the central case, with an annual value approximately 73 percent higher than the central analysis. This portion of the sensitivity analysis represents a potential upper bound of delay costs with respect to duration assumptions made for this analysis. While the true duration of an incident where no HAZMAT is not known, it is likely that the duration lies between the value used in the central case where A = 100% and the sensitivity where A = 0%.

**Table 71. Social Cost of Delay Under Alternative Assumptions Related to Impact of HAZMAT on Probability and Duration of Closure (2021$)**

| Category | Presence of HAZMAT accounts for 0% of probability and duration of closure in incidents without fire/evacuations<br><br>Central Case | Presence of HAZMAT accounts for 50% of probability and duration of closure in incidents without fire/evacuations | Presence of HAZMAT accounts for 100% of probability and duration of closure in incidents without fire/evacuations |
|---|---|---|---|
| Social Cost of AR (2021$) | $124,172 | $198,742 | $214,369 |
| Percent Change Compared to Central Case | N/A | +60% | +73% |

## 9.2 Emissions

As explained in Section 3.5.4, the emissions estimates for the central analysis are derived from dynamometer measurements of particular locomotives during their line-haul operations in North Carolina. The locomotives were manufactured in the 1970s and rebuilt between 2008 and 2012. The emissions rates found for those locomotives in some cases exceeded even Tier 0 standards. Although many such older locomotives are owned and operated by freight railroads, newer and cleaner locomotives have also been added to fleet and would likely be used for line-haul operations while older locomotives might be used more often for yard operations. This sensitivity analysis performs some high-level adjustments to estimate the social cost of delay to estimate the impacts if higher-tier locomotives were used in line-haul operations of freight and passenger trains. The technical details of the sensitivity analysis for emissions of freight locomotives and passenger locomotives are discussed in Section 3.5.5 and Section 4.2.5, respectively. The central case emissions are factored by the relative difference between newer Tiers and Tier 0 emissions standards. For example, the latest emission standards (Tier 4) would result in reductions of over 80 percent for NOX and $PM_{2.5}$ emissions, as shown in Table 32. Recall that the EPA regulations relate only to criteria pollutants, so greenhouse gas emissions such as CO2 are not impacted in this sensitivity analysis.

The sensitivity analysis considers the impact of reduced emissions on the social cost of waiting and rerouting. This does not impact business costs since the social cost of emission is not directly borne by the railroad. As a result, the decision whether to reroute high priority traffic is not affected.

Finally, the central analysis assumed that the entire line-haul locomotive fleet had the same emissions profile as the two locomotives studied by Graver and Frey (2013). This sensitivity analysis represents the estimates of social cost of delay if the entire locomotive fleet were to change emissions profiles to that of locomotives that complied with each higher Tier. In practice, the distribution of locomotives by Tier will change gradually as existing locomotive are replaced or refurbished. The fleet at any point in time will be a mix of multiple Tiers.

Table 72 shows the social cost per incident for NARs and ARs (where high priority freight may be rerouted) under various assumptions of the Tier of the locomotives used for line-haul operations. Under an assumption that all locomotives have an emissions profile like Tier 1, the difference in cost is minor, just 1 percent. The Tier 1 standards are the same as Tier 0 for particulate matter and just 8 percent lower for NOx. Under the assumption that all locomotives are Tier 2 or Tier 3, NOx emissions are reduced 31 percent and particulate matter is reduced 55 percent. As a result, NAR costs are reduced 19 percent and AR costs are reduced 14 percent relative to the central case. Under the assumption that all locomotives are Tier 4, NOx emissions are reduced 84 percent and particulate matter is reduced 86 percent. As a result, NAR costs are reduced 32 percent and AR costs are reduced 22 percent relative to the base case.

**Table 72. Social Cost of Delay Due to Presence of HAZMAT with Alternative Emissions Profiles**

| Incident Type | Tier 0 (Central Case) | Tier 1 | Tier 2/3 | Tier 4 |
|---|---|---|---|---|
| Social Cost of NAR with Closure (2021$) | $28,027 | $27,896 | $22,765 | $19,100 |
| Percent Change Compared to Central Case | 0% | -0.5% | -19% | -32% |
| Social Cost of AR (2021$) | $124,172 | $123,940 | $106,974 | $96,589 |
| Percent Change Compared to Central Case | 0% | -0.2% | -14% | -22% |

# 10. Case Study: Application to Improved Tank Car Design

The case study discussed in this section illustrates how the model of social cost of delay from HAZMAT rail incidents presented in this report can be used to analyze the impacts of certain policy proposals. Specifically, this case study estimates the avoided social cost of delay from preventing crude oil releases during the 10-year period from January 1, 2010 to December 31, 2019.

Feedback from reviewers noted that the analysis period of 2010 to 2019, used to understand the characteristics of HAZMAT rail incidents in the central analysis, did not accurately reflect the impacts of recent regulations implemented regarding safety for the transport of Class 3 flammable liquids. Reviewers also noted that during this period, crude oil volumes were unusually high. That period involved the use of older designs of tank cars which have since been phased out due to regulatory actions. To address the concern expressed by reviewers, this case study presents an alternative estimate of the social cost of delay due to HAZMAT rail incidents which assumes there are no crude oil releases during that 10-year period. As such, this assumption is an optimistic simplification. However, it is instructive to the purpose of both addressing the concern raised by reviewers that the risk of crude oil releases is over-estimated and presenting an example of how the model can be used to analyze the impacts of certain policy proposals.

## 10.1 Regulatory Background

The Fixing America's Surface Transportation Act (FAST Act) mandates commodity-specific phase-out of jacketed and non-jacketed DOT-111 and CPC-1232 tank cars for Class 3 flammable liquids and that tank cars used to transport Class 3 flammable liquids meet the DOT-117, DOT-117P, or DOT-117R specifications.[119] For unrefined petroleum products including crude oil, phase-out dates for DOT-111 tanks cars (jacked and non-jacketed) occurred in 2018, and non-jacketed CPC-1232 phase-out date occurred in 2020.[120] As a result, the data used for analysis in this report largely covers a time period prior to the phase-out date requirements outlined in the FAST Act. Bureau of Transportation Statistics analysis using data provided by the Association of American Railroads shows that almost all DOT-111 (jacketed and non-jacketed) tank cars had been phased out of use for transportation of crude by 2016, while use of retrofitted and new DOT-117 tank cars increased beginning in 2016.[121]

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[119] Public Law 114–94 Fixing America's Surface Transportation Act (2015), https://www.govinfo.gov/content/pkg/PLAW-114publ94/pdf/PLAW-114publ94.pdf.

[120] The phase-out date for unrefined petroleum (including crude oil) for jacketed CPC-1232 tank cars is May 1, 2025.

[121] United States Department of Transportation. Bureau of Transportation Statistics, "Fleet Composition of Rail Tank Cars Carrying Flammable Liquids: 2021 Report," accessed 2023, https://doi.org/10.21949/1523084.

## 10.2 Methodology

In the data from the PHMSA Form 5800.1 during the period 2010 through 2019, 19 ARs involved crude oil. These incidents were flagged if the material was listed as "Petroleum Crude Oil" or "Petroleum Sour Crude Oil" or "Crude Oil, Petroleum." Of those incidents, where car markings were identified, all incidents involved DOT-111 tank cars.[122] Among incidents with closures, the average duration of closure from all ARs (n=109) is 34 hours and the average duration of closure from incidents that did not involve crude (n=96) is 31 hours. The difference in closure duration is minor. Among NARs with closures, two incidents (out of 92 total) involved crude oil.

Given that the available data from the PHMSA Form 5800.1 reporting showed no crude oil incidents during that period involved the newer designed DOT-117 tank car, the DOT-117 tank design appears to be effective at preventing crude releases. Thus, performing a case study assuming there are no crude releases, while optimistic and a simplification of real-world risks, is useful to understanding the possible magnitude of the avoided delay costs from the DOT-117 tank cars. The decline in crude-by-rail traffic volumes may also be partly responsible for that finding.

To estimate the impact of avoiding all crude oil release, the parameters $p(f)$ and $p(i|f)$ from Equation 1 are re-estimated using the incident data after removing the 19 crude oil release incidents. Recall that $p(f)$ is the probability of an AR on facility type, $f$,(i.e., mainline, siding, or unknown) and $p(i|f)$ is the probability of a certain incident type, $i$, (i.e., fire, evacuation, or no fire/evacuation) given a certain facility type. The re-estimation reflects a reduction in probability of fire or evacuation and a change in the distribution of those incidents across facility types. The expected duration of closure for an incident is not altered in this case study.

The result of this comparison is a reduction in the total number of expected incidents from 268 ARs over 10 years to 249 over 10 years, and from 92 NARs to 90 NARs over 10 years. In addition to fewer incidents occurring, there is a slight difference in where those incidents occur with fewer incidents on mainline track, as shown in Table 73 which can be compared to Table 14 for the central analysis. The distribution of incidents by incident type for ARs not involving crude in the Form 5800.1 data is shown in Table 74 and can be compared to Table 15 for the central analysis. In addition, of the 249 total incidents, four involved fatalities and these were not HAZMAT-related. Therefore, the proportion of non-fatal ARs is adjusted to 98.4 percent from 98.5 percent in the central analysis.

[122] One AR among the 19 involving crude was noted to have no markings identified for involved tank cars, and no major artery closure. However, media review of the incident showed that the involved tank cars were DOT-117R specifications and that the track was likely closed. https://www.mprnews.org/story/2018/06/23/crews-scramble-to-clean-up-oil-spill-after-nw-iowa-train-derailment

Table 73. Count and Percent of Incidents by Facility Type for Incidents Not Involving Crude Oil (for Non-Fatal ARs)

| Facility Type ($f$) | Non-Fatal ARs p($f$) |
|---|---|
| Mainline | 98 (40%) |
| Siding/Yard | 72 (29%) |
| Unknown | 75 (31%) |

Table 74. Count and Percent of Incidents by Facility Type and Incident Type for Incidents Not Involving Crude Oil (for Non-Fatal ARs)

| Facility Type ($f$) | No Evacuation or Fire $p(i=0\|f)$ | Fire $p(i=1\|f)$ | Evacuation $p(i=2\|f)$ | Fire and Evacuation $p(i=3\|f)$ |
|---|---|---|---|---|
| Mainline | 51 (52%) | 7 (7%) | 31 (32%) | 9 (9%) |
| Siding/Yard | 58 (81%) | 0 (0%) | 12 (17%) | 2 (3%) |
| Unknown | 63 (84%) | 4 (5%) | 7 (9%) | 1 (1%) |

## 10.3 Results

Compared to the central analysis case, reducing the frequency of incidents and adjusting the distribution of incident types to reflect ARs which did not involve crude oil reduces the expected annual social cost of delay.

In calculating the expected annual social cost of delay due to presence of HAZMAT, the number of incidents per year for both NARs and ARs is lower than in the central case. Comparing results in Table 75 to those in the central case (Table 69), the expected annual social cost of delay is reduced by approximately $0.8 million under this application. This finding suggests that the improved tank car design and lower volumes of crude oil by rail have provided benefits of $0.8 million per year in the form of avoided delay.

Table 75. Summary of Social Cost of Delay due to HAZMAT Incidents When Freight Railroads Choose to Wait or Reroute with Application to Improved Tank Car Design

| Incident Type | Social Cost per Incident (2021$) | Incidents per Year | Expected Annual Social Cost of Delay (2021$) |
|---|---|---|---|
| NAR with Closure | $28,027 | 9.0 | $252,241 |
| AR (Rerouting High Priority Freight) | $101,660 | 24.9 | $2,531,325 |
| Total | N/A | N/A | $2,783,566 |

# 11. Conclusion

This final report presents the results of a research and modeling effort to estimate the social cost of delay resulting from presence of HAZMAT in incidents on rail. The estimates of the cost of delay developed in this research can be combined with estimates of other components of the cost of an incident (property damage; fatalities and injuries; environmental clean-up, remediation and restoration; repair; evacuation; emergency response; etc.) to generate an estimate of the total social cost of a HAZMAT rail incident. Traffic delay may result from some HAZMAT rail incidents if the track is closed to clear damaged or derailed train equipment, clean up the HAZMAT, and/or repair the track. As a result of the track being closed, rail traffic needs to either wait until an incident is cleared and track is repaired or reroute around an incident. If traffic reroutes around the incident, that traffic not only incurs higher costs due to longer travel time, but the increased traffic may result in additional congestion-caused delay on the alternate route. The delay would be experienced by the freight rail traffic and any passenger rail traffic that may use the impacted rail lines. A nearby roadway may also be closed if the incident blocks a grade-crossing, if debris from the incident blocks or damages the roadway, if the area falls under an evacuation order due to the possibility of a HAZMAT release, or if the roadway is needed to stage equipment for the response effort. In such cases, delay is also experienced by roadway users.

- For NARs (with a typical closure period of four hours), this analysis finds a typical social cost from delay of roughly $28,000, or between $22,000 and $34,000 with a 95 percent confidence interval. Over the ten-year period of analysis (January 1, 2010 through December 31, 2019) there were 9.2 NARs with closures per year on average; therefore, the annual delay cost of NARs is estimated to be approximately $258,000.
- This analysis finds that the typical cost attributable to HAZMAT in an AR is roughly $157,000, when analyzed assuming that all railroad freight traffic will wait for the incident to be cleared, or between $117,000 and $197,000 with a 95 percent confidence interval. During the analysis period, there were 26.8 ARs per year on average. The typical annual cost of delay due to the presence of HAZMAT in an ARs is estimated to be roughly $4,203,000.[123]
- When estimated under the possibility that railroads might chose to reroute high priority traffic if that option results in lower costs to the business, this analysis finds that for ARs, the average cost of delay attributable to HAZMAT is approximately $124,000, or between $83,000 and $166,000 with a 95 percent confidence interval. Thus, the possibility of rerouting lowers estimated delay costs from HAZMAT by roughly one fifth from the waiting-only value. During the 10-year period of analysis, there were 26.8 ARs annually on average. The typical annual cost of

[123] Because the analysis of ARs accounts for not only the impact of HAZMAT on the duration of closure but also the probability of a closure, the HAZMAT-related delay cost is estimated for all ARs (not just those with closures).

delay attributable to the presence of HAZMAT in ARs is estimated to be $3,586,000.

Table 76. Summary of Social Cost of Delay due to HAZMAT in Rail Incidents

| Incident Type | Social Cost per Incident (2021$) | Incidents per Year | Average Annual Social Cost of Delay (2021$) |
|---|---|---|---|
| NAR with Closure | $28,027 | 9.2 | $257,846 |
| AR (Rerouting High Priority Freight) | $124,172 | 26.8 | $3,327,811 |
| **Total** | N/A | N/A | $3,585,658 |

## Results of Sensitivity Analyses and Case Study

In the central analysis discussed above, data related to certain key issues was not available and therefore the modeling used either incomplete data or made informed assumptions. The impact of alternative means of addressing two of those key issues is explored in this report: the assumptions related to the impact of the presence of HAZMAT on probability and duration of closure in ARs, and an investigation of alternative estimates of the emissions from locomotives.

The first sensitivity analysis considers two alternative assumptions related to the impact of the presence of HAZMAT on the probability and duration of closure for ARs that do not involve a fire or evacuation. One is an extreme case where all of the delay as a result of the AR is ascribed to the presence of HAZMAT. The other is a middle case where half of the probability of closure and half of the duration of a closure is ascribed to the presence of HAZMAT. Those two sensitivities, combined with the central case where none of the delay for incidents without fires or evacuations is ascribed to HAZMAT, explores the full range of possibilities of the social cost of delay due to HAZMAT in ARs related to this issue.

Table 77. Social Cost of Delay Under Alternative Assumptions Related to Impact of HAZMAT on Probability and Duration of Closure (2021$)

| Category | Presence of HAZMAT accounts for 0% of probability and duration of closure in incidents without fire/evacuations<br><br>Central Case | Presence of HAZMAT accounts for 50% of probability and duration of closure in incidents without fire/evacuations | Presence of HAZMAT accounts for 100% of probability and duration of closure in incidents without fire/evacuations |
|---|---|---|---|
| Social Cost of Delay for AR (2021$) | $124,172 | $198,742 | $214,369 |
| Percent Change Compared to Central Case | N/A | +60% | +73% |

The second sensitivity analysis considers the impact of changing locomotive emission assumptions. The central analysis used the emissions profile of two specific locomotives used in line-haul operations in North Carolina. The locomotives were manufactured in the 1970s and rebuilt between 2008 and 2012. The emissions rates found for those locomotives in some cases exceeded even Tier 0 standards. Although many such older locomotives are owned and operated by freight railroads, newer and cleaner locomotives have also been added to railroad fleets and would likely be used for line-haul operations while older locomotives might be used more often for yard operations. This sensitivity analysis performs some high-level adjustments to find the impact to the social cost of delay if higher-tier locomotives were used in line-haul operations of freight and passenger trains.

**Table 78. Social Cost of Delay Due to Presence of HAZMAT with Alternative Emissions Profiles**

| Category | Tier 0 (Central Case) | Tier 1 | Tier 2/3 | Tier 4 |
|---|---|---|---|---|
| Social Cost Delay for NAR with Closure (2021$) | $28,027 | $27,896 | $22,765 | $19,100 |
| Percent Change Compared to Central Case | 0% | -0.5% | -19% | -32% |
| Social Cost of Delay for AR (2021$) | $124,172 | $123,940 | $106,974 | $96,589 |
| Percent Change Compared to Central Case | 0% | -0.2% | -14% | -22% |

Feedback from reviewers noted that the analysis period of 2010 to 2019, used to understand the characteristics of HAZMAT rail incidents in the central analysis, did not accurately reflect the impacts of recent regulations implemented regarding safety for the transport of Class 3 flammable liquids. Reviewers also noted that during this period, crude oil volumes were unusually high. That period involved the use of older designs of tank cars which have since been phased out due to regulatory actions. To address the reviewers' concern, this case study presents an alternative estimate of the social cost of delay due to HAZMAT rail incidents that assumes there are no crude oil releases during that 10-year period. The results of the case study suggest that the improved tank car design and lower volumes of crude oil by rail have provided a $0.8 million benefit per year in the form of avoided delay.

# Appendix A: Review of Literature

Two types of delay are of interest for this project. The first type of delay arises from the closure of a rail link. Trains will be delayed as they must wait for the rail link to re-open or because the railroad may opt to reroute the train on an alternative, longer or slower route. If a railroad decides to reroute trains, that adds additional traffic on that alternative route. That additional traffic may increase congestion and add delay to the trains using that alternative route.

This literature review will first discuss methods for estimating direct delay resulting from the closure of a rail link (the delay experienced by trains that are waiting for the rail line to re-open). The second section of this literature review will discuss models for estimating delay related to increases in rail traffic due to congestion on alternative routes. No studies that attempted to estimate the costs of re-routing were identified. The final sections present a variety of additional findings from the literature relevant to this project.

## Modeling of Delay Resulting from Rail Line Closures

"A Prediction Model for Broken Rails and an Analysis of their Economic Impact" provides an informative example of a theoretical rail delay model resulting from closure of a rail line, in addition to a well-defined methodology for monetizing rail delay (Schafer & Barkan, 2008). The number of train-hours of delay (additional travel time relative to free flow) is modeled as a simple calculation that considers the length of the closure and the train arrival rate, as shown in Equation 44.

$$D = T + \sum_{n=1}^{m}(T - nt)$$

**Equation 44. Total Train Delay (from Schafer & Barkan, 2008)**

Where $D$ is total train delay for multiple trains

$T$ is total delay time for service interruption (the duration of the closure)

$m$ is number of following trains delayed equal to $T$ divided by $t$ (rounded to the nearest integer)

$t$ is hours per train arrival

In this delay equation, the first train experiences delay equal to the duration of the closure ($T$). Each subsequent train experiences an amount of delay shorter than $T$ which is determined by the train arrival rate ($t$). This formulation appears to neglect the idea that after the track is repaired and put back into service, additional time will be required for the backlog of trains to pass through the site of the closure.

In “Train Delay and Economic Impact of In-Service Failures of Railroad Rolling Stock” the authors developed a parameterized model of rail delay based on simulations run with Rail Traffic Controller (RTC)(Schlake et al., 2011). They conducted 24 simulation runs with a mix of 1-, 3-, and 5-hour service disruptions running on single track.[124] They used simulation parameters shown in Table 79, randomly varied distribution of train starts, and varied TPD. They then conducted a second set of simulation runs with double tracks.

The authors then fit an exponential curve for each delay duration and track type (single or double) using the average duration of delay as the dependent variable. Table 80 below shows the expected average delay based on duration of closure for single and double track. For double track segments, the authors noted the average delay was small and constant until traffic exceeded 48 train per day.

**Table 79. Simulation Parameters for Rail Closure Simulations**

| Descriptors | Units | (Schlake et al., 2011) |
|---|---|---|
| Route Length | *Miles* | 260 |
| Max speed | *MPH* | 50 |
| Tracks | *Number* | Single \| Double |
| Locomotives | *Count* | 3 |
| Cars | *Count* | 115 |
| Train Length | *Feet* | 6,325 |
| Siding Length | *Feet* | 8,000 |
| Siding Spacing | *Miles* | 10 |

[124] Service disruptions resulted in a complete closure of the rail link, making it functionally equivalent, in terms of delay, as a HAZMAT incident. Notably however, HAZMAT incidents are commonly longer in duration than the values analyzed in (Schlake et al., 2011).

Table 80. Closure Based Delay from Simulations

| Volume | Single Track, 1 Hour of Closure (Schlake et al., 2011) | Single Track, 3 Hours of Closure (Schlake et al., 2011) | Single Track, 5 Hours of Closure (Schlake et al., 2011) | Double Track, 1 Hour of Closure (Schlake et al., 2011) | Double Track, 3 Hours of Closure (Schlake et al., 2011) | Double Track, 5 Hours of Closure (Schlake et al., 2011) |
|---|---|---|---|---|---|---|
| *TPD* | *Average delay in hours* | *Average delay in hours* | *Average delay in hours* | *Average delay in hours* | *Average delay in hours* | *Average delay in hours* |
| 10 | 1 | 3 | 8 | 1 | 3 | 5 |
| 15 | 1 | 5 | 12 | 1 | 3 | 5 |
| 20 | 2 | 8 | 18 | 1 | 3 | 5 |
| 25 | 3 | 11 | 27 | 1 | 3 | 5 |
| 30 | 4 | 17 | 40 | 1 | 3 | 5 |
| 35 | 5 | 26 | 60 | 1 | 3 | 5 |
| 40 | 7 | 39 | 89 | 1 | 3 | 5 |
| 50 | 13 | 87 | 199 | 1 | 4 | 6 |
| 60 | * | * | * | 1 | 4 | 6 |
| 70 | * | * | * | 2 | 5 | 12 |
| 80 | * | * | * | 2 | 8 | 19 |
| 90 | * | * | * | 3 | 12 | 28 |
| 100 | * | * | * | 3 | 19 | 41 |
| 120 | * | * | * | 6 | 37 | 92 |

* Schlake, et al. (2011) does not present results for single track above approximately 50 TPD.

This analysis developed an extension to the theoretical model presented by Schafer & Barkan (2008) to include the additional delay after a closure is clear, as trains must pass one-by-one through the site of the closure. The bottleneck model expressed in Section 3.6.1 in the body of this report includes both the delay caused by the closure, and additional delay due to track capacity limitations.

Figure 19, Figure 20, and Figure 21 show comparisons of Schafer & Barkan (2008) train delay formula, the Schlake, et al. (2011) train delay simulation results, and the bottleneck model used in this analysis for 1-, 3-, and 5-hour. The bottleneck model results rely on an assumed capacity of 50 TPD the approximate capacity of a single track with a uniform traffic mix (see Table 23. *Capacity Ranges for Signal Type and Number of Tracks*). The comparison shows that the bottleneck model used in this analysis very closely approximates the estimates derived from explicit simulation modeling which strongly suggests that the bottleneck model is sufficient for estimating the delay from waiting for a closure, at least for cases where there is some amount of excess capacity.

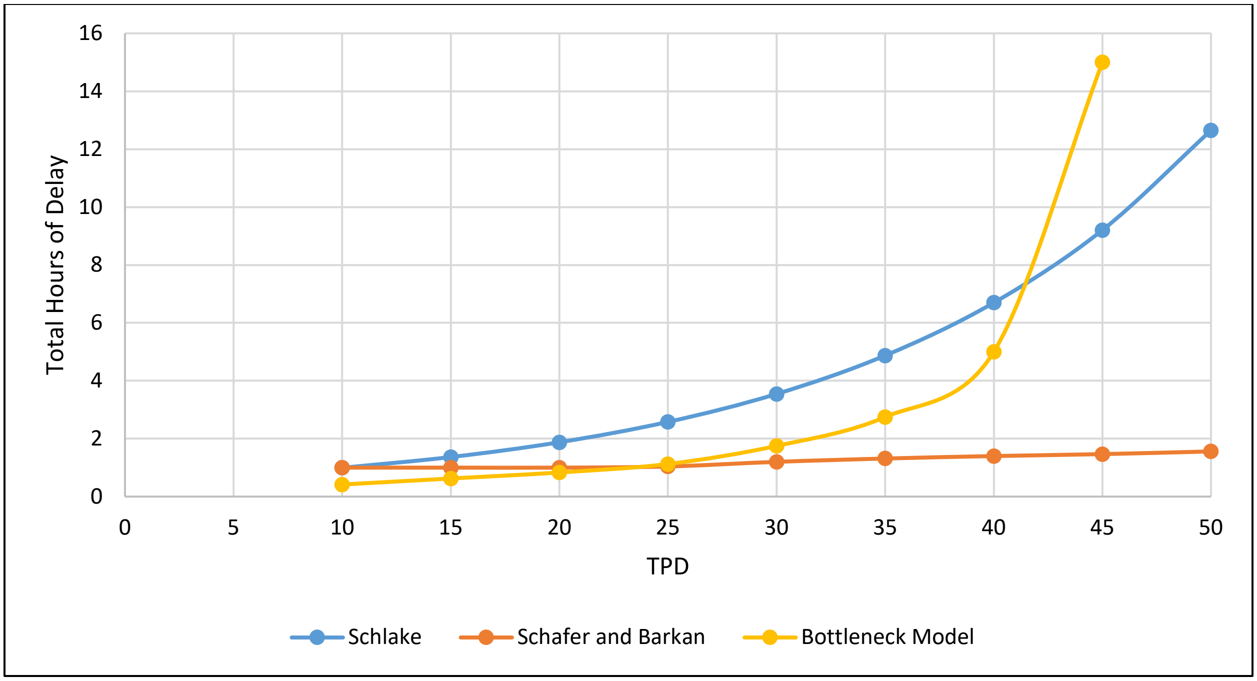


**Figure 19. Comparison of Rail Closure Model Results, One-Hour Closure**

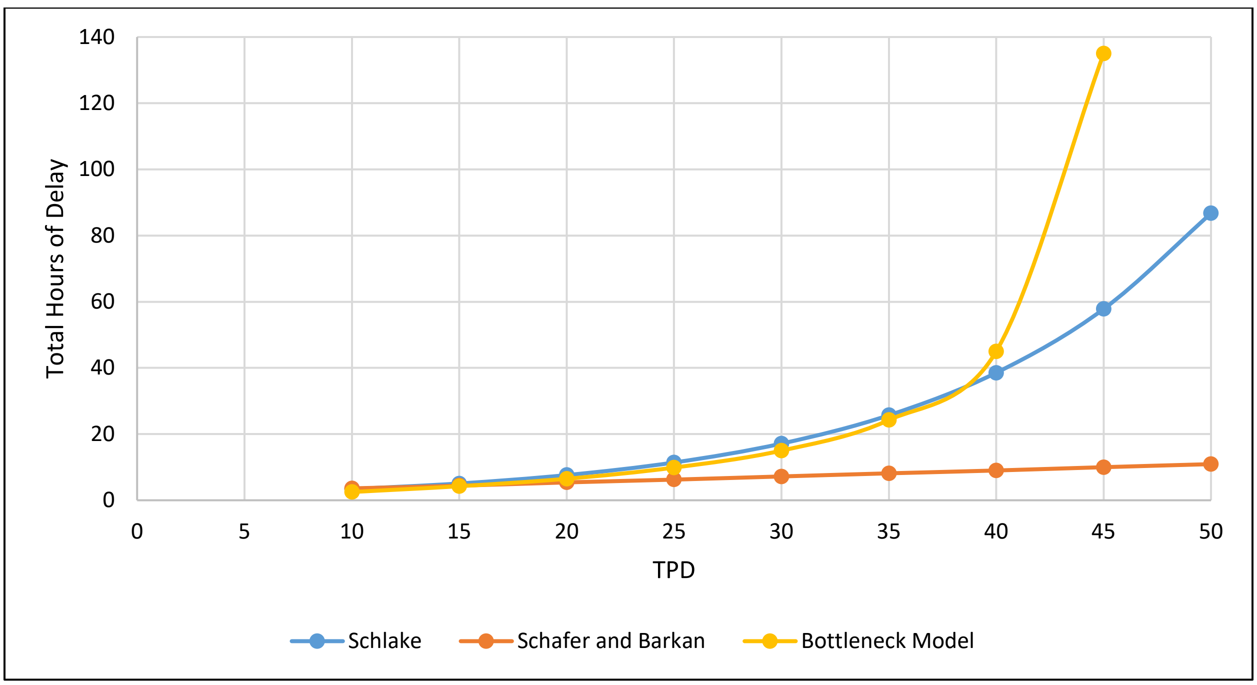


**Figure 20. Comparison of Rail Closure Model Results, Three-Hour Closure**

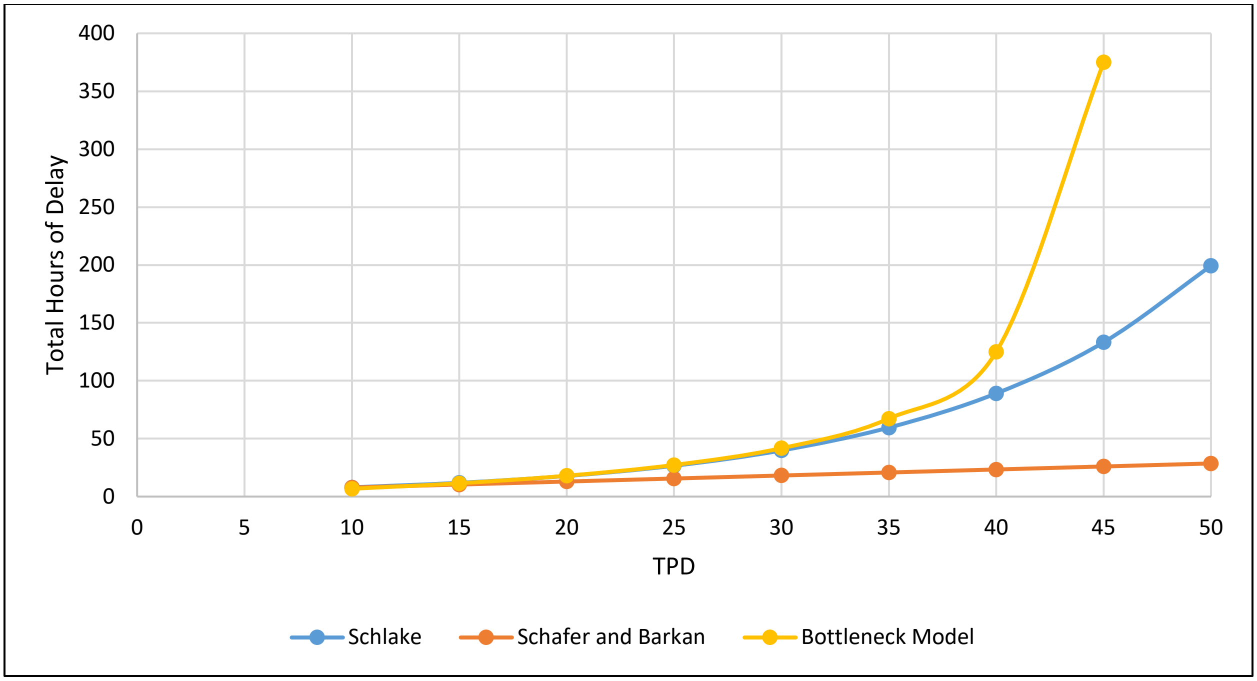


**Figure 21. Comparison of Rail Closure Model Results, Five-Hour Closure**

While not included in the bottleneck model as presented above, there may be further additional delay as trains require additional time to resume normal speeds after being halted. For instance, one study assumes that accelerating and decelerating out of and into slow orders can take an additional 30 minutes (Lovett et al., 2017).

Lovett et al. (2017) provides analysis of the operation and cost effects from slow orders (temporary speed restrictions on rail lines). The authors developed a model to quantify additional costs from a temporary speed restriction on a rail track segment. Speed restrictions reduce the throughput capacity of a rail line. The authors note that with low levels of rail traffic, headways may be long enough that subsequent traffic – traffic not directly affected by the speed restriction – may not be delayed. They note, however, that this is an uncommon scenario in North America, where railroads generally do not have fixed headways and multiple trains can bunch together. Further, they note that a majority of North American rail lines are single track, so that operations are heavily dependent on the travel time between passing sidings.

## Modeling Congestion-Related Delay

There are broadly three approaches to modeling congestion-related rail delay. *Simple formulas* relate theoretical capacity to TPD, *Simulation models* use rail modeling software to simulate the interaction of train and track elements, but have generally been "cost and time prohibitive" (Krueger, 1999) and too computationally intensive to apply to larger scale scenarios, such as simulating a regional (or larger) rail network (Lai & Barkan, 2009). *Parametric models* provide a practical compromise between the other approaches. They generally use the theoretical models relating key factors such as traffic volume and rail infrastructure to capacity, congestion, or delay, while using simulations to estimate the model parameters (Krueger, 1999). Each of these types of models are discussed in turn below, followed by other singular delay estimation efforts of interest.

## Theoretical Models of Capacity/Delay

Understanding a track segment's capacity is required when estimating congestion-caused delay. However, measuring railroad capacity is a complex topic. *Theoretical capacity* is an engineering concept that calculates the maximum possible throughput assuming maximum locomotive speeds achieved at all times, uniform train characteristics, uniform distribution of trains through the day, and the same train priority " (Krueger, 1999). *Practical capacity* is an approximation that acknowledges railroad operations in the real world never have that type of uniformity required to achieve their theoretical capacity. Practical capacity is usually estimated as approximately 60 to 70 percent of theoretical capacity.[125] Another approach to understanding the capacity of a rail segment is to consider maximum allowable runtime which is based on the hours of service allowed for crewmembers (Prokopy & Rubin, 1975).

## Simulation Congestion Modeling

In contrast to assigning a single number as the capacity of a rail line, some analysts acknowledge that even below a stated "capacity" volume, additional trains will slow down run times. This type of analysis generally uses simulation models to infer a relationship between minutes of train delay (per train-mile) and the volume of trains on a segment. Micro simulations of dispatching behavior may be modeled with tools such as AnyLogic, Vissim, and RTC. RTC is frequently used in developing parametric congestion and delay models, as in Dingler (2010), Sogin et al. (2013), and Sogin et al. (2016).

"The Impact of Operational Strategies and New Technologies on Railroad Capacity" is a master's thesis in which Dingler (2010) uses RTC software to analyze the impact of train type heterogeneity and Positive Train Control (PTC) on rail capacity. At least two other articles were published based on this thesis, but the thesis provides the greatest detail on methodology and results relevant to future development of a parametric rail congestion model.[126]

The work involved estimating delay in minutes per 100 train-miles and found that the maximum average delay did not occur when rail traffic is perfectly mixed (50 percent each), but when traffic is 75 percent bulk trains and 25 percent intermodal. The report contains graphs presenting curves that relate TPD (independent variable) to delay (dependent variable). These curves show average delay increasing at an

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[125] Mitra et al. (2010) cite Kraft (1982) as stating that practical capacity is 60-70% of theoretical capacity.
[126] See also (M. Dingler et al., 2009) and (M. H. Dingler et al., 2009).

increasing rate.

Dingler (2010) also discusses the impact of PTC, also called communications-based train control, on capacity. He found that PTC can enhance capacity under some circumstances, have little or no effect under others, and in some cases may reduce capacity.

In “Measuring the Impact of Additional Rail Traffic Using Highway and Railroad Metrics,” the authors estimate the delay impact from adding additional passenger trains to existing freight volumes (Sogin et al., 2012). When doing so, they compare that incremental impact to the impact from additional freight trains. The analysis was conducted using RTC, with the simulation of a single-track operation with simplified operations (e.g., 15 miles between crossovers, average signal spacing of 2 miles, freight train consists of 115 hopper cars with a maximum speed of 50 MPH, and a baseline of 24 TPD).

The authors continued to develop their model in “Comparison of Capacity of Single- and Double-Track Rail Lines” (Sogin et al., 2013). This paper uses a parameterized model to analyze how adding passenger trains, running at higher speeds, differentially impacts freight train delay based on whether operations are in a single track or double track environment.

The authors used four key factors in simulations in a full factorial design: number of tracks, TPD, maximum passenger train speed, and traffic mix (i.e., percent freight). They use a three-day simulation period with freight trains run 24 hours per day, but passenger trains run during the daytime only.

In “Analyzing The Transition From Single- To Double-Track Railway Lines With Nonlinear Regression Analysis” the authors estimate delay impact on various track configurations, studying the transition between single and double track. The authors study the interaction between traffic volume, composition, and speed differential for passenger and freight trains for different mixes of track compositions (percent double track).

Table 81 provides a description of simulation parameters used in the Dingler (2010), Sogin et al. (2013) and Sogin et al. (2016) analyses. The table shows that similar parameters are used for the simulations.

Table 82 compares the resulting estimates of delay. Dingler (2010) sees a relatively steep rate of increasing delay as the volume of TPD increases, though at around 30 TPD Dingler finds a similar level of delay per 100 miles as Sogin et al. (2013) and Sogin et al. (2016). Notably, for double track there is virtually no delay until daily train volumes reach 65 TPD in Sogin et al. (2013). Sogin et al. (2016) estimates substantially lower delay on double track than on single track.

Table 81. Simulation Parameters for Rail Congestion Simulations

| Descriptors | Units | (M. H. Dingler, 2010) | (Sogin et al., 2013) | (Sogin et al., 2016) |
|---|---|---|---|---|
| Route Length | Miles | 262 | 265 | 240 |
| Max speed | MPH | 50 | 50 | 50 |
| Tracks | Number | Single | Single \| Double | Single \| Double |
| Locomotives | Count | 3 | 3 | 3 |
| Cars | Count | 115 | 115 | 115 |
| Train Length | Feet | 6325 | 6325 | 6325 |
| Siding Length | Feet | 8700 | 7920 | 10560 |
| Siding Spacing | Miles | 10 | 15 | 10 |
| Intermodal Share | Percent | 0 to 100 | 0 | 0 |
| Passenger Share | Percent | 0 | 0 to 100 | 0 or 25 |

Table 82. Congestion Based Delay from Simulations

| Volume | Single Track, All Trains Bulk (M. H. Dingler, 2010) | Single Track, All Trains Bulk (Sogin et al., 2013) | Double Track, All (Samuel L Sogin, 2016) Trains Bulk (Sogin et al., 2013) | Single Track, All Trains Bulk (Sogin et al., 2016) | Double Track, All Trains Bulk (Sogin et al., 2016) |
|---|---|---|---|---|---|
| TPD | Delay in minutes per 100 train-miles | Delay in minutes per 100 train-miles | Delay in minutes per 100 train-miles | Delay in minutes per 100 train-miles | Delay in minutes per 100 train-miles |
| 10 | 6 | 5 | 0 | 11 | 0.2 |
| 15 | N/A | 20 | 0 | 13 | 0.3 |
| 20 | 18 | 25 | 0 | 17 | 0.4 |
| 25 | N/A | 30 | 0 | 21 | 0.5 |
| 30 | 33 | 35 | 0 | 27 | 0.6 |
| 35 | N/A | 55 | 0 | 34 | 0.8 |
| 40 | 53 | 65 | 0 | 44 | 1.0 |
| 50 | 74 | N/A | 0 | 70 | 1.6 |

# Parametric Models of Delay

"Parametric Analysis of Railway Line Capacity" is the seminal work on parametric capacity modeling (Prokopy & Rubin, 1975). The parametric model is built off of a simulation model developed by Peat Marwick (1976). The primary relationship is between train delay and number of trains dispatched. The relationship varies with spacing of sidings, or percent double track.[127]

[127] See page 27 for the curves (Prokopy & Rubin, 1975).

Prokopy & Rubin (1975) found that line capacity was considerably less than widely believed, with delays exceeding acceptable limits before a line will lock-up. Capacity was determined by the number of tracks and the operating speed. Also, the authors found a non-linear relationship between average delay per train and the volume of trains, with delay increasing at a faster rate the greater the volume of traffic, all else equal. However, they found a linear relationship satisfactorily described the relationship at lower volumes.

Also notable and relevant, the authors found it was difficult to determine a maximum allowable run time for trains, and so used the 12 hours of maximum crew hours of service as an upper limit (Prokopy & Rubin, 1975). While the resulting estimates are included in the report, the estimates are over 40 years old and likely no longer relevant.

“Parametric modeling in rail capacity planning” discusses a proprietary rail capacity model developed by the Canadian National (CN) by the author (Krueger, 1999). It is an application of a similar method used by (Prokopy & Rubin, 1975) according to Lai & Barkan (Lai & Barkan, 2009).

In this model, the factors impacting capacity are:

- Plan (Infrastructure)
    - Length of division: longer divisions take longer to traverse.
    - Meet Pass Planning Point Spacing: the average spacing of locations used to meet or overtake trains. Sidings less than standard train length are disregarded.
    - Meet Pass Planning Point Uniformity: Standard deviation of meet and pass planning point spacing. A value of zero represents a plan with uniform spacing.
    - Intermediate Signal Spacing Ratio: Measure of signal spacing to siding spacing, with intermediate signals increasing capacity.
    - Percent double track: Segments greater than 6,000 feet in length but less than 2 miles are considered sidings. Locations less than 6,000 feet are ignored.
- Traffic
    - Traffic Peaking Factor: maximum trains in four hours and average trains in four hours.
    - Priority probability: a function of the number of priority classes, daily number of trains, and number of trains in each priority class.
    - Speed ratio: ratio of fastest train speed to slowest train speed.
    - Average minimum run time.
- Operating Parameters
    - Track outages: number of hours the plant is out of service.
    - Temporary slow order.
    - Train stop time.
    - Maximum trip time threshold.

Krueger (1999) developed a functional form for train delay, where train delay is a function of a combined track characteristics, traffic and operating parameter developed using simulation modeling, $A_0$, traffic volume, V, and a constant, B. The author posited the functional form Train Delay = $A_0e^{BV}$, and used this relationship to develop track capacity curves relating TPD to over the road time in hours. The model is not available to the public and, while it is simpler to run than simulation models, it still requires a detailed data describing the traffic and physical characteristics of the rail line. This report is not directly of use for this research, but it does highlight the wide variety of factors that impact rail line capacity.

In “Enhanced Parametric Railway Capacity Evaluation Tool,” Lai and Barkan (2009) discuss some enhancements to the CN parametric rail capacity model initially presented in Krueger (1999) and as with the Krueger paper, the resulting parameters are not provided. They provide a concise overview of the CN model. The paper explains that theoretical models may be too simple for anything other than high-level comparisons and simulations are too computationally intensive for use at the network level. The authors note that parametric models fill the gap, being suitably detailed to capture salient infrastructure and operational details while remaining tractable.

The stated goal of “Estimation of Railroad Capacity Using Parametric Methods” is to develop a parametric model based on public information that can be used by State Departments of Transportation to analyze rail capacity (Mitra et al., 2010). The methodology, however, used to estimate the parametric model is opaque. It is unclear from the paper, as presented, whether they are presenting results from Prokopy and Rubin (1975) or using an engineering formula of theoretical capacity.

The paper notes that CN model has advanced the work done by Prokopy and Rubin (1975) but that the software and its results are not available to public. Due to uncertainty in how this model was developed, it is not recommended to use it as a basis for estimating delay costs from hazardous material rail incidents.

## Other Modeling Efforts

“Statistical estimation of railroad congestion delay” is a unique example of estimating delay using statistical data (Gorman, 2009). It provides a useful teaching example of a stringline schematic for a train division. The data comes from BNSF division level data for five years across eight divisions with varying length and TPD. The author introduced a methodology to separately identify magnitudes of different types of delay causal factors: Primary, occurring to the train in question, and secondary, caused by other trains on network as well as capacity related factors. The article presents a predictive model of train delay using a variety of highly specific regressors such as number of passes and overtakes, departure headway, and others. While Gorman (2009) presents significant insights into congestion delay modeling, the specificity of regressors used makes their methodology difficult to use in this research effort.

NCHRP 755 Report “Comprehensive Costs of Highway-Rail Grade Crossing Crashes” provides a detailed discussion of a model framework used to estimate exposure rates, primary cost effects, and secondary cost effects of highway-rail grade crossing accidents (Brod et al., 2013). The exposure rate and primary cost effect analysis (monetizing estimated casualty and property damage from grade crossing crashes) are not of interest to our study, but the report’s approach to estimating secondary cost effects is of interest. The report identifies three secondary cost areas:

1. Delay and rerouting cost, which is a function of VOT for persons delayed in highway traffic, and operating cost of rerouting trains and highway users.

2. Supply chain transport cost, which is a function of supply chain delay costs (the opportunity cost of capital during delayed delivery, as well as other costs of late delivery or redelivery such as overtime pay) and diversion costs (occurring when damaged track causes a diversion, and includes the cost of transferring freight to other vehicles or containers, and the opportunity or rental cost of the replacement vehicle or container). The report notes this varies by shipment and commodity type.
3. Supply chain inventory cost, which is a function of loss of shipment value and the cost of reliability risk. The report notes this varies by shipment and commodity type and provides a general framework for including these costs in a delay cost model.

The report lists three possible approaches to addressing rare catastrophic crashes, where the degree of property damage and number of injuries and fatalities is far in excess of that for a typical rail crossing crash. As hazardous material rail crashes are, fortunately, rare, but potentially catastrophic, the report's insight is relevant to the proposed hazardous material rail study. The report emphasizes that these catastrophic crashes are challenging to estimate due to their high cost but low probability. The authors chose the option of excluding these rare catastrophic events from their analysis, but also mentioned two other potential approaches: presenting these worst-case scenarios separately, particularly for studies intending to mitigate these types of crashes or including a "best-guess estimate" of their costs, given their high per incident cost but low probability of occurrence.

"Delay and Environmental Costs of Truck Crashes," focuses on the delay impacts resulting from truck crashes (Hagemann et al., 2013). Using a series of microsimulations, the authors developed a formula to express net delay as a function of roadway volumes and duration of closure, and produced a formula specific to rural and urban non-highways which would be most relevant to this study.

Equation 45. *Formula to Determine Total Vehicle Delay*

shows the formula developed to model delay as a function of traffic volume and duration of delay. To the extent that a rail incident impacts roadway users, this parametric model is useful in estimating the delay costs to highway users. The parameters a, b, c, d, e, and f were estimated using goodness of fit approaches to reproduce the original simulation results and are provided in the report.

$$Delay = a + b \times \frac{1}{1 + e^{-\left(\frac{volume - c}{d}\right)}} \times \frac{1}{1 + e^{-\left(\frac{duration - e}{f}\right)}}$$

**Equation 45. Formula to Determine Total Vehicle Delay**

# Other Findings from Literature

## Value of Travel Time Reliability

On the topic of **value of travel time reliability for freight**, the *NCHRP Research Report 925 Estimating the Value of Truck Travel Time Reliability* provides a thorough review of literature on truck freight reliability, and proposes methods and examples for conducting surveys and estimating the value of travel time reliability (Guerrero et al., 2019). They define reliability as a "lack of variability in travel times … relative to expectations." Guerrero et al. (2019) note that reliability costs include direct costs of transportation (e.g., additional driver wages, fuel, etc.) and costs to shippers (e.g., production disruptions, missed intermodal transfers, etc.). They generally note this cost is incurred due to truck firms and shippers building "slack" into travel time estimates.

Guerrero et al. (2019) also discuss the nonlinearity of unreliability costs. Transportation costs increase as travel time exceeds the expected arrival time, with prolonged delays impacting other shipments as the driver, truck and other resources are not available. There are also impacts to shipper and receiver costs, where early arrivals may cause production or staff disruptions, late deliveries cause additional costs due to disrupted production, but exceedingly long delays may lead the receiver or shipper to activate contingencies (e.g., ship replacement products).

The authors present a model to calculate the additional cost to transportation carriers due to built-in travel time "slack" as a function of distance and time-based costs, volume of carrier truck trips per year, the fixed costs of truck ownership, and distribution of deviances from expected travel times.

Additionally, they present a model to calculate additional costs to shippers, as a function of the value of goods, rate of depreciation, and distribution of deviances from expected travel times. Finally, they use these cost models to model two methods of calculating a Value of Reliability (VOR) either as a function of the standard deviation of travel times or the 95$^{th}$ percentile delay, the latter of which the authors suggest better corresponds to truck operator's understanding of reliability.

**Long-distance passenger travel VOR** is estimated, for air travelers in "The Economic Cost of Airline Flight Delay" (Peterson et al., 2013). As no literature currently estimates to value of travel time reliability for long-distance rail passengers in the U.S. (i.e., Amtrak passengers), this paper was reviewed for potential applicability for long-distance passenger VOR estimates. The authors focus on the economic cost (lost macroeconomic output) resulting from business travelers due to "extra time of air travel due to flight delays [that] result in lost business productivity" (Peterson et al., 2013). The impact of delay on leisure travelers is captured by decreased consumer spending. Neither of those approaches are an appropriate methodology for estimating social costs or benefits.

## Time of Day Considerations

In Sogin et al. (2013), the authors noted an advantage of freight railroads have over both public transit and highways is that the demand on the infrastructure is usually uniform across a 24 hour period. However, in a congested time period for a railroad, there is often not a time period of low demand to clear out congestion within the network. As a result, a period of severe derailment can back up railroad traffic for days as well cause lengthy detours. This detail provided by Sogin supports the idea of using a uniform distribution of rail volumes over a 24 hour period rather than needing to allocate traffic volumes across time of day.

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