Taylor & Francis
Taylor & Francis Group

International Journal of Sustainable Transportation

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/ujst20

Comparative evaluation of highways and railroads using life-cycle benefit-cost analysis

Sarita Rattanakunuprakarn, Mingzhou Jin, Michael Sussman & Powell Felix

To cite this article: Sarita Rattanakunuprakarn, Mingzhou Jin, Michael Sussman & Powell Felix (09 Oct 2024): Comparative evaluation of highways and railroads using life-cycle benefit-cost analysis, International Journal of Sustainable Transportation, DOI: 10.1080/15568318.2024.2411588

To link to this article: https://doi.org/10.1080/15568318.2024.2411588

Published online: 09 Oct 2024.

INTERNATIONAL JOURNAL OF SUSTAINABLE TRANSPORTATION
https://doi.org/10.1080/15568318.2024.2411588

Taylor & Francis
Taylor & Francis Group

REVIEW ARTICLE

Comparative evaluation of highways and railroads using life-cycle benefit-cost analysis

Sarita Rattanakunuprakarn[a], Mingzhou Jin[a], Michael Sussman[b], and Powell Felix[c]

[a]Department of Industrial and Systems Engineering and Institute for a Secure and Sustainable Environment, The University of Tennessee at Knoxville, Knoxville, TN, USA; [b]OnTrackNorthAmerica, Inc, Philadelphia, PA, USA; [c]Indiana Boxcar Corporation, Connersville, IN, USA

ABSTRACT

The transportation sector holds a substantial influence on our quality of life and the environment. In contrast to rail transport, road transport carries a heightened risk of environmental and social issues. These include, but are not limited to, congestion, accidents, community segregation and encroachment, air pollution, toxic releases, water and soil pollution, and impacts on wildlife vitality. With the surge in global freight volume, the heavy reliance on road transport and underutilization of railroads will prove inadequate to meet the escalating demand and exacerbate existing environmental and social concerns. Therefore, transportation investment evaluations must comprehensively and consistently consider environmental, social, and economic factors. This study develops a Life-cycle Benefit-Cost Analysis and an accessible tool to capture overall nationwide impacts across various stages of transport infrastructure and equipment life cycles. We compare highways and railroads, considering actual and maximum capacities, to identify the most cost-effective and sustainable investment. Our results show that trucking costs $370.07 per thousand ton-miles, 4.85 times higher than rail at $76.37 per thousand ton-miles. We also highlight further research needed to address the issues of data unavailability, limited metric scope, and computational method limitations.

ARTICLE HISTORY
Received 1 December 2023
Revised 28 August 2024
Accepted 21 September 2024

KEYWORDS
Benefit-cost analysis; highways; life-cycle assessment; railroads; sustainable transportation

1. Introduction

The highway system in the United States serves as the primary mode of transportation for freight and passengers. Currently, trucks handle a significant portion of domestic freight shipments, accounting for 72.2% in 2021 (Costello, 2022). However, the escalating issue of traffic congestion, driven by a multitude of factors such as urbanization, population expansion, insufficient infrastructure development, and the increasing dependence on personal vehicles and trucks, poses a critical challenge. This congestion results in extended travel times, elevated transportation expenses, reduced overall system dependability, and plays a substantial role in various environmental and social problems, particularly the emission of greenhouse gases and air pollution. The emissions released by these vehicles, such as carbon dioxide, nitrogen oxides, and particulate matter, significantly contribute to air pollution, leading to respiratory problems and environmental degradation. In addition to air quality issues, accidental spills of hazardous materials and improper waste disposal can contaminate water bodies, threatening aquatic ecosystems and potentially affecting drinking water supplies. Additionally, the increased use of trucks results in a higher accident rate on the roads, causing injuries and fatalities. The noise pollution emitted by these vehicles can also significantly impact the well-being of individuals living near major transportation routes. Research by Link et al. (2016) showed that the costs associated with noise pollution, road accidents, and wear and tear during peak hours were 12 to 46 times higher than climate change costs, depending on vehicle types. Here, the climate change costs were estimated to be in the range of €14 to €51 per tonne of CO2-equivalent emission in the 2002 price. Even with the 2024 CO2-equivalent emission costs estimated at around €150 (Quinet, 2019), the costs associated with noise pollution, road accidents, and wear and tear during peak hours are still much higher than climate change costs. Moreover, the growing demand for vehicles often prompts the expansion of the transportation network, leading to the destruction of natural habitats and ecosystems, including deforestation, habitat fragmentation, and loss of biodiversity.

Addressing the environmental concerns requires concerted efforts to promote sustainable transportation alternatives and reduce reliance on trucks. One sustainable and efficient alternative to highways is the rail system. Due to its considerable capacity and energy efficiency, railroads have lower environmental and social impacts on a per-ton-mile basis. However, implementing such a system requires substantial investments in rail infrastructure, including constructing new tracks, upgrading existing ones, expanding the rail network for better coverage and accessibility, and establishing efficient handling facilities. Despite these challenges,

CONTACT Mingzhou Jin jin@utk.edu Department of Industrial and Systems Engineering and Institute for a Secure and Sustainable Environment, The University of Tennessee at Knoxville, Knoxville, TN 37996, USA.

the advantages of the rail system make it an attractive option for certain situations. For example, it can accommodate large volumes of goods and passengers, making it ideal for transporting heavy or bulk items over long distances. Additionally, it can effectively handle projected increases in freight volumes, which are anticipated to grow by 50% by 2050 (Solomon & Singer, 2021). In contrast, relying on trucks as the primary transportation mode would be inadequate to meet predicted demand while also exacerbating congestion and the existing shortage of 78,000 truck drivers, which is only slightly lower than the peak of 81,258 in 2021 (Premack, 2022). As an added benefit, the rail system maintains a more predictable schedule and ensures greater reliability for shippers and travelers than highways.

When comparing transportation investment alternatives, it is crucial to consider not only the capital investment, operating costs, and maintenance costs, but also the environmental and social impacts of each mode. To evaluate these impacts, we propose a Life-Cycle Benefit-Cost Analysis (LBCA) method, which combines the Benefit-Cost Analysis (BCA) approach with the life-cycle analysis. The LBCA method enables an interpretable and consistent evaluation of the economic efficiency of highway and railroad projects, capturing impacts across different stages of the transport infrastructure and equipment lifecycles. Our LBCA method encompasses a wide range of metrics, including land value, initial construction, operations, maintenance, traffic safety, congestion, greenhouse gas emissions, water quality, noise pollution, and wildlife vitality. By considering these metrics, we provide a comparative evaluation of highways and railroads in terms of their economic efficiency, measured in 2020 US dollar value per thousand ton-miles. We analyze two scenarios, actual flows, and theoretical maximum flows, allowing for a comprehensive understanding of the potential benefits and costs of each mode. To facilitate the adoption of LBCA as a decision-making tool, we create a user-friendly Excel spreadsheet for interested parties. Our research highlights the importance of considering the full range of impacts associated with transportation investment alternatives. By utilizing the LBCA approach, decision-makers can make informed choices about sustainable and efficient transportation solutions. The integration of economic, environmental, and societal factors through LBCA ensures that transportation investments align with long-term sustainability goals while maximizing benefits and minimizing negative impacts.

2. Literature review

BCA is a powerful and extensively used tool for assessing the economic efficiency of various investment projects and policies in terms of their advantages and disadvantages. Benefits refer to the positive outcomes or advantages that result from implementing the project or policy. These can include increased productivity, improved safety and public health, enhanced environmental quality, or any other positive impacts. Costs, on the other hand, represent the expenses or sacrifices incurred in implementing the project or policy, such as construction costs, operational costs, or foregone opportunities. The BCA process typically involves several key steps. Firstly, the analyst identifies all relevant benefits and costs associated with the project or policy. This may require extensive data collection and analysis. Next, the analyst assigns monetary values to these benefits and costs, accounting for both short-term and long-term impacts. This step often involves estimating future costs and benefits and discounting them to present values. Once the benefits and costs are quantified, they are compared to determine the net benefits. One common application is assessing the economic returns associated with transportation infrastructure projects and determining preservation strategies for existing transportation assets. In addition to the financial impact, this standardized, systemic approach can also consider the environmental and social impacts of the project by quantifying these potential economic losses as monetary values. There are several BCA methodologies established by many organizations. Examples of BCA process guidelines include Puget Sound Regional Council BCA, Federal Aviation Authority Airport (FAA) BCA guidance, Transportation Investment Generating Economic Recovery grants program, Washington State Department of Transportation freight rail benefit cost (Goodchild et al., 2014), the new Better Utilizing Investments to Leverage Development transportation discretionary grants program, Federal Highway Administration (FHWA) fright benefit cost, The American Association of State Highway and Transportation Officials benefit analysis for highways, The National Center for Fatality Review and Prevention freight transport BCA (M. S. Lee & Jin, 2020). Table 1 summarizes factors commonly considered in BCA methodology.

Based on the literature review, BCA has been used in infrastructure projects to make decisions regarding single transportation modes, to compare segregated transportation modes, and to evaluate multimodal transport. Various factors have been commonly evaluated for both rail and truck transportation modes, including capital cost, operational costs, transport time savings, reduction in the number of miles, traffic safety, reliability, maintenance cost, and environmental effects such as air pollutant emission, noise emission, and climate endangerment. While BCA offers a valuable decision-making framework, it is important to acknowledge its limitations. Challenges in BCA arise at various stages of the methodology, starting with metric selection, which often varies significantly across research projects. Some papers only partially consider impacts across the economic, environmental, and social categories, and even among those papers, they tend to focus on specific phases of the lifecycle rather than adopting a holistic approach. Several factors contribute to this variation, including the inapplicability of certain metrics to certain projects and the unavailability of necessary data. For instance, when examining upstream activities in a product's lifecycle, such as raw material extraction and production, assessing associated impacts like environmental effects or financial costs can be intricate and challenging to determine. Time and budget also limit the scope of the analysis, as collecting the necessary data requires significant resources. BCA can be heavily dependent on predictive data, such as transportation patterns,

Table 1. Summary of BCA metrics.

Reference	Methodology	Categories	B/C components
Bohmhold & Weiss, 2015	BCA	IC, ENV, LV, SO, ECON	Labor, materials, energy, labor and admin of assets, maintenance of assets and equipment, air pollution, pavement, safety, mobility, reliability
Dharmadhikari et al., 2016	BCA	IC, OP, SO, ECON	Labor, materials, contractor, ROW, maintenance of assets and equipment, safety, congestion, mobility
U.S. Federal Railroad Administration, 1990	BCA	OP, ENV, SO, ECON	Maintenance of assets, end of life value, air pollution, employment, price of service, tax revenue, profit and revenues
Federal Railroad Association, 2016	BCA	IC, OP, ENV, SO, ECON	Capital cost, labor and admin of assets, maintenance of assets and equipment, air pollution, safety, connectivity, mobility
Goodchild et al., 2014	BCA, Scorecard	IC, OP, ENV, LV, SO, ECON	Labor, materials, contractor, ROW, labor and admin of assets, maintenance of assets and equipment, energy sustainability, air pollution, noise, water, land use changed the reduce VMT, safety, congestion, accessibility, employment, mobility, reliability, price of service, revenue
Gühnemann et al., 2012	BCA, MCA	ENV, SO	Air pollution, noise, accessibility
Khattak et al., 2018	BCA, ROI	OP, ENP, SO, ECON	Energy, energy sustainability, air pollution, noise, water, wildlife vitality, safety, congestion, accessibility, equity, property value, mobility, price of service
Korytárová & Papežíková, 2015	BCA	OP, ENV, SO, ECON	Labor and admin of assets, maintenance of assets and equipment, air pollution, noise, safety, congestion, employment, mobility
Lee & Jin, 2020	BCA, WEB	SO, ECON	Connectivity, accessibility, reliability
Leleur et al., 2007	BCA, MCA	OP, ENV, SO, ECON	Labor and admin of assets, maintenance of assets and equipment, air pollution, noise, safety, connectivity, accessibility, mobility
Mascoop, 2017	BCA	IC, ENV, SO, ECON	Materials energy, labor and admin of assets, maintenance of assets, insurance, air pollution, safety, congestion, employment, capacity, mobility, tax revenue
Rezvani et al., 2015	BCA	IC, OP, ENV, SO	Construction costs, maintenance of assets, air pollution, noise, safety, congestion
Siciliano et al., 2016	BCA	IC, OP, ENV, SO, ECON	Labor, materials, energy, labor and admin of assets, maintenance of assets and equipment, insurance, air pollution, noise, water, wildlife vitality, nature and landscape (now in env), safety, congestion, urban effect, capacity, mobility
Spasovic et al., 2018	BCA, Demand models	OP, ENV, SO, ECON	Energy, air pollution, safety, mobility
Tolliver & Lindamood, 1993	BCA	OP, LV, SO, ECON	Energy, labor cost, maintenance of assets, opportunity of investment, congestion, property value, mobility, price of service, profit and revenue, user profit
Walther et al., 2015	BCA	IC, OP, ENV, SO, ECON	Materials, labor and admin of assets, air pollution, noise, safety, connectivity, accessibility, mobility, reliability, price of service

Note. Abbreviation in the table: LV is Land Value Metric, IC is Initial Construction Metric, OP is Operating Metric, ENV is Environmental Metric, SO is Social Metric, ECON is Economic Metric, Web is wider economic benefit.

traffic forecasts, project lifespan assessments, freight demands, and discount rates, all of which could reduce the efficiency and accuracy of the project (Dharmadhikari et al., 2016; Korytárová & Papežíková, 2015).

In addition, the performance of BCA can be affected by analysts' decision criteria, especially when attempting to quantify metrics that are not easily monetized, including willingness to pay, the extent of displeasure, and mitigation costs. Personal judgment and experience, as well as the design of rigorous questionnaires or the choices of factors, play a significant role in these approaches, which might make them susceptible to bias, uncertainty, and human error. Finally, another challenge is the tendency to overlook transparency after decisions are made. It is crucial for the infrastructure options selected by evaluators to be publicly disclosed, recognized, and accepted to prevent potential opposition that could cause delays or rejections (Leleur et al., 2007). As a result, the outcomes of such research may not be interpretable, comparable, accessible, or applicable to new transportation systems or different scenarios.

To address all the above issues, it is necessary to develop a rigorous and structured LBCA that can better estimate the long-term impacts of a project while maintaining the attainability and robustness of the analysis. Our approach involves analyzing the life cycle of transportation infrastructure and equipment and identifying a comprehensive range of metrics to evaluate overall impacts, including economic, environmental, and social aspects, throughout various stages of the project's lifespan. By conducting a comprehensive LBCA, we can ensure that the impacts of transportation projects are accurately estimated and can be effectively compared to other potential projects or scenarios.

3. Proposed LBCA framework and calculation procedures

In attempting to embrace all potential benefits and costs that can emerge over the life cycles of transportation projects, we sort the components using two similar but slightly different groupings of life-cycle stages: the life cycle of the infrastructure and the life cycle of the transportation equipment. The LCA of the infrastructure consists of five stages: (1) extraction, processing, or manufacturing, (2) construction, (3) operation, (4) maintenance and upgrading, and (5) end-of-life and recycling. For the LCA of transportation equipment, the stages are (1) extraction or processing, (2) manufacturing, (3) operation, (4) maintenance and upgrading, and (5) end-of-life and recycling. The differences between the LCA of infrastructure and that of equipment lie in the first and second stages for the following reasons: For the LCA of infrastructure, we combined the extraction, processing, and manufacturing of materials or parts into the first stage and defined *construction* as a separate second stage. The construction stage is a significant part of the infrastructure life cycle, including land transformation processes, machinery operations, and activities required to build railroads, civil engineering structures, systems, land occupation, and traffic. On the other hand, for equipment, such as railcars, locomotives, loaders, trucks, and containers, the manufacturing and assembly of equipment parts are separated from the material extraction and processing in the first stage. We defined *manufacturing* as the second stage, as this is the important stage in the equipment lifecycle rather than construction. The definition of infrastructure can cover several things, such as road surfaces, foundations, bridges, tunnels, tracks, stations, electrification, signaling, communication systems, and so on. For transportation equipment, highway transportation includes tractors and trailers while railroad transportation systems include locomotives and railcars. Figure 1 illustrates all the associated activities in the life cycles of highway and railroad infrastructures and equipment.

To estimate the national benefits and costs for transportation projects, our value-based year is 2020. To better see the investment needs that align with the annual budget, we evaluated life-cycle benefits and costs over a 35-year analysis period of highways and railroads using annual worth, which is called the equivalent uniform annual cost (EUAC). When utilizing the present value, it is necessary to apply a 7% discount rate, as recommended by the U.S. Department of Transportation (USDOT, 2022) for conducting BCA. Since this work is nationwide scale, we multiply the cost per mile by the total mileages of each transportation mode and then divide by the annual 2020 freight ton-miles carried by each transportation mode as represented in Equation (1). Equation (1) will be used throughout this paper to estimate the EUAC of all the metrics.

$$EUAC = \frac{unit\ cost\ per\ mile \times mileage\ of\ the\ systems}{ton - miles\ of\ freight} \quad (1)$$

Due to the factors discussed above in the literature review and defined life-cycle stages, we have researched and assessed the currently available data, and we propose the following five LBCA metrics, including land use, initial construction, operating, environment, and social metrics.

3.1. Land use metric

This metric compares the highway and rail surface land acreage and the right-of-way (ROW) needed by either mode to meet their transportation requirements. The ROW includes the travel lane, shoulder, sidewalk area, and other public spaces that extend beyond the paved road, including areas for public utilities such as electrical power lines, sewer lines, and drainage systems. If no ROW exists for transportation infrastructure construction, land and ROW need to be acquired. For highway ROW, the FHWA indicates that new interstate roads require a ROW width of 150 to 300 feet or more for a 4-lane divided highway. In contrast, a generation ago, a 2-lane highway with a narrow shoulder and often a deep ditch beyond it needed a ROW of just 50 to 75 feet (Federal Highway Administration, 2017). Similarly, the 2024 Roadway Design Manual published by the North Carolina Department of Transportation specifies that the ROW width for a four-lane section typically ranges from 250 to 300 feet for rural projects and 150 to 200 feet for urban projects (North Carolina Department of Transportation, 2024). For railroad ROW, the Missouri Department of Transportation (2024) indicates that railroads typically require a minimum ROW width of 100 feet, centered on the main track centerline, to operate effectively. Similarly, the Wisconsin Department of Transportation's Facilities Development Manual (Wisconsin Department of Transportation, 2019) notes that railroad right of way is often 100 feet wide, generally split as 50 feet on each side of a single track or 25 feet outside of multiple tracks.

The land use cost can be quantified using the land value factor up by the size of the area required for each project. The recent land value estimation published by the Bureau of Economic Analysis was conducted by Larson (2015), using data from 2000 to 2009. The total land values in 2009 were estimated to be worth \$23 trillion for approximately 1.89 billion acres across the U.S., which equals \$12,169.31 per acre. This includes ecosystems (root systems such as alfalfa), basic siting improvements (fencing, irrigation, and land clearing), property value (households, businesses, and government), and land natural resources (timber, water, hunting, and fishing rights) (Larson, 2015). This estimated value is parcel-level data (at the census tract), allowing the land area analysis by ownership sectors. The 2009 land value corresponds to a more recent study conducted by Nolte (2020), which introduces high-resolution maps depicting private land value. This study not only incorporates parcel-level data on ownership, price, and demographics, as previous research has done, but also factors in additional elements such as building footprints, terrain, accessibility, land cover,

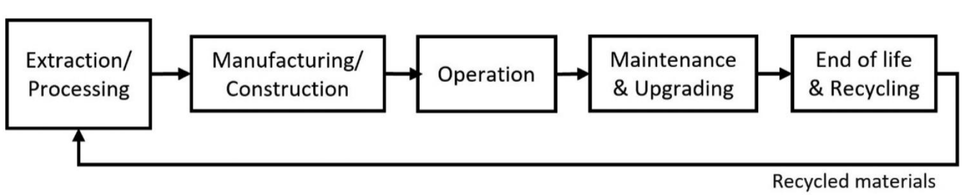

Figure 1. Life cycle of railroads and highway infrastructure and equipment.

hydrography, and flood risk and protection. Since the values from both years are consistent and similar, we can assume that the 2009 land value estimated by Larson (2015) at $12,169.31 per acre remains valid for the year 2020, without the need for adjustment due to inflation rates.

The cost of ROW is shared among road users, including passenger cars, public transportation, and commercial transport vehicles, as they all utilize the same road space. Therefore, the cost will be divided and shared based on the space taken by each vehicle, which is measured in PCE (Passenger Car Equivalent). We based the cost responsibility of trucks on the case study of North Carolina's highway infrastructure, as outlined in the research of Hasnat et al. (2021). Starting from this juncture in the research, we will denote this concept as "truck cost allocation," encompassing vehicles ranging from Class 8 (i.e. 4AST or fewer axles with a single trailer) to Class 13 (i.e. 7AMT for seven or more axles with multi-trailers), in accordance with the FHWA vehicle classification system. After applying the truck cost allocation of 7.08% for ROW costs (Hasnat et al., 2021) to the present land value of $12,169.31 per acre, we obtained the land value of $862 per acre for the highway system.

In estimating the EUAC over a 35-year analysis period for highways and railroads, we begin by converting the present land value of $862 per acre using a 7% real discount rate, as recommended by the DOT for BCA analysis (U.S. Department of Transportation (USDOT), 2022). This results in an EUAC of $66.54 per acre per year across the 35-year lifecycle. Moving forward, we determine the required ROW area for each mode of transport. Assuming a standard width of 75 feet per lane (equivalent to 0.0142 miles per lane) for highways, we calculate an area requirement of 9.09 acres per lane mile by converting 0.0142 miles to space using a factor of 640. This estimation doesn't encompass auxiliary facilities like parking and gas stations; we consistently account for such aspects across research metrics. Consequently, the annual land cost is computed at $604.9 per lane mile or $1,209.89 per mile for a two-lane, single-way highway. Extending this assessment to the nation's freight volume, we multiply the $1,209.89 per mile by the total length of the U.S. national highway system of 161,188 miles (Federal Highway Administration, 2000) and divide by the total ton-miles transported by trucks in 2020 of 2,233,588,364,732 ton-miles (Bureau of Transportation Statistics, 2022a). This yields an EUAC of $0.000085 per ton-mile for a two-lane, single-way highway and $0.00017 per ton-mile for the four-lane, two-way national highway system.

In scenario two, with the U.S. highway freight system at its peak capacity of 12,943,396,400,000 ton-miles, as computed in Appendix A, the allocation of truck costs for the ROW expenditure would increase from 7.08% to 30.63%. This shift is based on the premise of escalating the annual highway volume from 2,233,588,364,732 to 12,943,396,400,000 ton-miles while retaining the passenger vehicle volume at its existing level. Consequently, the annual cost of land value per mile for a two-lane highway surges to $5,234.25. Analogous to the scenario involving the actual freight volume, this cost is multiplied by the length of the national highway system and then by 2 to account for the transformation from a two-lane, single-way configuration to a four-lane configuration, after which it's divided by the estimated ton-mile of maximum flow. The resultant calculation yields an EUAC for land use in the context of maximum flow, amounting to $0.00013 per ton-mile.

To estimate EUAC attributed to land value for railroads, we employed the same national land value of $12,169.31 per acre, while excluding train cost allocation considerations due to Class I railroads' ownership and operation of their freight railroad infrastructure. Assuming a 100-foot-wide railroad ROW (equivalent to 0.0189 miles), we determined a requirement of 12.12 acres per mile, excluding considerations for auxiliary facilities, terminals, bridges, and the like. After converting the national land value to an EUAC, the resulting EUAC for railroad land value was calculated at $940 over 35 years. By multiplying the 12.12-acre ROW area by the land value cost of $940 per acre, the EUAC land value amounted to $11,393 per mile. Extendingthis assessment to the nation's railroad freight volume, the $11,393 per mile value was multiplied by the Class I network road mileage, 92,190 miles (Association of American Railroads, 2021) and divided by the total ton-miles moved by railroads in 2020, 1,439,814,000,000 ton-miles (Bureau of Transportation Statistics, 2022b), resulting in an estimated EUAC for land use specific to the mainline railroad context of approximately $0.00073 per ton-mile.

Similarly, the EUAC cost per ton-mile can be determined by calculating the land value cost of $11,393 per mile, multiplying it by the Class I network road mileage of 92,190 miles, and then dividing the result by the estimated maximum flow of 24,059,285,250,000 ton-miles as computed in Appendix A. Consequently, the EUAC for land use in the context of maximum flow is assessed at $0.00004 per ton-mile for the mainline.

3.2. Initial construction metric

This measures factors affecting the capital costs of building transportation infrastructure, including material, labor, equipment, energy, land transformation, and related construction activities. The Washington State Department of Transportation published the national average construction cost of $2.3 million per lane mile of a 1.02-mile diamond interchange project (Washington State Department of Transportation, 2002). This cost captures new alignments of four-lane structures, surfacing, paving, barriers, and pavement striping. We converted this 2002-dollar value into a 2020-dollar value by using the National Highway Construction Cost Index (NHCCI) 2.0 provided by Federal Highway Administration (2020). The result is $4,713,047 per lane mile in 2020 dollars. We validated this national average cost with the 2024 estimated cost published by FDOT. According to FDOT, the cost for the new construction of a divided 4-lane rural interstate with 10′ paved outside shoulders and 4′ inside shoulders is $10,097,170.21. For the new construction of a divided 4-lane urban interstate with a closed

22′ median and barrier wall, with 10′ shoulders inside and outside, the cost is $20,646,066.98. In our research, we estimated the cost to be $4,713,047 per lane mile. Converting this to a 4-lane divided interstate, the total cost is $18,852,188, which falls within the range of FDOT's estimates.

Then, we account for the cost allocation for trucks based on Hasnat et al. (2021), which state that trucks account for 35.87% of interstate new pavement construction costs. It is worth noting that this cost allocation is much higher than the cost allocation for land value. The logic for this comes from the impacts that trucks and other vehicles have on the infrastructure. For ROW, the cost allocation is based only on space taken by vehicles (PCE). However, for construction cost allocation, Hasnat et al. (2021) also consider the fact that heavy-duty trucks have a higher rate of deterioration in highway conditions. After applying this percentage, we obtained $1,690,570 per lane mile or $3,381,140 for a two-lane, one-way highway. After distributing this cost over 35 years using a 7% discount rate, the EUAC of initial construction is estimated to be $261,139 per mile. The EUAC of initial construction per ton-mile across the nation's freight volume for highways is estimated by multiplying this EUAC of initial construction of $261,139 per mile by the total length of national highways at 161,188 miles and dividing by the total ton-miles of fright transported by trucks of 2,233,588,364,732 in 2020. Then, we double this result to derive the EUAC of initial construction of $0.0377 ton-mile for a four-lane, two-way highway.

To calculate the initial construction cost for the estimated maximum flow case, we recalculated the cost allocation for trucks by proportioning it with the estimated maximum freight volume. We obtain the cost allocation for new pavement construction cost which is increased from 35.87% to 76.42% compared to the actual flow given passenger vehicle volume remains the same. Consequently, the EUAC of initial construction of $261,139 per mile increased to $556,364 per mile for the maximum flow. Then, we estimate the EUAC of initial construction under maximum flow by multiplying the cost of $556,364 per mile by the total mileage of 161,188 miles and divided by the estimated maximum flow of 12,943,396,400,000 ton-miles. Then, we double the result to account for a four-lane, two-way highway system, resulting in $0.0139 ton-mile.

In most cases, ongoing roadway construction results in a partial or full road closure, which will cause delays, travel route change, increased risk of accidents, etc. The road user costs (RUC) quantifies the impacts of the construction for road users, including the increase of fuel cost, maintenance cost, tire wear cost, crash cost, depreciation cost, and finance charges. In addition, it also leads to the local impact cost which includes reduced business revenue in surrounding areas, and increased congestion of linked road networks. However, this cost is considered an indirect cost and generally neglected by state DOTs because of the complexity and intensive use of resources. The Tennessee DOT suggested including RUCs in the calculation method instead of only focusing on direct construction costs while appraising the best bidder. To determine whether RUCs should be included in contracts, the following criteria are ranked in descending order of influencing decision-making: the location, duration, complexity, and dollar value of the project (Shrestha et al., 2021). State DOTs tend to calculate the RUCs for high-traffic urban projects and projects that need to be completed in a short time to minimize impacts on road users (Shrestha et al., 2021). They conclude the daily RUC of $50,162.27 per day based on a case study in Sullivan County in Tennessee with a Length of work zone of 0.75 miles and a total highway of 5.37 miles. Using A + B contract evaluation, the daily RUC times the number of days to complete the construction which is the RUC of this specific project added to the estimated construction cost is estimated to be 237.53% of the construction cost. However, we cannot integrate this cost into our initial construction cost metric due to the national scale of the project which makes us unable to identify the length of construction sites across the US highway system. We suggest that when practitioners apply our construction cost to their project, they should calibrate for this RUC adding to the construction cost only if they consider the project of building a new highway. To derive RUC for a project, analysts need to provide specific information for their construction zone, speed limit, original route length, detour length, and other traffic characteristics. The calculation procedure and tool can be found in the research of Shrestha et al. (2021).

As for freight railroad infrastructure in the United States, construction costs have not been widely disclosed. Blaze (2020) reported a construction cost of $3.5 to $4.5 million per mile for a single-track main line and an additional $1 to $1.5 million per mile to build a parallel second main track. The cost is roughly estimated from the costs of rails, ties, ballast, sub-compaction, and grading. Note that building a completely new track has greater costs than the common case in real situations, which is building new parallel tracks beside the existing tracks. However, this study considers only single-track lines based on the assumption that our LBCA compares new infrastructure construction projects. After distributing a single-track construction cost of $4 million over 35 years, the EUAC of mainline construction is estimated to be $308,936 per mile with a discount rate of 7%. We multiply this cost by the class I miles of road, which is 92,190 miles, and divide it by the actual ton-miles or estimated ton-miles, which are 1,439,814,000,000 and 24,059,285,250,000, respectively, to calculate the EUAC for the initial construction, resulting in $0.01978 per ton-mile for actual flow and $0.00118 per ton-mile for estimated maximum flow.

3.3. Operating metrics

These metrics encompass factors that influence operating costs and have impacts on the utilization and upkeep of transportation infrastructure and equipment. We have segmented this metric into six elements encompassing both benefits and costs: energy, labor, and administrative expenses, maintenance of transportation infrastructure, end-of-life infrastructure valuation, equipment expenditures, and maintenance of transportation equipment.

3.3.1. Energy

The cost associated with diesel fuel or energy used for transporting goods is a significant factor. According to a Texas A&M Transportation Institute report (Kruse et al., 2022), average fuel efficiencies were reported as 151 ton-miles per gallon for freight trucks and 472 ton-miles per gallon for freight railroads in 2019 at the national level. The fuel efficiency for trucks is based on combination truck data at the national level, as indicated in the BTS report. This is under the assumption of a truckload weighing 25 tons and maintaining the same speed on the empty return trip. Rail efficiency is drawn from national-level data primarily derived from the R-1 reports of the Surface Transportation Board (STB) and partially from sources within the railroad industry and the Securities and Exchange Commission. For the analysis, the average weekly diesel price from the U.S. Energy Information Administration (2022) was taken as $4.5 per gallon in 2022. With these inputs, we can proceed to calculate the EUAC of energy per ton-mile as follows:

$$EUAC_{HW}\ of\ energy = \frac{avg\ fuel\ efficiency}{fuel\ prices} = \frac{4.5(\ \$/gallon)}{151(ton - miles/gallon)} = 0.0298(\ \$/ton - mile) \tag{2}$$

$$EUAC_{RR}\ of\ energy = \frac{4.5(\ \$/gallon)}{472(ton - miles/gallon)} = 0.0095(\ \$/ton - mile) \tag{3}$$

For this metric, we cannot provide the estimation of EUAC for the maximum flow scenario due to the lack of resources. New fuel consumption under the maximum flow scenario needs to be identified because it will vary depending on new traffic and operating characteristics such as operating weight, moving speed, and the fuel efficiency of vehicles.

3.3.2. Labor and administration

This metric assesses the labor and administrative costs associated with delivering the necessary transportation service, encompassing employee salaries, wages, and benefits. According to the American Transportation Research Institute (ATRI) (Leslie & Murray, 2021), the average compensation for drivers, including wages and benefits, amounted to $0.737 per mile in 2020. Respondents were able to choose benefits from a range of categories, such as health insurance, paid vacation, 401K, dental insurance, paid sick leave, vision insurance, and per diems. Notably, this figure does not encompass performance-based bonuses designed to attract talent, enhance safety practices, and improve driver retention. In order to compute the EUAC of driver compensation per ton-mile, we multiply the mean driver compensation per mile of $0.737 by the total truck vehicle miles, thereby establishing the total costs for the year 2020. We then divide this result by the total truck freight ton-miles for the year 2020. Consequently, the average driver compensation per ton-mile for the specific scenario in 2020 stands at $0.0997. Moreover, for the scenario of maximum flow—assuming that truck flows reach highway capacity—the corresponding value is calculated to be $0.0369. These numerical values are derived through the subsequent calculations:

$$\begin{aligned} &Actual\ EUAC_{HW}\ of\ L\&A\ for\ actual\ flow \\ &= \frac{driver\ compensation \times truck\ vehicle\ miles}{ton - miles} \\ &= \frac{0.737(\ \$/mile) \times 302,141,000,000(mile)}{2,233,588,364,732(ton - miles)} \\ &= 0.0997(\ \$/ton - mile) \end{aligned} \tag{4}$$

$$\begin{aligned} &Estimated\ EUAC_{HW}\ of\ L\&A\ for\ maximum\ flow \\ &= \frac{driver\ compensation \times estimated\ truck\ vehicle\ miles}{estimated\ ton - miles} \\ &= \frac{0.737(\ \$/mile) \times 698,943,405,600(mile)}{12,943,396,400,000(ton - miles)} \\ &= 0.0369(\ \$/ton - mile) \end{aligned} \tag{5}$$

The average L&A cost during maximum truck flows in 2020 is notably 63% lower compared to actual flows, primarily due to the significantly higher truckload of 20 tons in the maximum flow scenario as opposed to the actual 7.39 tons. Diverging from truck carriers, railroads exhibit distinct L&A cost dynamics stemming from their lack of infrastructure ownership, exempting them from direct highway management expenses. Instead, railroads are encumbered by covering train conductor labor outlays and infrastructure management expenditures, with the operating costs outlined in the R-1 report (Surface Transportation Board, 2022). Using the BNSF R-1 report as an exemplar for Class I railroads, the calculated annual L&A cost amounted to $7,343,009,000 for 2020. Notably, depreciation costs were excluded from this figure due to their non-cash flow nature, having been estimated primarily for tax purposes. Similar to the highway cost methodology, the EUAC under actual flow conditions, denoted in dollars per ton-mile, is computed by dividing the total annual cost by the annual ton-miles:

$$\begin{aligned} &Actual\ EUAC_{RR}\ of\ L\&A\ for\ actual\ flow \\ &= \frac{BNSF\ labor\ and\ administration\ cost}{BNSF\ ton - miles} \\ &= \frac{7,343,009,000(\ \$/\mathrm{year})}{588,919,405,000(ton - miles)} = 0.0125(\ \$/ton - mile) \end{aligned} \tag{6}$$

If we assume the railroad flows reach the BNSF maximum capacity (estimated in Appendix A), the average L&A cost per ton-mile for railroads in 2020 is estimated at $0.0369 based on the following calculation. Again, the average L&A cost under maximum flows for railroads is about

70.86% lower than that under actual flows in 2020 because each train carries more tons under the maximum flow scenario.

$$\begin{aligned}&\textit{Estimated } EUAC_{RR} \textit{ of L\&A for maximum flow}\\&= \frac{\textit{BNSF labor and administration cost}}{\textit{estimated BNSF ton} - \textit{miles}}\\&= \frac{7,343,009,000(\ \$/\textit{year})}{5,841,664,400,000(\textit{ton} - \textit{miles})}\\&= 0.0013(\ \$/\textit{ton} - \textit{mile}) \qquad (7)\end{aligned}$$

3.3.3. Maintenance of transportation infrastructure

This metric quantifies the cost of maintenance necessary to ensure the continued viability and safety of freight transportation, encompassing both material purchases and labor during the maintenance process. According to the ADOT's Roadway Maintenance Costs Report (Maricopa Association of Governments, 2019), the national average maintenance cost stood at $28,020 per lane mile in 2015. This nationwide cost encompasses maintenance activities on interstates, freeways, highways, bridges, landscaping, lighting, and more. We adjusted this 2015 cost to 2020 using a 4% inflation rate, resulting in an EUAC of $34,091 per lane mile for highways. For truck in-house maintenance cost allocation based on load-related expenses, Class 8 to Class 13 trucks accounted for an estimated 88.33% of the total interstate maintenance costs (Hasnat et al., 2021). These total costs were gathered from 2014 to 2017 for maintenance work performed by the NCDOT, covering activities such as asphalt overlay, patching, grading, drainage, shoulder repair, pavement markings, landscaping, sealing, slope protection, traffic control devices, ITS setup, and more (Hasnat et al., 2021). It's crucial to note that this in-house maintenance cost does not encompass external maintenance for major projects that involve contractors. By multiplying the EUAC of maintenance, $34,091 per lane mile, by the 88.33% cost allocation for trucks, we obtain an EUAC of truck maintenance cost at $30,112 per lane mile or $60,224 per mile for a two-lane highway. To convert this per mile cost into per-ton-mile cost, we must multiply it by the system's length and divide it by annual ton-miles:

$$\begin{aligned}&\textit{Actual } EUAC_{HW} \textit{ of infrastructure maintenance for actual}\\&\textit{flow} = \frac{\textit{annual maintenance cost} \times \textit{national highway system}}{\textit{ton} - \textit{miles in } 2020}\\&= \frac{60,224(\ \$/\text{mile}) \times 2 \times 161,188(\textit{mile})}{2,233,588,364,732(\textit{ton} - \textit{miles})}\\&= 0.0087(\ \$/\textit{ton} - \textit{mile}) \qquad (8)\end{aligned}$$

As with any calculations involving truck cost allocations, the cost allocation will be increased from 88.33% to 97.93% when using maximum flow highway volume, assuming passenger vehicle volume remains the same. Therefore, the annual maintenance of transportation infrastructure cost per mile for a two-lane highway increased to $66,661 and EUAC of maintenance cost can be assessed as follows:

$$\begin{aligned}&\textit{Estimated } EUAC_{HW} \textit{ of infrastructure maintenance for}\\&\textit{maximum flow}\\&= \frac{\textit{annual maintenance cost} \times \textit{national highway system}}{\textit{estimated ton} - \textit{miles}}\\&= \frac{66,661(\ \$/\text{mile}) \times 2 \times 161,188(\textit{mile})}{12,943,396,400,00(\textit{ton} - \textit{miles})}\\&= 0.0017(\ \$/\textit{ton} - \textit{mile}) \qquad (9)\end{aligned}$$

For railroad maintenance costs, we sourced the BNSF annual repair and maintenance expenditure, totaling $2,788,492,000, from the 2020 R-1 report (Surface Transportation Board, 2022). Maintenance costs encompass various elements, including wages, materials, tools, supplies, and fuel. We then divided this figure by BNSF's ton-miles in 2020, which amounted to 588,919,405,000. This calculation yielded an EUAC of $0.0047 per ton-mile for freight railroads. In the case of maximum capacity operations, we lack data regarding potential increases in maintenance costs as we handle higher loads. Consequently, we assume that railroad maintenance costs will remain consistent with those of the actual scenario, which stands at $0.0047 per ton-mile.

$$\begin{aligned}&\textit{Actual } EUAC_{RR} \textit{ of infrastructure maintenance}\\&= \frac{\textit{annual maintenance cost}}{\textit{BNSF ton} - \textit{miles in } 2020}\\&= \frac{2,788,492,000(\ \$/\text{year})}{588,919,405,000(\textit{ton} - \textit{miles})} = 0.0047(\ \$/\textit{ton} - \textit{mile}) \qquad (10)\end{aligned}$$

3.3.4. End of life infrastructure value

This metric assesses the remaining value of transportation infrastructure after a 35-year analysis period, based on its functional life. The FHWA recommends a minimum 35-year life-cycle cost analysis period for new and repaired pavement projects (Walls & Smith, 2018). However, the DOT's BCA guidance suggests that analysts limit the analysis scope to no more than 30 years and consider the remaining useful life when assets have lifetimes exceeding 35 years (USDOT, 2022). This shorter threshold is recommended because, in later years, the present value diminishes significantly due to discount rates and long-term cash flow predictions carry greater uncertainty, potentially affecting analysis credibility. Considering both recommendations, we have chosen a 35-year useful life for transportation infrastructure and determined the remaining useful life at the analysis period's end. FHWA suggests calculating the salvage value based on the assumption that the remaining life of a transportation asset reflects a prorated cost of the last rehabilitation expenses (Walls & Smith, 2018). FHWA's major rehabilitation costs, as reported by Transportation for America (2019), were $471,071 per lane mile for concrete and $211,761 for asphalt in 2017 dollars, gathered from six states, including California, Kansas, Michigan, Minnesota, Texas, and Washington. According to Sullivan (2006), 60% of the US highway interstate system consists of concrete. However, this doesn't apply to other road types primarily paved with asphalt. Therefore, we have decided to utilize the average cost between these two road types, which is $341,416 per lane mile. Converting this value to 2020 dollars with a 4% inflation rate, we have an average rehabilitation cost of $384,047. Assuming the last rehabilitation occurs in the 30th year, and the analysis period concludes at 35 years, the infrastructure's remaining life is 10 years, assuming that rehabilitation extends the end-of-life period by 15 years. Consequently, the salvage value can be calculated as $384,047 $\times$ 10/15 = $256,031 per lane mile at the end of the lifecycle. By calculating the EUAC of the salvage value using a 7% discount rate, we determine that the annual salvage value over 35 years is $19,774.3 per lane mile applying a 7% discount rate. Given that we are considering a four-lane, two-way highway system, we multiply this value per lane mile by 4 to obtain the total salvage cost per mile for our analyzed system. Subsequently, we can evaluate the actual EUAC of salvage value in dollars per ton-mile using the following formula:

$$\begin{aligned} &Actual\ EUAC_{HW}\ of\ infrastructure\ salvage\ value \\ &= \frac{annual\ salvage\ value \times national\ highway\ system}{ton-miles\ in\ 2020} \\ &= \frac{19,774.3(\ \$/\text{lane-mile}) \times 4(\text{lane}) \times 161,188(mile)}{2,233,588,364,732(ton-miles)} \\ &= 0.005708(\ \$/ton-mile) \end{aligned} \tag{11}$$

In the scenario of maximum capacity, there is a lack of data regarding deterioration rates or any potential increase in the frequency of rehabilitation when trucks carry heavier loads. Consequently, we assume that the salvage value will remain consistent with that of the actual scenario.

For determining railroad salvage value, we utilize annual rail depreciation data from the 2020 BNSF R-1 report (Surface Transportation Board, 2022). At the beginning of 2020, the depreciation cost was $55,643,790,000, and at the end of the year, it amounted to $57,024,412,000. The difference between these values is $1,380,622,000. Dividing this by BNSF's route-miles gives us $1,380,622,000/22,384 = $61,679 per route-mile per year. Employing the straight-line depreciation method, we calculate the initial construction cost minus the total salvage value over 35 years as $4,000,000—$61,679 $\times$ 35 years). Consequently, the salvage value of the railroad infrastructure at the end of its lifecycle is $1,841,236 per route-mile. To determine the annual worth, considering the future worth (salvage value at the end of the 35th year), the EUAC of salvage value after 35 years amounts to $13,319.4 per route-mile in present value, with a 7% discount factor. Finally, we compute the EUAC of salvage value (SV) in dollars per ton-mile using the following formula:

$$\begin{aligned} &Actual\ EUAC_{RR}\ of\ infrastructure\ salvage\ value \\ &= \frac{annual\ salvage\ value}{BNSF\ ton-miles\ in\ 2020} \\ &= \frac{13,319.4(\ \$/\text{route-mile}) \times 22,384(\text{route-miles})}{588,919,405,000(ton-miles)} \\ &= 0.000506(\ \$/ton-mile) \end{aligned} \tag{12}$$

Similar to the scenario of maximum capacity described earlier, we lack data on the potential deterioration rate and increased rehabilitation frequency resulting from higher loads. Consequently, we assume that in the estimated maximum flow case, the depreciation cost remains constant, resulting in the same salvage value of $0.000506 per ton-mile. It's important to note that the current depreciation cost is influenced by aging infrastructure and the operation of trains. Thus, BNSF's annual depreciation may appear higher compared to the calculation for a new project with fresh infrastructure and equipment. This assumption suggests that the additional payload does not significantly accelerate equipment deterioration and is primarily intended for rough estimations. Furthermore, the annual depreciation used here stems from the existing infrastructure currently in use, which may age over time, resulting in higher depreciation costs. An alternative perspective should consider market costs and the value of road and track materials, encompassing factors like sales commission, demolition activities, disposal, and environmental remediation. Asset value can be derived from recycling for on-site infrastructure reconstruction (e.g. recycling concrete, gravel, and sand as structural fill, reusing recycled asphalt for new roads, and re-laying unused rails) or considered as a market disposition value. In the latter case, the adaptability of end-of-life assets should be taken into account (e.g. repurposing ties as biomass fuel chips for waste-to-energy plants or using them as landscaping timbers, and converting scrap metal into new products). The promotion of reuse and recycling initiatives plays a crucial role in reducing environmental impacts, including waste in landfills, the extraction of new materials, pollution, energy consumption, and more.

3.3.5. Transport equipment

The transport equipment metric encompasses expenses related to leasing and purchasing various transportation assets such as trucks, containers, locomotives, rail cars, and more. These costs may involve license fees, registration, insurance, and taxes. Transportation services' insurance costs encompass essential coverage for injuries, property damage, and hazardous material spills, with rates influenced by factors like commodity type, shipment volume, susceptibility to loss, special transportation methods, and others. The cost breakdown for a truck includes lease or purchase expenses of $0.271 per mile, truck insurance at $0.087 per mile, truck permits and licenses amounting to $0.016 per mile, and tolls totaling $0.037 per mile, as reported by Leslie and Murray (2021). These figures were obtained from respondents to the ATRI's survey for for-hire fleets. By multiplying the \$0.411 per mile by the truck vehicle miles of 302,141,000,000 in 2020 (Bureau of Transportation Statistics, 2022c) and subsequently dividing it by the total truck freight ton-miles of 2,233,588 million in 2020 (Bureau of Transportation Statistics, 2022a), we derive the EUAC transport equipment cost of \$0.056 per ton-mile as follows:

$$\begin{aligned} &Actual\ EUAC_{HW}\ of\ equipment \\ &= \frac{equipment\ cost \times truck\ VMT}{ton-miles\ in\ 2020} \\ &= \frac{0.411(\$/\text{mile}) \times 302,141,000,000(mile)}{2,233,588,364,732(ton-miles)} \\ &= 0.056(\$/ton-mile) \end{aligned} \tag{13}$$

In scenarios of maximum flow, we assume an increase in average truck loads to 20 tons, resulting in the following EUAC transport equipment cost:

$$\begin{aligned} &Estimated\ EUAC_{HW}\ of\ equipment \\ &= \frac{equipment\ cost \times estimated\ VMT}{estimated\ ton-miles} \\ &= \frac{0.411(\$/\text{mile}) \times 698,943,405,600(mile)}{12,943,396,400,00(ton-miles)} \\ &= 0.021(\$/ton-mile) \end{aligned} \tag{14}$$

The railroad transport equipment cost was determined using the total annual equipment cost of \$2,117,493,000 from the 2020 BNSF R-1 report (Surface Transportation Board, 2022). This cost was employed to calculate the EUAC transport equipment costs for railroads, considering both actual ton-miles and maximum flows, through the following equations:

$$\begin{aligned} &Actual\ EUAC_{RR}\ of\ equipment \\ &= \frac{annual\ equipment\ cost}{BNSF\ ton-miles\ in\ 2020} \\ &= \frac{2,117,493,000(\$)}{588,919,405,000(ton-miles)} \\ &= 0.0036(\$/ton-mile) \end{aligned} \tag{15}$$

$$\begin{aligned} &Estimated\ EUAC_{RR}\ of\ equipment \\ &= \frac{annual\ equipment\ cost}{estimated\ BNSF\ ton-miles} \\ &= \frac{2,117,493,000(\$)}{5,841,664,400,000(ton-miles)} \\ &= 0.0004(\$/ton-mile) \end{aligned} \tag{16}$$

3.3.6. Maintenance of transport equipment

This encompasses maintenance costs necessary for ensuring the viability and safety of freight transportation equipment. In 2020, the repair and maintenance cost for trucks was \$0.195 per mile, while tire costs amounted to \$0.043 per mile, as reported by Leslie and Murray (2021). Consequently, the total cost sum equaled \$0.238 per mile. The study included data from 138,930 truck-tractors, which collectively covered a distance of over 12 billion vehicle miles traveled (VMT) and maintained an average fleet size of 1,130 power units nationwide. To calculate the EUAC for transport equipment costs, we multiplied this unit cost by the truck vehicle miles of 302,141,000,000 in 2020 (Bureau of Transportation Statistics, 2022c) and then divided it by the total truck freight ton-miles of 2,233,588 million in 2020 (Bureau of Transportation Statistics, 2022a). Given the absence of data regarding truck deterioration rates under higher truckloads, we assume that the truck maintenance cost remains constant, matching the actual case at \$0.0322 per ton-mile.

$$\begin{aligned} &Actual\ EUAC_{HW}\ of\ equipment\ maintenance \\ &= \frac{maintenance\ cost \times truck\ VMT}{ton-miles\ in\ 2020} \\ &= \frac{0.238(\$/\text{mile}) \times 302,141,000,000(mile)}{2,233,588,364,732(ton-miles)} \\ &= 0.0322(\$/ton-mile) \end{aligned} \tag{17}$$

Regarding railroads' equipment repair and maintenance cost, we rely on the value of \$630,353,000 calculated from Schedule 410 in the 2020 BNSF R-1 report (Surface Transportation Board, 2022). This figure includes the costs of repair, maintenance, inspection, lubrication, and cleaning of locomotives, freight cars, and other equipment such as trailers, containers, and computers and data processing equipment. For the maximum flow scenario, we adopt a similar assumption to the truck maintenance cost, assuming that the value remains consistent with the actual flow case. The EUAC of equipment maintenance costs is estimated using the following equation:

$$\begin{aligned} &Actual\ EUAC_{RR}\ of\ equipment\ maintenance \\ &= \frac{annual\ maintenance\ cost}{BNSF\ ton-miles\ in\ 2020} \\ &= \frac{630,353,000(\$)}{588,919,405,000(ton-miles)} = 0.0011(\$/ton-mile) \end{aligned} \tag{18}$$

3.4. Environmental metrics

The environmental impact metric within transportation systems involves a thorough assessment that examines the ecological footprint of multiple factors. This encompasses the analysis of greenhouse gas emissions, criteria air pollutants, releases of toxic substances from hazardous materials, noise pollution, contamination of water and soil, as well as the repercussions for wildlife vitality.

3.4.1. Greenhouse gases

Greenhouse gases (GHGs) consist of emissions generated throughout the lifecycle of transport infrastructure, encompassing construction, operation, maintenance, disposal, and recycling processes. These emissions significantly contribute to global warming. The Interagency Working Group, a collaboration involving the EPA, DOE, and other agencies, conducted an assessment of the social costs associated with GHGs. They projected the monetized impacts of the three major GHGs—carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O)—from 2020 to 2050. These impacts include changes in agricultural productivity, health, property damages due to increased flood risk, and energy system costs. In 2020, the social costs were set at $51 per metric ton for CO2, $1,500 per metric ton for CH4, and $18,000 per metric ton for N2O, considering a 3% discount rate for average impacts (Interagency Working Group, 2021). Fluorinated gases (e.g. HFCs, PFCs, SF6, and NF3) constitute the fourth GHG category according to the U.S. Environmental Protection Agency (2021), yet they contributed only 3% of total GHG emissions in 2020 (U.S. Environmental Protection Agency, 2021). Due to limited research on their emission rates and social costs, we have excluded these gases from our analysis.

To calculate transportation emission costs, knowledge of emission rates is essential. Emission factors for medium- and heavy-duty trucks stand at 211 grams per ton-mile for CO2, 0.002 grams per ton-mile for CH4, and 0.0049 grams per ton-mile for N2O (U.S. Environmental Protection Agency, 2021). Rail emissions factors are 22 grams per ton-mile for CO2, 0.0017 grams per ton-mile for CH4, and 0.0005 grams per ton-mile for N2O (U.S. Environmental Protection Agency, 2021). With this data, we determine the GHG costs for both transportation modes in 2020 using the following equations:

$$\begin{aligned} GHGs\ \text{Cost}_{HW} &= \text{summation of } (\text{social costs} \times \text{emission rates}) \\ &= [51(\ \$/metric\ ton) \times 211(grams/ton - miles) \\ &\quad + 1,500(\ \$/metric\ ton) \times 0.002(grams/ton - miles) \\ &\quad + 18,000(\ \$/metric\ ton) \times 0.0049(grams/ton - miles)] \\ &\quad /1,000,000(\text{grams/metric ton}) \\ &= 0.0109(\ \$/ton - mile) \end{aligned} \tag{19}$$

$$\begin{aligned} GHGs\ \text{Cost}_{RR} &= [51(\ \$/metric\ ton) \times 22(grams/ton - miles) \\ &\quad + 1,500(\ \$/metric\ ton) \times 0.0017(grams/ton - miles) \\ &\quad + 18,000(\ \$/metric\ ton) \times 0.0005(grams/ton - miles)] \\ &\quad /1,000,000(\text{grams/metric ton}) = 0.0011(\ \$/ton - mile) \end{aligned} \tag{20}$$

3.4.2. Criteria air pollutants

Criteria air pollutants constitute a group of air pollutants stemming from fuel emissions, known to contribute to smog, acid rain, and various health hazards. As estimated by Kruse et al. (2022), the emission rates of HC or VOC, NOx, PM10, and CO in grams per ton-mile are 0.0221, 0.4487, 0.0191, and 0.1898, respectively, for trucks, and 0.0083, 0.2181, 0.0053, and 0.0564, respectively, for rail transport. Emission factors for VOC, carbon monoxide, nitrogen oxides, and PM10 in locomotive exhaust are classified into eight tiers of emission standards. This categorization is based on the locomotive's original manufacturing year. The Bureau of Transportation Statistics (2021a) provides U.S. average emissions rates per vehicle for the years 2000, 2010, 2020, and 2030 (projected future year), encompassing HC, exhaust CO, exhaust NOx, and exhaust PM2.5, inclusive of brake wear PM2.5, tire wear PM2.5, and other PM2.5.

In terms of PM2.5 emission rates for 2020, heavy-duty vehicles, specifically diesel trucks with more than two axles or four tires, emitted PM2.5 at a rate of 0.106 grams per mile, encompassing brake wear at 0.009 grams per mile and tire wear at 0.004 grams per mile (Bureau of Transportation Statistics, 2021a). To convert the PM2.5 emission rate of 0.106 grams per mile to grams per ton-mile, we multiplied it by the total VMT in 2020 and then divided it by 2020 ton-miles, yielding a heavy-duty vehicle PM2.5 emission rate of 0.0143 grams per ton-mile. In comparison, the industry-average freight rail registered a PM2.5 emission rate of 0.0120 g/short ton-mile in 2018, according to the 2018 Technical Documentation of U.S. Environmental Protection Agency (2018).

As for SOx emission rates, which are originally in tons per VMT, they need to be converted into grams per ton-mile. Truck SOx emission stands at 0.00000002 tons per VMT, equivalent to 0.0025 grams per ton-mile. Meanwhile, rail SOx emission is recorded at 0.00000079 tons per VMT, equating to 0.0002 grams per ton-mile (Kruse et al., 2022). To facilitate this conversion from short tons to grams, a multiplier of 907,185 is applied. Table 2 summarizes emission rates and associated damage costs.

The 2020 monetized damage costs for emissions in 2021 can be primarily derived from the DOT's BCA Guidelines. According to Kruse et al. (2022), these estimates include $15,600 per metric ton for NOx, $41,500 per metric ton for SOx, $748,600 per metric ton for PM2.5, and $2,138 per metric ton for VOC as specified in the DOT guidance. However, the DOT guidance does not provide an economic value for PM10 emissions (USDOT, 2022). As PM10 has relatively minimal health impacts and demands fewer resources for management and emissions control (Y. Lee et al., 2021), it is inappropriate to apply the economic damage value of PM2.5 to PM10, in accordance with the DOT BCA Guidance (USDOT, 2022). To address the scarcity of available data, the social cost factor for PM10 is derived from a New Zealand case study conducted by Kuschel (2022). This study comprehensively examined public health,

Table 2. Emission rates and damage costs of criteria air pollutants.

Mode	Unit	HC/ VOC	SOx	PM2.5	PM10	NOx	CO
Truck	emission rates (g/ ton-mile)	0.0221	0.0025	0.0143	0.0191	0.4487	0.1898
Railroad	emission rates (g/ ton-mile)	0.0083	≈ 0	0.0120	0.0053	0.2181	0.0564
Both	Damage costs ($/ metric ton)	2,138	41,500	748,600	170,663	15,600	1.5

mortality, morbidity, and productivity loss. According to Kuschel's findings, in 2019, the cost of damage associated with PM10 was NZ$503,346 per metric ton in urban areas and NZ$38,480 in rural areas. To facilitate the comparison, these figures are converted to US dollars using an exchange rate of one New Zealand Dollar to 0.63 US Dollars. Consequently, the damage cost for PM10 is determined to be $317,085 per metric ton in urban areas and $24,241 in rural areas. Therefore, this study employs an average damage cost of $170,663 per metric ton for PM10 emissions, calculated by combining the costs from both urban and rural areas. Kuschel (2022) also estimated the CO emission damage cost to be 4.52 NZ dollars per metric ton in urban areas and 0.35 NZ dollars in rural areas. These values equate to $2.85 per metric ton in urban areas and $0.22 in rural areas, or $1.535 per metric ton in US dollars. The damage cost associated with CO emissions is negligible in comparison to other pollutants and will not impact the total cost per ton-mile.

Using a similar approach as in the calculation of GHG social costs per ton-mile, these dollar values per metric ton are converted into dollars per gram and then multiplied by grams per ton-mile to determine the total social cost of criteria pollutants. In summary, the total social cost of criteria pollutants for trucks in 2020 amounts to $0.0213 per ton-mile, while for rail, it stands at $0.0133 per ton-mile in 2020.

3.4.3. Toxic releases

This metric evaluates both unintentional and intentional releases of environmentally harmful transported materials into the air. In 2020, incidents involving the transportation of hazardous materials in commerce resulted in three fatalities, 49 injuries, and property damage costs totaling $26,345,000 (Bureau of Transportation Statistics, 2021b). The unit cost of a fatality stood at $11,295,400 per incident, and an injury incurred a cost of $198,500 per incident (refer to Table 3 in Safety metric). Consequently, the combined cost for fatalities and injuries in highway transportation of hazardous materials in commerce totaled $43,612,700. When considering property damage, fatalities, and injuries, the overall annual cost amounted to $69,957,700. To determine the cost per ton-mile in the actual flow case, we divided this total by the total freight ton-miles in 2020, which were 2,233,588,364,732 ton-miles (Bureau of Transportation Statistics, 2022a). The estimated cost of hazmat incidents and property damages per ton-mile in 2020 was $0.00003. For the maximum flow scenario, we assumed this cost rate would remain constant at $0.00003 per ton-mile for hazardous material transport by highways, as there is no available research estimating new emissions for new truckloads.

$$\begin{aligned} EUAC_{HW}\ of\ toxic\ release &= \frac{annual\ incident\ cost}{ton - miles\ in\ 2020} \\ &= \frac{69,957,700(\ \$)}{2,233,588,364,732(ton - miles)} \\ &= 0.00003(\ \$/ton - mile) \end{aligned} \tag{21}$$

In 2020, for rail transport, there were six individuals injured, and no fatalities linked to the transport of hazardous materials. Additionally, the incurred costs for property damage totaled $27,945,000, as reported by Bureau of Transportation Statistics (2021b). By multiplying the number of incidents by the associated cost per case, we calculated the total cost of fatalities and injuries to be $1,191,000 for hazardous materials transported by rail. The overall cost, inclusive of property damage, totaled $29,136,000 in 2020. To determine the EUAC of total toxic release costs for railroads, we divided this overall cost by the 1,439,814,000,000 ton-miles of Class I transport in 2020. The resulting EUAC stood at $0.000021 per ton-mile in 2020, as demonstrated in the following equation. Similar to the highway toxic release cost, we presumed that the cost rate for the maximum flow scenario would persist at $0.00002 per ton-mile for hazardous material transport by rail.

$$\begin{aligned} EUAC_{RR}\ of\ toxic\ release &= \frac{annual\ incident\ cost}{Class\ I\ ton - miles\ in\ 2020} \\ &= \frac{29,136,000(\ \$)}{1,439,814,000,000(ton - miles)} \\ &= 0.00002(\ \$/ton - mile) \end{aligned} \tag{22}$$

3.4.4. Noise pollution, water and soil pollution, and wildlife vitality

These impacts encompass the influence of engines, rolling stock, and aerodynamics on the quality of life for both humans and animals residing in areas adjacent to transport infrastructure. They include factors such as annoyance, health issues, and biodiversity loss. Examples of water and soil pollution resulting from the transportation sector

Table 3. KABCO Highway-related crash severity rating, adapted from Harmon et al. (2018) and Shrestha et al. (2021).

Code	Severity	Description	Unit costs ($2016)
K	Fatal	Any injury that results in death within 30 days	$11,295,400
A	Incapacitating (Suspected Serious Injury)	Any injury other than a fatal injury that prevents the injured person from walking, driving, or normally continuing the activities the person was capable of (e.g. severe laceration, broken or distorted limbs, damaged skull, significant burns, and paralysis)	$655,000
B	Evident Injury (Suspected Minor Injury)	Any injury other than code K and A that is evident to observers at the scene (e.g. abrasions, bruises, minor cuts, minimal bleeding)	$198,500
C	Possible Injury	Any injury reported that is less severe than non-incapacitating evident injury (e.g. pain, nausea, hysteria, limping, momentary loss of consciousness)	$125,600
O	Property Damage Only	Property damage that reduces the monetary value of that property without any bodily harm	$11,900

include microplastics from tires, copper emissions from brake pads and rail wear, asphalt wear, fuel contamination from oil drips and leaks, petroleum leaks from underground storage tanks, material spillage from vehicle exhaust, organic compounds, chemicals, radiation, biohazard materials, oil and gas, and certain infrastructure construction and maintenance activities like rock and soil excavation, painting, deicing practices using substances like CaCl2 and NaCl, pesticide application to roadside and trackside vegetation, disposal practices, and solid waste impact on the water quality of adjacent streams and downstream areas. These issues are interlinked with roadside soil quality, involving contaminants washed into the surrounding soil, erosion of disturbed soils (e.g. excavation areas and impervious surfaces), and damage to soil structure. Concerning wildlife impacts, both construction and operational activities can influence the life expectancy, habitat, health, and reproduction of animals, creating physical barriers that restrict animals' access to their habitat and pose a threat to population stability.

A European case study conducted by Siciliano et al. (2016) quantified the costs associated with these impacts. In 2016, the average costs of noise pollution were reported at 2.5 euros per 1,000 ton-km for highways and 1 euro per 1,000 ton-km for railroads, accounting for rural and urban areas for noise variations for railroads (Siciliano et al., 2016). Water and soil pollution costs were documented at 1 euro per 1,000 ton-km for highways and 0.4 euros per 1,000 ton-km for railroads. Biodiversity losses were exclusively linked to highway transportation, with a cost of 0.5 euro per 1,000 ton-km. The standard rail in the case study maintained an average speed of approximately 60 km/h, equivalent to the speed of a US Class 3 railroad. These values were originally expressed in euros per 1000 ton-km, and for conversion to dollars per ton-mile, we assumed an exchange rate of one EUR to 1.11 USD, considering one ton-km as equivalent to 0.684931507 ton-miles. Consequently, the resulting costs in 2016 US dollars per ton-mile were as follows:

$$\begin{aligned} &\textit{Noise pollution } \text{cost}_{HW} \\ &= \frac{2.5(€) \times 1.11(\ \$/€)}{1000(ton - km) \times 0.684931507(ton - mile/ton - km)} \\ &= 0.0041(\ \$/ton - mile) \end{aligned} \tag{23}$$

$$\begin{aligned} &\textit{Noise pollution } \text{cost}_{RR} \\ &= \frac{1(€) \times 1.11(\ \$/€)}{1000(ton - km) \times 0.684931507(ton - mile/ton - km)} \\ &= 0.0016(\ \$/ton - mile) \end{aligned} \tag{24}$$

$$\begin{aligned} &\textit{Water and soil pollution } \text{cost}_{HW} \\ &= \frac{1(€) \times 1.11(\ \$/€)}{1000(ton - km) \times 0.684931507(ton - mile/ton - km)} \\ &= 0.0016(\ \$/ton - mile) \end{aligned} \tag{25}$$

$$\begin{aligned} &\textit{Water and soil pollution } \text{cost}_{RR} \\ &= \frac{0.4(€) \times 1.11(\ \$/€)}{1000(ton - km) \times 0.684931507(ton - mile/ton - km)} \\ &= 0.00065(\ \$/ton - mile) \end{aligned} \tag{26}$$

$$\begin{aligned} &\textit{Wildlife vitality } \text{cost}_{HW} \\ &= \frac{0.5(€) \times 1.11(\ \$/€)}{1000(ton - km) \times 0.684931507(ton - mile/ton - km)} \\ &= 0.0008(\ \$/ton - mile) \end{aligned} \tag{27}$$

$$\begin{aligned} &\textit{Wildlife vitality } \text{cost}_{RR} \\ &= \frac{0(€) \times 1.11(\ \$/€)}{1000(ton - km) \times 0.684931507(ton - mile/ton - km)} \\ &= 0(\ \$/ton - mile) \end{aligned} \tag{28}$$

We additionally adjusted these values to 2020 US dollars, yielding noise pollution costs of $0.0047 per ton-mile for highways and $0.0019 per ton-mile for railroads. Water and soil pollution costs amounted to $0.0019 per ton-mile for highways and $0.0008 per ton-mile for railroads. Wildlife vitality costs were estimated at $0.0009 per ton-mile for highways and $0 per ton-mile for railroads.

Regarding noise pollution, the BCA guidance offered suggested costs in 2020 dollars: $0.0197 per 23 VMT for buses and trucks in all locations, $0.0033 per VMT for buses and trucks in rural areas, and $0.0393 per VMT for buses and trucks in urban areas (USDOT, 2022). It's important to note that these values were specifically designed for projects involving modal shifts, implying their applicability when there are known reductions in VMTs on the highway following the implementation of a new project. Currently, there is a dearth of explicit guidance for independently estimating noise pollution costs in transportation projects. The BCA guidance proposes that researchers and practitioners can quantitatively evaluate this metric using clearly defined thresholds, such as decibel levels or specific times of operation (for example, nighttime or daytime) (USDOT, 2022).

3.5. Social metrics

Social costs in transportation comprise a broad range of factors, both tangible and intangible, that profoundly influence individuals' and communities' quality of life. These costs extend beyond financial considerations, delving into deeper, often less quantifiable aspects of well-being. In this study, we categorize social costs into three primary types: safety, travel congestion, and the enjoyment of natural landscapes and tranquility.

3.5.1. Safety

Safety costs pertain to the expenses associated with fatalities and injuries per ton-mile of freight transport. These expenses include medical treatment, property damage, lost productivity, insurance administration, emergency services, as well as non-monetary costs related to reduced quality of life and pain and suffering. In their 2016 analysis, Harmon et al. (2018) categorized highway crashes by severity, outlining their costs in 2016 dollars, as depicted in Table 3. These values represent comprehensive costs, encompassing economic impacts such as medical expenses, property damage, and the costs of goods and services related to crash response. They also account for workplace costs stemming from employee absences, congestion-related impacts like increased fuel consumption and pollution for those not directly involved in the accident, and societal crash costs, which capture the monetized value of pain and suffering.

According to Kruse et al. (2022), they compiled data regarding fatalities and injuries per billion ton-miles of truck transport. In 2018, this data indicated a ratio of 2.2212 fatalities per billion ton-miles and a ratio of 55.1714 injuries per billion ton-miles, sourced from the Large Truck and Bus Crash Facts 2018 report by the Federal Motor Carrier Safety Administration. For railroads, data from 2019 was utilized, revealing a ratio of 0.4793 fatalities per billion ton-miles and a ratio of 4.6207 injuries per billion ton-miles. Utilizing these figures, we computed safety costs for both transportation modes using the following equations:

$$\begin{aligned} &Safety\ cost_{HH} \\ &= \left(\frac{number\ of\ incidents}{billion\ ton-mile} \times \frac{billion\ ton-mile}{ton-mile} \times unit\ cost\right) \\ &= \left(\frac{2.2212 \times 11,295,400(\ \$)}{1,000,000,000(ton-mile)}\right) \\ &\quad + \left(\frac{55.1714 \times 198,500(\ \$)}{1,000,000,000(ton-mile)}\right) \\ &= 0.036(\ \$/ton-mile) \end{aligned} \tag{29}$$

$$\begin{aligned} &Safety\ cost_{RR} \\ &= \left(\frac{number\ of\ incidents}{billion\ ton-mile} \times \frac{billion\ ton-mile}{ton-mile} \times unit\ cost\right) \\ &= \left(\frac{0.4793 \times 11,295,400(\ \$)}{1,000,000,000(ton-mile)}\right) \\ &\quad + \left(\frac{4.6207 \times 198,500(\ \$)}{1,000,000,000(ton-mile)}\right) \\ &= 0.006(\ \$/ton-mile) \end{aligned} \tag{30}$$

These values were subsequently adjusted to 2020 dollars, incorporating a 4% inflation rate. As a result, the safety cost was assessed at $0.042 per ton-mile for highways and $0.007 per ton-mile for railroads.

3.5.2. Travel congestion

There are two types of congestion: recurring and non-recurring. Recurring congestion refers to persistent disruptions in highway and railroad capacity. Non-recurring congestion encompasses unforeseen events, such as accidents and severe weather. Both types of congestion lead to time and fuel inefficiencies, elevated labor expenses, safety expenditures, and vehicle wear and tear. The recommended congestion cost in the DOT's 2022 BCA Guidance was $0.212 per VMT in 2020 for buses and trucks across all locations: urban and rural. To convert this figure to a per ton-mile basis, we use the ratio between the 2020 VMT and ton-miles in the US. By multiplying the congestion cost of $0.212 by the ratio of 302,141,000,000 vehicle miles to 2,233,588,364,732 ton-miles, the result is approximately $0.0287 per ton-mile.

For freight railroad congestion costs, an estimate indicated that grade crossing congestion incurred an annual cost of $465,137,996 in the year 2000 (Gorman, 2008). Given the total annual ton-miles of 1,465,960 million in 2000 (Bureau of Transportation Statistics, 2022b), the corresponding grade crossing congestion cost was computed at $0.0003 per ton-mile in 2000, equivalent to $0.0007 per ton-mile when adjusted to 2020 dollars. Additionally, in 2020, freight trains caused delays of 700,000 min to passenger trains, according to Amtrak (National Railroad Passenger Corporation, 2021). To calculate the passenger rail traffic congestion cost, we utilized values of travel time savings of $47.1 per person-hour in 2015-dollar value (U.S. Department of Transportation, 2016). This value represents a weighted average, considering 59.6% personal trips and 40.4% business trips, based on intercity travel *via* high-speed rail. Given an average occupancy of approximately 286 persons per Amtrak train in 2016 (National Railroad Passenger Corporation, 2016), the rail traffic congestion cost can be calculated as follows:

$$\begin{aligned} &Passenger\ rail\ congestion\ cost \\ &= \frac{value\ of\ time \times time \times number\ of\ passengers}{ton-mile} \\ &= \frac{47.1(\ \$/person-hr) \times 700,000(\text{min}) \times 286(passengers)}{60(\text{min}/hr) \times 1,439,814,000,000(ton-miles)} \\ &= 0.00011(\ \$/ton-mile) \end{aligned} \tag{31}$$

Subsequently, after adjusting this value to 2020 dollars, the estimated passenger rail traffic congestion cost was determined to be $0.00013 per ton-mile. Therefore, the overall traffic congestion cost, including grade crossing and passenger rail congestion, amounted to $0.00083 per ton-mile.

3.5.3. Peaceful enjoyment of nature and landscape

This metric evaluates the qualitative impacts on human land use near road and rail transportation corridors, with a specific emphasis on livability influenced by the frequency of vehicle movement and its impact on the natural and scenic beauty of the landscape. Siciliano et al. (2016) presented values of 0.7 euros per 1,000 ton-kilometers for highways and 0 euros per 1,000 ton-kilometers for railroads as the transportation cost associated with disrupting peaceful enjoyment. We converted these values into US dollars per ton-mile using the following equations and subsequently adjusted them to 2020-dollar values. As a result, the estimated cost for disrupting peaceful enjoyment was \$0.0013 per ton-mile for highways and \$0 per ton-mile for railroads.

$$\begin{aligned} &\textit{Peaceful enjoyment } \text{cost}_{HW} \\ &= \frac{0.7(€) \times 1.11(\ \$/€)}{1000(ton - km) \times 0.684931507(ton - mile/ton - km)} \\ &= 0.0008(\ \$/ton - mile) \end{aligned} \tag{32}$$

$$\begin{aligned} &\textit{Peaceful enjoyment } \text{cost}_{RR} \\ &= \frac{0(€) \times 1.11(\ \$/€)}{1000(ton - km) \times 0.684931507(ton - mile/ton - km)} \\ &= 0(\ \$/ton - mile) \end{aligned} \tag{33}$$

4. Computational results and discussions

Using the methods and data outlined in the calculation procedures section, this section presents an LBCA comparison between highways and railroads. Table 4 provides a summary of the comparison results in 2020 dollars per thousand ton-miles for each mode, including calculations for both actual 2020 flows based on the BTS and R1 report data and theoretical maximum flows as described in Appendix A.

Based on the computational results presented in Table 4, the total current cost of a highway project amounts to \$370.07 per thousand ton-miles, which is roughly 4.85 times higher than the total current cost of a railroad project, estimated at \$76.37 per thousand ton-miles. Figure 2 visually illustrates all the benefits and costs associated with both modes of transportation, with the blue area representing the costs of the highway project and the orange area representing the costs of the railroad project. When we group the metrics for the highway project, the largest proportion of expenses includes driver wage and benefit costs, transport equipment costs, safety costs, and initial construction costs, in order of significance. In comparison, for the railroad project, the largest group of metrics includes initial construction costs, criteria pollutants, labor and administration costs, and energy costs, respectively. The remaining metrics, which have not yet been discussed, contribute minimally to the total cost, accounting for less than 10% each. It is important to highlight that although initial construction costs may appear to be a substantial component of railroad expenses, they comprise only approximately 25.9% of the total cost of railroads. Additionally, when comparing this metric to highways, we find that the initial construction costs for highways are 1.91 times higher than those incurred by railroads. Regarding overall costs, the only metric where railroads are more expensive than highways is land value. This cost disparity arises because the allocation of costs for trucks among highway users is solely based on the space taken up by vehicles (PCE). Since passenger cars occupy a larger proportion of space compared to trucks, they bear a greater responsibility for the land value cost.

5. Conclusion, limitations, and future research

This section discusses the applicability of the developed LBCA tool, its limitations, and future research needs, including metrics with insufficient quality data and the treatment of end-of-life values.

5.1. Applicability of the LBCA tool

Our tool evaluates the comprehensive benefits and costs associated with surface freight transportation, considering

Table 4. Life-cycle benefit and cost comparison between highway and railroad projects in 2020 dollars per thousand ton-miles.

	Highway		Railroad	
Cost element	Actual flow	Max flow	Actual flow	Max flow
Land Use Metric				
Land value	\$0.17	\$0.13	\$0.73	\$0.04
Initial Construction Metrics				
Initial Construction	\$37.69	\$13.86	\$19.78	\$1.18
Operating Metrics				
Energy	\$29.80	\$29.80	\$9.53	\$9.53
Labor and Administration	\$99.70	\$36.85	\$12.47	\$1.26
Maintenance of Transportation Infrastructure	\$8.69	\$1.66	\$4.73	\$4.73
End of Life Infrastructure Value	(\$5.71)	(\$5.71)	(\$0.51)	(\$0.51)
Transport Equipment	\$55.60	\$20.55	\$3.60	\$0.36
Maintenance of Transport Equipment	\$32.19	\$32.19	\$1.07	\$1.07
Environmental Metrics				
Greenhouse Gases	\$10.85	\$10.85	\$1.13	\$1.13
Criteria Pollutants	\$21.27	\$21.27	\$13.31	\$13.31
Toxic releases	\$0.03	\$0.03	\$0.02	\$0.02
Noise Pollution	\$4.74	\$4.74	\$1.62	\$1.62
Water and Soil Pollution	\$1.90	\$1.90	\$0.65	\$0.65
Wildlife Vitality	\$0.95	\$0.95	–	–
Social Metrics				
Safety	\$42.16	\$42.16	\$7.41	\$7.41
Congestion	\$28.70	\$28.70	\$0.83	\$0.83
Peaceful Enjoyment	\$1.33	\$1.33	–	–
Total	\$370.07	\$241.27	\$76.37	\$42.64

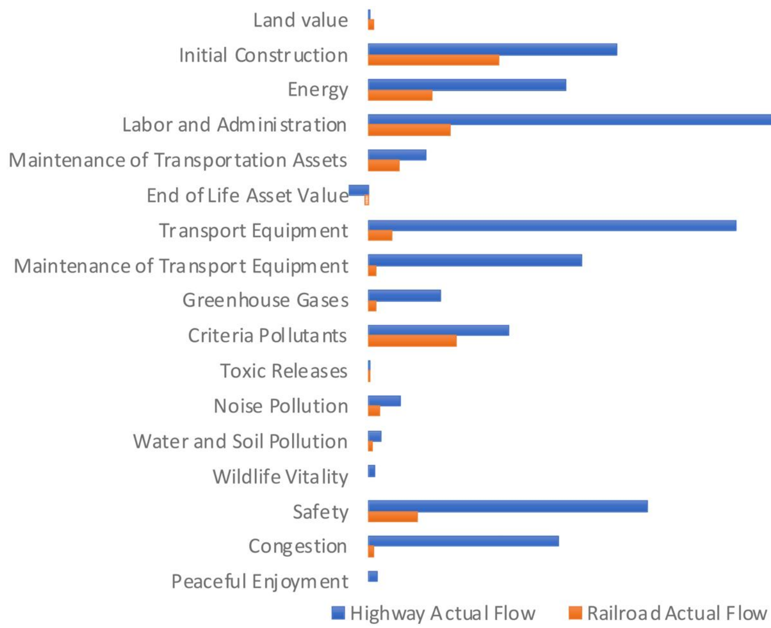

Figure 2. 2020 costs per ton-mile of highway and railroad projects.

financial and non-financial dimensions, such as social and environmental factors, throughout their life cycles. Users have the flexibility to calculate metrics effortlessly using provided default values or opt to customize them for specific projects, requiring a certain level of effort and expertise. In terms of case-specific implementation, this tool may be more suitable for researchers or experts with experience working in the logistics and transportation industry than the general public. For the public, the tool offers a broad understanding of the differences between transportation modes, aiding projects seeking public support and promoting environment-conscious policies. Even though this research primarily uses national-level data as a representative average for the entire country, when applying LBCA to specific cases, analysts should recognize the importance of accounting for local characteristics and transportation dynamics. Applying LBCA to different areas requires careful consideration of each location's unique attributes to ensure accurate results. For instance, when comparing LBCA applied to two different intersections—one in a dense urban area and another in a suburban neighborhood—the outcomes can vary significantly, especially with congestion and gas emissions being much higher in the dense urban area. Various factors influence the analysis, such as distinct traffic flow patterns, congestion levels, transportation operations, accessibility of transportation networks, and regulatory frameworks. Additionally, metrics like land value, energy prices, labor costs, and environmental impacts can vary between locations. We further discuss the factors and methodologies required to acquire new values for metrics in the future research section.

In addition, this research focuses on a nationwide analysis across the US without accounting for any unique characteristics of freight, traffic, and operations. Variations from the average scenarios, such as differing mixes of freight types and destination locations, will alter our benefit and cost analysis results. For example, rail systems optimized for bulk transport may not be as efficient or cost-effective when handling diverse, smaller shipments with varying destinations. If railroads were to transport a mix of freight similar to highways, their costs could increase due to factors such as carrying lighter loads per mile, the need for more frequent stops to service diverse destinations, and different handling requirements. Similarly, if highway transportation were to serve long-haul destinations, costs could rise due to factors like mandatory driver rest stops.

Concerning the tool's performance, despite considerable efforts to collect and improve accuracy, certain data inconsistencies persist. These discrepancies arise from the utilization of data from diverse sources, including different levels such as national, local, state, or international data, and are particularly notable in the assessment of environmental impacts. Furthermore, the scope of our tool is restricted to transportation infrastructure and equipment, excluding support infrastructure such as railroad yards, terminals, gas stations, and power stations. It also specifically targets conventional transport equipment such as diesel locomotives and trucks, omitting the inclusion of emerging technologies like electric or hydrogen trucks. In the next subsection, we will further discuss the limitation of this study caused by data availability in more detail.

5.2. Limitations of this study caused by data availability

The growing awareness of transportation's environmental impacts has spurred researchers to consider additional metrics for comparing transportation alternatives. These impacts encompass a range of factors, such as microplastic pollution, light pollution, water and soil pollution, noise and vibration damage, biodiversity loss, changes in environmental esthetics, and the value of end-of-life infrastructure and equipment. However, our LBCA tool does not incorporate some of these impacts due to a lack of high-quality data that would enable a meaningful comparison between the two transportation modes. For some included metrics, we acknowledge limitations in the calculations due to data constraints. In this subsection, we categorize these metrics into two groups. First, we discuss the metrics excluded from our LBCA tool because they lack associated monetized values. Subsequently, we address metrics included in our analysis, noting that caution should be exercised by U.S. users because the data primarily originate from other regions and may not be entirely applicable to U.S. scenarios. Additionally, we examine the concept of end-of-life asset versatility, which has gained prominence in the context of sustainability, yet has not been integrated into our calculations.

5.2.1. Environmental metrics that are not included

In our proposed life-cycle BCA, we have omitted several crucial environmental metrics, namely microplastic pollution, light pollution, and vibration, due to data limitations. In this subsection, we will discuss the significance of these metrics and the availability of relevant data.

5.2.1.1. Microplastic pollution. Tires, comprising 19% natural rubber and 24% plastic polymer, are a significant source of microplastic emissions (Root, 2019). They produce two types of road microplastics: tire wear particles (TWPs) and brake wear particles (BWPs). In 2014, global emissions of PM2.5 and PM10 TWPs amounted to 31,967 tons and 317,466 tons, respectively (Evangeliou et al., 2020). PM2.5 BWPs totaled 108,247 tons, and PM10 BWPs reached 160,937 tons in annual global emissions. North America contributed substantially, with 22% of TWPs and 17% of BWPs. Due to their airborne nature, these microplastics can travel long distances and deposit on land and in the ocean. TWPs and BWPs accounted for 43% – 46% of PM2.5 deposits on land and 53% – 57% in the oceans. PM10 TWPs and BWPs, larger particles, were primarily deposited on land (65% – 72%) and to a lesser extent in the ocean (28% – 35%) (Evangeliou et al., 2020). These pollutants have significant adverse effects on people, animals, and the environment. For example, they often contain toxic chemicals and microorganisms (Carrington, 2020) and damage marine animals and aquaculture. J. Lee (2015) evaluated the economic losses to UK shellfish, mollusk, and aquaculture in 2012 based on the microplastic density. While there's no specific research on their impact on human health, it's widely believed that microplastics may harm humans, particularly in densely populated regions where exposure to PM2.5 and PM10 can cause respiratory diseases (Evangeliou et al., 2020). Research by Goßmann et al. (2021) demonstrated that car tire wear significantly contributes to microplastic pollution in various samples, including road dust, sediments, marine salt, and mussels. Car-to-truck tire wear ratios were as high as 16:1 across all samples. In contrast, railroads, mainly composed of iron, steel, and metal, do not commonly emit microplastics, with only occasional synthetic rubber use in brake systems. Consequently, research on brake shoe microplastic release from railroads is lacking, and no data exists to quantify its environmental impact, precluding its inclusion in this study.

5.2.1.2. Light pollution. Artificial light pollution, emanating from diverse sources like buildings, public spaces, advertising, and transportation, poses a multifaceted threat. It disrupts animal habitats, mating behaviors, wildlife, human health, and astronomy. Research by Gallaway et al. (2010) estimated that poor lighting design contributes to nearly $7 billion in annual light pollution costs due to excessive energy consumption in the U.S. Numerous studies have explored the negative impacts of light pollution on ecosystems. For instance, it has been linked to a 47% reduction in moth caterpillar populations in hedgerows and disruptions in caterpillar development (Boyes et al., 2021), altered moths' abundance and their role in nocturnal pollen transport (Macgregor et al., 2017), sleep disturbances in birds (Aulsebrook et al., 2020), and changes in loggerhead turtle behavior during nesting and hatchling phases (Silva et al., 2017). However, the impact on human health remains a subject of debate. Svechkina et al. (2020) conducted a systematic review of seventy-four articles, revealing possible health issues like tumors, breast cancer, sleep disorders, and weight gain associated with light pollution. Yet, these findings are still tentative, and the reversibility of the impacts is uncertain (Svechkina et al., 2020). Moreover, some studies have assessed the economic aspects of light pollution, considering investment, maintenance, and energy costs (Narisada & Schreuder, 2004) and the benefits of reducing crime and accident rates (Bhagavathula et al., 2021; Narisada & Schreuder, 2004). Remarkably, no research has quantified the monetary toll of transportation-induced light pollution on humans and ecosystems. This represents a significant knowledge gap that merits further investigation.

5.2.1.3. Vibration. Transportation system vibrations can negatively impact human well-being and health. Factors such as vibration intensity, frequency, distance from the source, and land use types all play a role. Federal Aviation Administration (2021) evaluated ground-borne vibrations of rail transit operations and constructions for the likelihood of annoyance using the FTA Manual. This evaluation focused on residential areas within 200 feet and institutional areas within 100 feet of the project alignment, as well as vibration-sensitive structures. If a new project's construction and operation vibrations increase by less than three vibration decibels (VdB) compared to existing levels, it won't contribute to vibration issues (Federal Aviation Administration, 2021). However, this may not apply to freight railroad transportation due to greater distances, lower operation frequency, and minimal incremental effects. Freight trucks produce less intense but more frequent vibrations. The vibration intensity of freight trucks is less than the vibration caused by the railroads, but its frequency could be much higher. There is no existing study quantifying the impacts on people associated with freight rails and trucks.

5.2.2. Environmental metrics that are included but require cautions

While European countries have extensively studied social and environmental costs, such research has been relatively limited in the United States. We include European data-based values for several impacts in our LBCA. It is important to note that when combining these European-derived values with U.S. costs for other impacts, it may compromise metric consistency, requiring caution from users. The environmental metrics in question encompass noise, water and soil pollution, biodiversity losses, and effects on nature and landscapes. For our analysis, we rely on more recent research conducted by Siciliano et al. (2016) that aligns with the BCA Guidelines of the European Commission and exclusively represents costs in Europe. Each of these metrics will be discussed in detail below.

5.2.2.1. Noise pollution. The U.S. DOT's BCA Guidance suggests noise pollution costs of $0.0197 per VMT for buses and trucks for all locations, $0.0033 per VMT in rural areas, and $0.0393 per VMT in urban areas in 2020 (USDOT, 2022). These values are primarily intended for projects involving modal shifts, enabling the estimation of noise pollution cost savings through a reduction in VMT. Alternatively, analysts can provide a qualitative estimate of noise pollution in BCA when VMT reductions are unknown. If a quantitative approach is chosen, a clear explanation of the threshold (e.g. decibel levels and operation times) is required (USDOT, 2022). Notably, the guidance lacks specificity in calculating noise pollution costs for different transportation modes. The FAA does include noise costs in project evaluations, applying them to projects like commuter rail and bus realignments, and changes in operational frequency, following noise level prediction methods and screening analysis (Federal Aviation Administration, 2021). However, the focus has been primarily on mass transit sectors rather than freight transport. Beyond the U.S. studies, the Victoria Transport Policy Institute in Canada (Litman, 2020) compiled traffic noise cost data from various countries for a wide range of land transport modes, including cars, electric cars, vans, mid-size trucks, heavy trucks, buses, motorcycles, and trains. The costs were also segregated into several categories depending on speed, different times of day, and characteristics of the area (i.e. urban, suburban, and rural). Most research they reviewed focuses on passenger transportation, with only CE Delft, the independent research and consultancy organization in the Netherlands, being a rare source of noise cost data for freight trains in 2008.

5.2.2.2. Water and soil pollution. Transportation has a direct impact on water and soil quality through hazardous material leaks resulting from operational activities and maintenance, such as fuel, lubricant, paint, brake fluid, road salt, hydraulic fluids, wooden tie preservation, and pesticide applications, as well as accidents. Chemicals from these incidents can either directly contaminate water sources or seep into the ground and eventually reach groundwater or downstream bodies of water. Moreover, chemicals, whether in particle or emission form, ultimately settle on land or water surfaces. Furthermore, the impermeable surfaces of transportation infrastructure can hinder the infiltration of surface water into the soil, heightening the risk of flooding and the transmission of pollutants to water sources far beyond adjacent areas. This issue is predominantly associated with dense road networks, influenced by the number of household vehicles and the preference for single-family homes, with limited consideration for highway traffic. This oversight may stem from the relatively small proportion of impervious surfaces linked to highway infrastructure (Hecht & Andrew, 1997). Victoria Transport Policy Institute (2015) reviewed articles on water pollution and hydrologic impacts resulting from transport facilities and vehicle usage. The cost categories include oil pollution, tanker spills, road salt contamination, cleanup of leaking tanks, highway runoff control, and stormwater management, among others.

5.2.2.3. Biodiversity losses. The assessment of costs related to wildlife and traffic safety typically relies on statistical data regarding collisions between wildlife and vehicles (National Highway Traffic Safety Administration, 2021). These costs are primarily focused on the impacts affecting humans, encompassing factors such as human fatalities and injuries, property damage, and time lost, without considering the impact on the animals involved. Additionally, expenses associated with mitigation efforts, such as the construction of road fences, wildlife crosswalks, and wildlife grids, should be considered (Seiler et al., 2016). However, the value of lost animals, while acknowledged in research, lacks standardized values and is often excluded from the analysis (Gren & Jägerbrand, 2019). Notably, existing research does not adequately address how the transportation sector impacts habitats and contributes to the loss of animal life, leaving this aspect uncertain.

5.2.2.4. Impact on nature and landscape. The development of expressways can lead to visual degradation and annoyance for those within sight. While some researchers acknowledge this issue, they argue that quantifying the cost of visual intrusion is not feasible (Lawson, 2007). In a more practical approach, the University of Karlsruhe in Germany and the Swiss Federal Office for Spatial Development recommended evaluating the cost of landscape degradation by estimating the expenditures needed to dismantle transportation structures and restore natural conditions. In our research, we derive the external cost of nature and landscape from the work of Siciliano et al. (2016), who utilized values from the European Commission's transport white paper. However, the methodology or factors used to estimate this cost are not explicitly identified.

5.2.3. Versatility of the end-of-life value

The current life-cycle cost analysis approach recommended by the FHWA primarily focuses on the remaining value of assets at the end of the analysis, typically based on the last rehabilitation. However, this method overlooks the condition of underlying pavement layers and neglects potentially costly reconstruction expenses beyond the analysis period. While they argue that these assumptions are considered feasible due to small salvage values at the end of the analysis (e.g. 30 years for pavement) (Musselman et al., 2020), it is crucial to consider a broader perspective. In reality, the value of these residuals may remain significant or have the potential for recycling and reuse. In the context of road infrastructure, managing waste and by-products promotes the recycling and reutilization of secondary materials, given the continual growth in by-product volumes and disposal costs. When assessing the BCA of this metric, it is essential to benchmark the cost of utilizing recovered materials against conventional materials. The guidance provided by Chesner et al. (2008) outlines the use of waste and by-product materials in six key highway construction applications, including Asphalt Concrete, Portland Cement Concrete, Granular Base, Embankment or Fill, Stabilized Base, and Flowable Fill. Despite this guidance, the incorporation of this concept into the BCA of transportation projects has not been realized. This broader aspect of the versatility of the end-of-life value still requires more attention in research.

5.3. Future research

In the preceding section, we identified three primary challenges hindering the inclusion of monetary values for factors in LBCA: data unavailability, limited metric scope, and computational method limitations. Some impacts are intangible and difficult to measure, for example, the annoyance and distraction of noise and distress from esthetic degeneration of the environment. Additionally, certain metrics necessitate specialized personnel and equipment for measurement and analysis. When assessing human health impacts, attributing causation to a single factor is complex due to uncontrollable external variables. Consequently, it is more feasible to gauge factor impacts through controlled animal experiments, such as observing moth population reductions in response to artificial light exposure. This preference for ecosystem-focused research over human-centric studies has been observed in prior investigations. In this section, we will outline the future research direction for comprehensive comparisons of life-cycle benefits and costs in freight transportation systems. This will encompass input data, anticipated outcomes, and promising methodologies.

To evaluate the noise and vibration impact of freight transport in the U.S., we rely on European case studies as a guide for methodology. These studies emphasize gathering data related to operational factors (e.g. speed, operating hours), exposure duration, population density in affected areas, and existing noise and vibration levels. Several open-source software tools, such as SoundPLAN, openPSTD, and IMMI, aid in sound propagation estimation. These tools require input parameters like scheduling (duration and frequency), average train car counts, speeds, and infrastructure conditions. Notably, SoundPLAN, recommended by the FTA, offers insights into the costs and benefits of noise reduction measures, such as noise barriers. Identifying affected areas, such as hospitals, schools, and residential zones, is crucial, as the impact varies depending on land use functionality. The European Commission's handbook on transport's external costs provides data on noise impact cost per dB per person-year for road and rail transport, aligned with WHO guidelines. Analysts can derive annual total costs by multiplying these costs by appropriate weights, differentiating between road and rail sectors. Given the variation in population density across urban, suburban, and rural areas, adjusting the impact estimation is essential for accurate assessment. It is worth mentioning that while individual trains may produce higher noise levels than trucks, the lower frequency of freight trains compared to highway trucks results in slightly lower decibel levels per ton (Hecht & Andrew, 1997). Additionally, it is important to consider that railroads are often situated remotely from communities, while highways can run through them, potentially making highway noise impact more significant.

Assessing the versatility of end-of-life value in transportation infrastructure is vital, especially in the current circular economy trend. For road infrastructure, asphalt finds reuse in new pavement projects, while railroad steel and wood have broader applications. Calculating costs for using reclaimed materials in pavement construction involves three aspects: material cost, installation cost, and life-cycle cost (Chesner et al., 2008). Material costs encompass six elements: (1) raw material price with disposal fee, (2) processing costs such as screening and crushing, (3) stockpiling expenses, (4) material loading, (5) transportation costs, and (6) producer profit. Installation costs are considered when using reclaimed materials with different design, construction, testing, or inspection needs compared to conventional materials. Lastly, life-cycle costs assess whether reclaimed materials alter maintenance requirements or the infrastructure's expected service life (Chesner et al., 2008). When using reused materials, a BCA should compare these costs with conventional materials. For railroad end-of-life value, similar considerations and cost elements apply. However, these scraps can be recycled into various products such as landscaping timbers, substructures, automotive parts, cans, and more. To simplify calculations, we can use scrap prices from the Scrap Price Bulletin offered by rail companies instead of considering varied recycled material values. Furthermore, the utilization of recycled materials has far-reaching effects, notably diminishing landfill waste, greenhouse gas emissions, energy consumption, resource extraction, production, and transportation. Nevertheless, estimating associated costs and end-of-life values based on these benefits demands substantial time and expertise. Multidisciplinary teams, including logistics, civil and environmental engineering, environmental science, geology, and materials science, are essential for future research in this area.

In the assessment of the cost of environmental esthetics, future research could explore two critical dimensions: firstly, quantifying the value of dissatisfaction arising from diminishing beauty, and secondly, evaluating the expenses associated with restoring natural esthetics. The calculation of the latter is relatively straightforward, as various European studies have already undertaken this task, involving the estimation of costs for dismantling transportation structures and reinstating natural conditions. Concerning the evaluation of the cost of dissatisfaction, despite its subjective nature and susceptibility to personal opinions, a rough estimate can be derived using the willingness-to-pay method. This involves conducting surveys to gauge how much residents are willing to invest in residing near transportation infrastructures. Alternatively, analysts can examine land values or asset values in proximity to these areas to determine any correlation with price fluctuations following the introduction of transportation infrastructures.

Another critical metric that demands increased attention for the successful implementation of the proposed LBCA in the U.S. is the impact on biodiversity. Currently, the costs associated with wildlife have predominantly focused on the valuation of human casualties and injuries resulting from collisions with road vehicles, as evidenced in existing literature. Some researchers approach this by framing it as the expense of restoring the previous environmental state, akin to the evaluation of environmental esthetics costs. This consists of mitigation expenditures, including the construction of road fences, wildlife crosswalks, wildlife grids, and the like. Further research is imperative to holistically assess the effects of transportation systems on biodiversity.

In the realm of water and soil pollution's societal costs, three distinct impacts are discerned in the literature: transport construction spills, operational spills, and stormwater management. The proposed LBCA already factors in hazardous material spills through the toxic release metric, including cleanup expenses, mitigation outlays, and property damage. Nevertheless, the intricacies of water and soil pollution extend beyond this scope. Accidents resulting in spills are quantifiable due to their evident impact scale, whereas maintenance and operational spills, though smaller, endure for longer periods and present monitoring challenges. The gradual accrual of pollutants in surface and underground waters complicates source attribution. Common pollution indicators encompass organic compounds and metals (Trumbull & Bae, 2000). In addition, detection and measurement, particularly for underground water, incur significant costs. Regarding stormwater management, impervious surfaces heighten pollutant deposition in remote areas and increase corrosion severity. Assessing this impact and its costs involves predicting the risk of inadequate space for stormwater drainage systems or the expenses associated with constructing retention basins to compensate for reduced natural drainage basins.

In recent years, research has increasingly focused on understanding the ecological impact of transportation. Key areas of investigation include microplastic pollution and light pollution. Regarding microplastic pollution, studies have examined the emissions of microplastics (i.e. TBPs and BWPs) from vehicles, distinguishing between emissions from cars and trucks, as well as the subsequent deposition of microplastics in both terrestrial and aquatic environments. Economic losses to the UK's aquaculture industry have also been analyzed. However, future research should investigate the impacts on humans and the adverse effects on marine life. The assessment of the costs associated with these consequences should encompass various aspects, including aquaculture, fisheries, human health, and property devaluation in regions marked by high pollution. This challenge necessitates a multidisciplinary approach, encompassing various fields such as behavioral mechanisms, the ingestion of microplastics by marine organisms, pollution levels in humans from water and seafood consumption, and the toxicity threshold for marine life and allergic reactions in humans. Collaborative research involving marine sciences, ecology, biology, chemical engineering, food science, epidemiology, and other disciplines is essential to comprehensively address this issue.

Turning to light pollution, current research is less comprehensive compared to microplastic pollution. Studies have predominantly focused on specific animal species (e.g. moths, birds, turtles) in proximity to light sources like lamp posts and port areas. There is a need to expand the scope and differentiate between transportation-induced light pollution and other sources of artificial light, such as buildings, public spaces, and advertising. Assessing the impact on human health is challenging due to the numerous factors influencing our quality of life. While some researchers suggest a link between artificial light and health issues like tumors, cancer, and sleep disorders, conducting controlled experiments across diverse living conditions and gathering sufficient data for conclusive results is difficult. Moreover, there is a lack of research quantifying the economic value of light pollution on both humans and ecosystems. Utilizing methods like the willingness-to-pay approach offers a promising means to assess associated costs to society.

Furthermore, as people increasingly prioritize environmental concerns and quality of life, it is imperative to conduct extensive research that keeps pace with technological advancements and socioeconomic shifts. Freight transportation is rapidly evolving with the emergence of various new technologies and operational improvements, including electric trucks and trains, hydrogen-powered trucks, autonomous driving, connected vehicles, automatic material handling, innovative pavement materials, lighter vehicles, increasing carload, and advancements in middle-mile and last-mile delivery, along with the use of drones, among others. Evaluating the impacts of new freight infrastructure projects now requires careful consideration of the development and adoption of these cutting-edge technologies and practices. However, unlike rail and waterway transportation, the energy intensity for trucks has not yet exhibited a clear downward trend (Vanek, 2019). The urgency for fast shipping trucks highlights an example where the push for small truck shipments impedes the adoption of new technologies and current best practices. Future research needs to facilitate the changes and make more comprehensive comparisons between different transportation modes. We anticipate that this research will serve as a valuable resource for academics, industry practitioners, and the general public, enabling them to make informed comparisons among different freight transportation options. Additionally, we hope that this report will inspire further research in this ever-evolving field.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This research was partially funded by OnTrackNorthAmerica, a non-profit organization dedicated for efficient and sustainable transportation, and the Center for Freight Transportation for Efficient & Resilient Supply Chain (FERSC), a Tier 1 University Transportation Center fund by the U.S. Department of Transportation.

ORCID

Sarita Rattanakunuprakarn http://orcid.org/0009-0005-1487-9970
Mingzhou Jin http://orcid.org/0000-0002-2387-8129

References

American Council for an Energy-Efficient Economy. (2021, November). *Maximizing truck load factor*. Retrieved April 5, 2022, from https://www.aceee.org/sites/default/files/pdfs/Load%20Factor%20Smart%20Freight%2011-18-21.pdf

Association of American Railroads. (2021). *Railroad facts 2021*. Retrieved May 2022, from https://my.aar.org/Pages/Product-Details.aspx?ProductCode=RFB2021Web

Aulsebrook, A. E., Connelly, F., Johnsson, R. D., Jones, T. M., Mulder, R. A., Hall, M. L., Vyssotski, A. L., & Lesku, J. A. (2020). White and amber light at night disrupt sleep physiology in birds. *Current Biology: CB*, *30*(18), 3657–3663.e5. https://doi.org/10.1016/j.cub.2020.06.085

Bhagavathula, R., Gibbons, R., & Kassing, A. (2021). *Roadway lighting's effect on pedestrian safety at intersection and midblock crosswalk*. Illinois Center for Transportation/Illinois Department of Transportation. https://doi.org/10.36501/0197-9191/21-028

Blaze, J. (2020, June 10). *Commentary: Do you want to build a freight railroad?* FreightWaves. Retrieved March 23, 2022, from https://www.freightwaves.com/news/commentary-do-you-want-to-build-a-freight-railroad

Bohmhold, A., Weiss, J. (2015). *Smart roadside initiative macro benefit analysis user's guide for the benefit-cost analysis tool*. Department of Transportation. Retrieved August 3, 2021, from https://rosap.ntl.bts.gov/view/dot/4038

Boyes, D. H., Evans, D. M., Fox, R., Parsons, M. S., & Pocock, M. J. (2021). Street lighting has detrimental impacts on local insect populations. *Science Advances*, *7*(35), eabi8322. https://doi.org/10.1126/sciadv.abi8322

Bureau of Transportation Statistics. (2021a). *Estimated U.S. average vehicle emissions rates per vehicle by vehicle type using gasoline and diesel*. Retrieved July 15, 2022, from https://www.bts.gov/content/estimated-national-average-vehicle-emissions-rates-vehicle-vehicle-type-using-gasoline-and

Bureau of Transportation Statistics. (2021b). *Hazardous materials fatalities, injuries, accidents, and property damage data*. National Transportation Statistics. Retrieved March 30, 2022, from https://www.bts.gov/content/hazardous-materials-fatalities-injuries-accidents-and-property-damage-data

Bureau of Transportation Statistics. (2022a). *Freight analysis framework*. Retrieved May 14, 2022, from https://www.bts.gov/faf

Bureau of Transportation Statistics. (2022b). *U.S. ton-miles of freight*. National Transportation Statistics. Retrieved April 24, 2022, from https://www.bts.gov/content/us-ton-miles-freight

Bureau of Transportation Statistics. (2022c). *U.S. vehicle-miles*. National Transportation Statistics. Retrieved April 24, 2022, from https://www.bts.gov/content/us-vehicle-miles

Carrington, D. (2020, July 14). *Car tyres are major source of ocean microplastics – study*. Retrieved September 30, 2022, from https://www.theguardian.com/environment/2020/jul/14/car-tyres-are-major-source-of-ocean-microplastics-study

Chambers, M., Goworowska, J., Rick, C., Sedor, J., et al. (2015). *Freight facts and figures 2015*. National Transportation Library. Retrieved June 23, 2022, from https://rosap.ntl.bts.gov/view/dot/32797

Chesner, W., Collins, R., MacKay, M., Emery, J. (2008). *User guidelines for waste and byproduct materials in pavement construction*. Federal Highway Administration. Retrieved January 25, 2022, from https://www.fhwa.dot.gov/publications/research/infrastructure/structures/97148/toc.cfm

Costello, B. (2022). *Economics and industry data*. Retrieved May 29, 2023. from https://www.trucking.org/economics-and-industry-data

Dharmadhikari, N., Lee, E. S., & Kayabas, P. (2016). The lifecycle benefit–cost analysis for a rural bridge construction to support energy transportation. *Infrastructures*, *1*(1), 2. https://doi.org/10.3390/infrastructures1010002

Evangeliou, N., Grythe, H., Klimont, Z., Heyes, C., Eckhardt, S., Lopez-Aparicio, S., & Stohl, A. (2020). Atmospheric transport is a major pathway of microplastics to remote regions. *Nature Communications*, *11*(1), 3381. https://doi.org/10.1038/s41467-020-17201-9

Federal Aviation Administration. (2021). *Final EIS document*. Retrieved August 4, 2021, from https://www.lgaaccesseis.com/final-eis-document

Federal Highway Administration. (2000). *Our nation's highways—2000*. Retrieved June 4, 2022, from https://www.fhwa.dot.gov/ohim/onh00/our_ntns_hwys.pdf

Federal Highway Administration. (2017). *Highway history – The size of the job*. Retrieved June, 23 2024. from https://www.fhwa.dot.gov/infrastructure/50size.cfm

Federal Highway Administration. (2020, January 16). *National highway construction cost index (NHCCI) 2.0*. Transportation Policy Studies. Retrieved May 11, 2022, from https://www.fhwa.dot.gov/policy/otps/nhcci/pt1.cfm

Federal Railroad Association. (2016, June). *Benefit-cost analysis guidance for rail projects*. https://railroads.dot.gov/elibrary/benefit-cost-analysis-guidance-rail-projects

Gallaway, T., Olsen, R. N., & Mitchell, D. M. (2010). The economics of global light pollution. *Ecological Economics*, *69*(3), 658–665. https://doi.org/10.1016/j.ecolecon.2009.10.003

Goodchild, A. V., Wygonik, E., McMullen, B. S., & Holder, D. (2014). Multimodal freight project prioritization. Technical report, Oregon. Dept. of Transportation. Research Section.

Goßmann, I., Halbach, M., & Scholz-Böttcher, B. M. (2021). Car and truck tire wear particles in complex environmental samples – A quantitative comparison with "traditional" microplastic polymer mass loads. *The Science of the Total Environment*, *773*, 145667. https://doi.org/10.1016/j.scitotenv.2021.145667

Gorman, M. F. (2008). Evaluating the public investment mix in US freight transportation infrastructure. *Transportation Research Part A: Policy and Practice*, *42*(1), 1–14. https://doi.org/10.1016/j.tra.2007.06.012

Gren, M., & Jägerbrand, A. (2019). Calculating the costs of animal-vehicle accidents involving ungulate in Sweden. *Transportation Research Part D: Transport and Environment*, *70*, 112–122. https://doi.org/10.1016/j.trd.2019.03.008

Gühnemann, A., Laird, J. J., & Pearman, A. D. (2012). Combining cost-benefit and multi-criteria analysis to prioritise a national road infrastructure programme. *Transport Policy*, *23*, 15–24. https://doi.org/10.1016/j.tranpol.2012.05.005

Harmon, T., Bahar, G. B., & Gross, F. B. (2018). Crash costs for highway safety analysis. Technical report, U.S. Federal Highway Administration. Office of Safety.

Hasnat, M. M., Bardaka, E., Findley, D., Goode, L. (2021, September 1). *North Carolina highway cost allocation and revenue attribution study*. Retrieved July 15, 2022, from https://rosap.ntl.bts.gov/view/dot/58919

Hecht, J., & Andrew, D. (1997). The environmental effects of freight. Technical report, Organization for Economic Co-operation and Development.

Interagency Working Group. (2021). Technical support document: Social cost of carbon, methane, and nitrous oxide interim estimates under executive order 13990. Technical report, White House.

Khattak, A., Noltenius, M., Cherry, C., Greene, D., Zhang, M., & Arvin, R. (2018). *Green generates green*. Tennessee Department of Transportation.

Korytárová, J., & Papežíková, P. (2015). Assessment of large-scale projects based on CBA. *Procedia Computer Science*, *64*, 736–743. https://doi.org/10.1016/j.procs.2015.08.602

Kruse, J. C., Farzaneh, R., Glover, B., Warner, J. E., Steadman, M., Jaikumar, R., & Lee, D. (2022). January). A modal comparison of domestic freight transportation effects on the general public: 2001 – 2019. National Waterways Foundation.

Kuschel, G. (2022, March 23). *Public health risks associated with transport emissions in NZ*. Retrieved July 26, 2022, from https://www.esr.cri.nz/assets/files/Risk-assessments/Transport-Air-Health-Final-Final_23Mar22.pdf

Larson, W. (2015). *New estimates of value of land of the United States*. BEA.

Lawson, J. (2007, June). *The environmental footprint of surface freight transportation* (Transportation Research Board Special Report, 291).

Lee, J. (2015). Economic valuation of marine litter and microplastic pollution in the marine environment: An initial assessment of the case of the United Kingdom. SOAS-CeFiMS.

Lee, M. S., & Jin, X. (2020). Incorporating reliability measures into the freight project prioritization decision support system. Technical report, Florida, Department of Transportation.

Lee, Y., Yang, J., Lim, Y., & Kim, C. (2021). Economic damage cost of premature death due to fine particulate matter in Seoul, Korea. *Environmental Science and Pollution Research International*, *28*(37), 51702–51713. https://doi.org/10.1007/s11356-021-14362-y

Leleur, S., Petersen, N. B., & Barfod, M. B. (2007). *The COSIMA approach to transport decision making: Combining cost-benefit and multi-criteria analysis for comprehensive project appraisal* [Paper presentation]. Korean Development Institute & World Bank Conference, Seoul, South Korea.

Leslie, A., & Murray, D. (2021). An analysis of the operational costs of trucking: 2021 update. Retrieved July 3, 2022, from https://trid.trb.org/View/1893377

Link, H., Nash, C., Ricci, A., & Shires, J. (2016). A generalized approach for measuring the marginal social costs of road transport in Europe. *International Journal of Sustainable Transportation*, *10*(2), 105–119. https://doi.org/10.1080/15568318.2013.861044

Litman, T. A. (2020). *Transportation cost and benefit analysis ii – Noise costs*. Victoria Transport Policy Institute. Retrieved October 2022, from https://www.vtpi.org/tca/tca0511.pdf

Liu, X., Xu, J., Li, M., Wei, L., & Ru, H. (2019). General-logistic-based speed-density relationship model incorporating the effect of heavy vehicles. *Mathematical Problems in Engineering*, 2019, 6039846. https://doi.org/10.1155/2019/6039846

Macgregor, C. J., Evans, D. M., Fox, R., & Pocock, M. J. (2017). The dark side of street lighting: Impacts on moths and evidence for the disruption of nocturnal pollen transport. *Global Change Biology*, *23*(2), 697–707. https://doi.org/10.1111/gcb.13371

Maricopa Association of Governments. (2019). *ADOT roadway maintenance costs*. https://azmag.gov/Portals/0/Documents-Ext/FLCP/Roadway-Maintenance-Summary-Report-October-2019.pdf

Mascoop, D. R. (2017). [*High-speed rail and local land development: case studies in London and Las Vegas*] [Master's thesis]. Massachusetts Institute of Technology.

Missouri Department of Transportation. (2024). *643.4 railroads – Engineering policy guide*. Retrieved June 23, 2024, from https://epg.modot.org/index.php?title=643.4_Railroads&oldid=53348

Musselman, J. A., West, R. C., & Director, P. (2020). Life cycle cost analysis–end of life considerations NCAT report 20–05.

Narisada, K., & Schreuder, D. (2004). *Light pollution handbook, volume 322*. Springer Science & Business Media. https://doi.org/10.1007/978-1-4020-2666-9

National Highway Traffic Safety Administration. (2021, August). Traffic safety facts 2019: A compilation of motor vehicle crash data. DOT HS 813141.

National Railroad Passenger Corporation. (2016). *National fact sheet FY 2016*. Retrieved April 5, 2022, from https://www.amtrak.com/content/dam/projects/dotcom/english/public/documents/corporate/nationalfactsheets/National-Fact-Sheet-FY2016-0717.pdf

National Railroad Passenger Corporation. (2021). *Amtrak host railroad report card 2020*. https://www.amtrak.com/content/dam/projects/dotcom/english/public/documents/corporate/HostRailroadReports/Amtrak-2020-Host-Railroad-Report-Card-FAQs.pdf

Nolte, C. (2020). High-resolution land value maps reveal underestimation of conservation costs in the United States. *Proceedings of the National Academy of Sciences of the United States of America*, *117*(47), 29577–29583. https://doi.org/10.1073/pnas.2012865117

North Carolina Department of Transportation. (2024). *Roadway Design Manual – Chapter 14 – Right of Way*. Retrieved June 28, 2024, from https://connect.ncdot.gov/projects/Roadway/Pages/RDM.aspx

Premack, R. (2022). *Washington lawmakers still believe there's a truck driver shortage*. Retrieved on May 26, 2023, from https://www.freightwaves.com/news/washington-lawmakers-still-believe-theres-a-truck-driver-shortage

Quinet, A. (2019). *The value for climate action – A shadow price of carbon for evaluation of investments and public policies*. France Stratégie. Retrieved June 26, 2024, from https://www.strategie.gouv.fr/sites/strategie.gouv.fr/files/atoms/files/fs-the-value-for-climate-action-final-web.pdf.

Rezvani, A. Z., Peach, M., Thomas, A., Cruz, R., & Kemmsies, W. (2015). Benefit-cost methodology for highway-railway grade crossing safety protocols as applied to Transportation Infrastructure Project Prioritization Processes. *Transportation Research Procedia*, *8*, 89–102. https://doi.org/10.1016/j.trpro.2015.06.045

Root, T. (2019, September). *Tires: The plastic polluter you never thought about*. National Geographic, 20. Retrieved September 2022, from https://www.nationalgeographic.com/environment/article/tires-unseen-plastic-polluter

Seiler, A., Olsson, M., Rosell, C., & Van Der Grift, E. A. (2016). SAFEROAD safe roads for wildlife and people: Cost-benefit analyses for wildlife and traffic safety. Technical report, CEDR.

Shrestha, J., Uddin, M., & Adebiyi, J. (2021). Calculating ad user cost for specific sections of highway for use in alternative contracting project. Technical report, Tennessee, Department of Transportation.

Siciliano, G., Barontini, F., Islam, D. M., Zunder, T. H., Mahler, S., & Grossoni, I. (2016). Adapted cost-benefit analysis methodology for innovative railway services. *European Transport Research Review*, *8*(4), 1–14. https://doi.org/10.1007/s12544-016-0209-5

Silva, E., Marco, A., da Graça, J., Pérez, H., Abella, E., Patino-Martinez, J., Martins, S., & Almeida, C. (2017). Light pollution affects nesting behavior of loggerhead turtles and predation risk of nests and hatchlings. *Journal of Photochemistry and Photobiology. B, Biology*, *173*, 240–249. https://doi.org/10.1016/j.jphotobiol.2017.06.006

Solomon, T., & Singer, N. (2021). *Freight activity in the U.S. expected to grow fifty percent by 2050*. Retrieved on May 29, 2023, from https://www.bts.gov/newsroom/freight-activity-us-expected-grow-fifty-percent-2050

Spasovic, L., Zhang, W., Besenski, D., & Pathak, C. (2018). Modeling the impacts of changes in freight demand, infrastructure improvements and policy measures on a metropolitan region. Technical report, Rutgers University. Center for Advanced Infrastructure and Transportation.

Sullivan, D. E. (2006). *Materials in use in U.S. interstate highways*. USGS Fact Sheet 2006-3127. Retrieved September 2022, from https://pubs.usgs.gov/fs/2006/3127/

Surface Transportation Board. (2022). *Annual report financial data 2020*. Retrieved May 13, 2022, from https://www.stb.gov/reports-data/economic-data/annual-report-financial-data/

Svechkina, A., Portnov, B. A., & Trop, T. (2020). The impact of artificial light at night on human and ecosystem health: A systematic literature review. *Landscape Ecology*, *35*(8), 1725–1742. https://doi.org/10.1007/s10980-020-01053-1

Tolliver, D. D., & Lindamood, B. A. (1993). Chaffee junction to Chaffee benefit cost analysis. Retrieved September 30, 2022 ,from https://www.ugpti.org/resources/reports/downloads/sp-114.pdf

Transportation for America. (2019). Repair priorities. Retrieved September 28, 2022, from https://t4america.org/wp-content/uploads/2019/05/Repair-Priorities-2019.pdf

Trumbull, N., Bae, C. (2000, January). *Transportation and water pollution*. Retrieved October 2022, from https://courses.washington.edu/gmforum/topics/trans_water/trans_water.htm

U.S. Department of Transportation. (2016). The value of travel time savings: Departmental guidance for conducting economic evaluations revision 2. Retrieved August 21, 2022, from https://www.transportation.gov/sites/dot.gov/files/docs/2016%20Revised%20Value%20of%20Travel%20Time%20Guidance.pdf

U.S. Department of Transportation. (2022, March 18). Benefit-cost analysis guidance for discretionary grant programs. Transportation Policy. Retrieved April 19, 2022, from https://www.transportation.gov/office-policy/transportation-policy/benefit-cost-analysis-guidance-discretionary-grant-programs-0

U.S. Energy Information Administration. (2022). *Gasoline and diesel fuel update*. Petroleum & Other Liquids. Retrieved May 13, 2022, from https://www.eia.gov/petroleum/gasdiesel/

U.S. Environmental Protection Agency. (2018). 2018 SMARTWAY logistics company partner tool: Technical documentation U.S. version 2.0.17. Technical report.

U.S. Environmental Protection Agency. (2021, April 1). *Emission factors for greenhouse gas inventories*. GHG Emission Factors Hub. Retrieved March 20, 2022, from https://www.epa.gov/sites/default/files/2021-04/documents/emission-factors_apr2021.pdf

U.S. Federal Railroad Administration. (1990). Benefit-cost methodology for the local rail freight assistance program. Technical report, Federal Railroad Administration.

Vanek, F. (2019). Mode and commodity perspectives on us freight energy consumption and CO2 emissions: Insights and directions for improvement. *International Journal of Sustainable Transportation*, *13*(10), 741–760. https://doi.org/10.1080/15568318.2018.1512690

Walls, J., & Smith, M. R. (2018, March 5). Life-cycle cost analysis in pavement design—interim technical bulletin. Technical report, Federal Highway Administration.

Walther, C., Monse, J., & Haßheider, H. (2015). Revision of project evaluation as part of the German federal transport infrastructure plan. *Transportation Research Procedia*, *8*, 41–49. https://doi.org/10.1016/j.trpro.2015.06.040

Washington State Department of Transportation. (2002, April 1). Highway construction cost comparison survey: Final report. National Transportation Library. Technical report, Washington State Department of Transportation.

Wisconsin Department of Transportation. (2019). *Facilities development manual*. Retrieved June 23, 2024, from https://wisconsindot.gov/rdwy/fdm/fd-17-55.pdf

Appendix A

Freight volume calculation under actual and maximum flows

In the United States, two primary sources of transportation data are the BTS (Bureau of Transportation Statistics, 2021b, 2022b) and the Freight Analysis Framework 4 (Bureau of Transportation Statistics, 2022a). These datasets were employed to convert the total values of specified metrics into dollars per ton-mile units. The numerical values in Tables 5 and 6 pertain to the actual transportation scenario. Data for highways were gathered for the years 2016, 2018, 2019, and 2020, while railroad data is specifically from the year 2020. Both modes encompass metrics such as annual ton-miles, tons hauled, and vehicle miles.

In addition to acquiring historical freight traffic volumes, we have calculated average and maximum annual ton-miles for both highways and railroads using theoretical models. Table 7 presents the parameters for both scenarios. In the maximum scenario, we assume that highways remain consistently busy 24 h a day, with a load factor of 80%. The actual truckload is determined by multiplying the truckload by the load factor.

We utilize the following equation to calculate the average volume of trucks traversing a randomly selected point within the U.S. highway network throughout the year, commonly known as the average flow:

$$Hourly\ flow(vehicles/hr) = density(vehicles/mile) \times speed(mph) \quad (34)$$

According to table 4-2 in Freight Facts and Figures 2015, the average truck speed on interstates can be approximated at 55 mph (Chambers et al., 2015). Additionally, research conducted by Liu et al. (2019) on the speed-density relationship provides valuable insights. Under free-flow conditions, when the speed is 90 km/h (approximately 56 mph), the density is estimated to be around 15 vehicles/km. Converting this to miles, the density is approximately 25 vehicles/mile. It is important to note that these vehicles refer to passenger cars, so a conversion is needed to obtain truck flow. Typically, one truck is equivalent to the traffic impact of three passenger cars. Therefore, at the speed of 55 mph, we derived the density of 8.33 trucks/ mile. Consequently, the average annual highway truck flow can be estimated as follows:

$$\begin{aligned} Flow(vehicles/year) &= 8.33(trucks/mile) \times 55(mph) \times 10(working\ hr) \\ &\quad \times 365(days/year) \\ &= 1,672,917(trucks/year\ at\ a\ random\ location) \end{aligned} \quad (35)$$

To calculate annual freight ton-miles from the estimated truck flow, we multiply the number of trucks per year by the length of the National Highway system, which is 161,188 miles. We also take into account a practical load of 8.475 tons. This figure is calculated based on the maximum load of 25 tons, adjusted for an average load factor of 57%. It also considers empty movements, which constitute approximately 20-35% of truck miles (American Council for an Energy-Efficient Economy, 2021). To put it simply, the actual load is approximately 33.90% of the maximum truckload. Consequently, we can determine the theoretically estimated annual average highway freight ton-miles as follows:

$$\begin{aligned} &Annual\ average\ highway\ ton-miles \\ &= 8.33(trucks/mile) \times 55(mph) \times 10(working\ hr) \times 365(days/year) \\ &\quad \times 161,188(miles) \times 8.475(tons) \\ &= 2,285,318,426,887(ton-miles) \end{aligned} \quad (36)$$

When comparing this theoretical estimation with the actual ton-miles of 2,233,588,364,732 in 2020, the estimated ton-miles value is only 2.32% higher than the actual data. This slight difference falls within an acceptable range, validating our calculation procedure. If we assume that trucks consistently flow along the U.S. highways 24 h a day with a higher load factor of 80%, we can calculate the estimated annual maximum highway ton-miles as follows:

$$\begin{aligned} &Annual\ maximum\ highway\ ton-miles \\ &= 8.33(trucks/mile) \times 55(mph) \times 24(working\ hr) \times 365(days/year) \\ &\quad \times 161,188(miles) \times 20(tons) \\ &= 12,943,396,400,000(ton-miles) \end{aligned} \quad (37)$$

Table 5. Actual U.S. highway volumes by year, including ton-miles, tons hauled, and vehicle miles.

Year	Freight ton-miles	Tons hauled	Vehicle miles
2016	2,060,780,000,000	11,595,143,427	287,895,000,000*
2018	2,033,921,000,000	11,920,161,455	304,864,000,000
2019	2,070,450,924,800	- *	300,051,000,000
2020	2,233,588,364,732	12,417,522,921	302,141,000,000

Note. * indicates that the data is not applied to the calculation.

Table 6. Actual U.S. railroad volumes in 2020.

Railroads	Railroad freight ton-miles	Railroad tons hauled	Freight train miles
Class I	1,439,814,000,000	1,389,076,087*	381,000,000
BNSF	588,919,405,000	511,801,000*	144,392,892*

Note. * indicates that the data is not applied to the calculation.

Table 7. Estimated characteristics of highway freight operations.

Parameter	Average	Maximum	Parameter	Average	Maximum
Density (trucks per lane mile)	8.33	8.33	Truckload (tons)	25	25
Speed (mph)	55	55	Load factor	33.90%	80.00%
Operating hours	10	24	Actual load (ton)	8.475	20
Operating days	365	365			

Table 8. Estimated characteristics of railroad freight operations.

Parameter	Average	Maximum	Parameter	Average	Maximum
Tons per Carload	52.9	110	Daily Trains at a Location	12	50
Cars per Train	77.1	130	Class I Miles in 2019	92,190	
Tons per Train	4,079	14,300	BNSF Miles in 2020	22,384	

Similarly, we have estimated the average and maximum railroad ton-miles per year using the parameters listed in Table 8. According to the Railroad Facts 2021 published by the Association of American Railroads (Association of American Railroads, 2021), the average cargo weight per carload in 2020 was estimated to be 52.9 tons. For Class I railroads, the average number of cars per freight train was reported as 77.1 cars in the same year (Association of American Railroads, 2021). By multiplying these figures, we can calculate the cargo per trainload, which amounted to 4,079 tons. Note that these carload and trainload values already account for empty freight cars. In terms of the daily train frequency at a randomly selected point within the U.S. railroad network, our estimates are grounded in consultations with experts in the field. We have considered an average of 12 trains per day, with a maximum limit set at 50 trains daily. The total U.S. miles of railroads is 136,729 miles for the freight rail network, including Class I, Regional, and Local railroads, with Class I railroads owning 92,190 miles of this network (Association of American Railroads, 2021). These miles of road represent the length of railways within the United States and exclude the extension of the Canadian Railroad. Additionally, "miles of road" refers to the total length of the railway system and does not specify the total length of tracks, as a unit of road may consist of multiple tracks. Yard tracks and sidings are also excluded from this number.

Assuming year-round operations for Class I railroads, we can estimate an annual flow of 4,380 trains at a random location. This calculation is derived by multiplying the daily rate of 12 trains by the total number of days in a year, resulting in 4,380 trains annually. When this figure is multiplied by the extent of Class I railroad road ownership, which spans 92,190 miles, the result is 403,792,200 train-miles per year. Then, we multiply the annual train-miles by the average load per train, set at 4,079 tons. The product of this calculation yields a total of 1,646,902,828,998 ton-miles of annual rail freight. The detailed calculation is as follows:

$$\begin{aligned} &Annual\ average\ Class\ I\ ton-miles \\ &= 4,380(trains/year) \\ &\times 92,190(miles) \\ &\times 4,079(tons/train) \\ &= 1,646,902,828,998(ton-miles) \end{aligned} \tag{38}$$

When comparing this theoretically estimated annual freight ton-miles with the actual ton-miles from FAF in 2020, we observed that the estimated ton-miles are 14.38% higher than the actual data, which falls within an acceptable range. To derive the estimation for the maximum potential ton-miles, two assumptions were made. Firstly, we assumed that the average cargo weight per carload is 110 tons. Secondly, we assumed that the average number of cars per freight train is 130. Multiplying these values, we calculated an average cargo load per train of 14,300 tons. Assuming that BNSF operates 365 days a year with 50 trains per day at a random location, the total number of trains per year would be 18,250. Based on these considerations, we computed the theoretically estimated annual maximum railroad ton-miles as follows:

$$\begin{aligned} &Annual\ maximum\ Class\ I\ ton-miles \\ &= 18,250(trains/year) \times 92,190(miles) \times 14,300(tons/train) \\ &= 24,059,285,250,000(ton-miles) \end{aligned} \tag{39}$$

By comparing the theoretically estimated annual freight ton-miles to the actual ton-miles in 2020, we observed a slight variance of only 1.85%, indicating the precision and dependability of our estimation. Since comprehensive expense data for Class I railroads is not publicly available, we have chosen to use BNSF as a representative for estimating certain costs and benefits. To calculate both the average and maximum flow of BNSF, we utilized the company's mileage data, which indicates that BNSF owns and operates a total of 22,384 miles of main track (Surface Transportation Board, 2022). This figure excludes yard tracks, sidings, and the Canadian Railroad extension. Assuming continuous operation throughout the year, we estimated the annual flow of BNSF at a random location by multiplying the average of 18 trains per day by 365, resulting in an estimated 6,570 trains per year at a random location. For the cargo load per train, we used the previously mentioned average trainload for Class I railroads, which stands at 4,079 tons. By multiplying these figures, we arrived at the following detailed calculation:

$$\begin{aligned} &Annual\ average\ BNSF\ ton-miles \\ &= 6,570(trains/year) \\ &\times 22,384(miles) \\ &\times 4,079(tons/train) \\ &= 599,809,191,739(ton-miles) \end{aligned} \tag{40}$$

To estimate the maximum flow in ton-miles for BNSF, we will apply the same conditions used for Class I railroads, involving an average cargo weight per carload of 110 tons and an average number of cars per freight train of 130. When we multiply these values, we arrive at an average cargo load per train of 14,300 tons. Assuming BNSF's continuous operation 365 days a year with 50 trains per day at a random location, the total number of trains per year will amount to 18,250. Based on these parameters, we calculated the theoretically estimated annual maximum railroad ton-miles as follows:

$$\begin{aligned} &Annual\ maximum\ BNSF\ ton-miles \\ &= 18,250(trains/year) \times 22,384(miles) \times 14,300(tons/train) \\ &= 5,841,664,400,000(ton-miles) \end{aligned} \tag{41}$$