

The Potential Influence of the Cost of Carbon on Asphalt Pavement Construction

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A thesis

submitted in partial fulfillment of the
requirements for the degree of

Master of Science in Civil Engineering

University of Washington

2025

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Program Authorized to Offer Degree:

Civil and Environmental Engineering

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Abstract

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Life Cycle Cost Analysis (LCCA) is a decision support method used in the roadway industry to compare the financial differences between alternative paving options. This project considers how the cost of carbon may be incorporated into LCCA studies, and what impact that may have on decision-making. A literature review on existing carbon costing avenues determined \$35/MTCO_{2e} at a discount rate of 2% to be a representative metric for case study analysis. Performing three Washington State highway paving case studies through the RealCost 3.0 software produced separate agency and user costs. The agency cost of carbon is calculated through the asphalt material's global warming potential (GWP), while the user cost of carbon is based on excess vehicle emissions due to traffic delays. At the previously assigned unit cost of carbon, case study LCCA results showed the cost of carbon to contribute around 1% of total agency and user value. A further sensitivity analysis determined that in order to reach 10% of project value, the cost of carbon would need to be between \$300 and \$500 per MTCO_{2e}. These results demonstrated that the value of greenhouse gas emissions would need to be much higher in order for it to play a significant role in decision-making in the pavement industry.

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Acknowledgments

These last two years at The University of Washington have been incredible, and I've learned so much as I've worked towards this master's thesis, supported by wonderful faculty and my peers. Primarily, I would like to thank my advisor Dr. Steve Muench, who provided me with continuous funding and supported me learning a new discipline in the world of pavement sustainability throughout this program. He also has fully encouraged me to follow my career goals (teaching), as well as my extracurricular pursuits (lots of climbing). I would also like to thank the rest of my committee, Dr. Joe Mahoney, Dr. Milad Ashtiani, and Dr. Julian Yamaura, for being such helpful members of the department and supporting me through my thesis defense. Additionally, thank you to Dr. Bethany Gordon for inviting me into her lab during my first year to teach me more about how research takes place in higher education.

I would also like to acknowledge the people at the Washington State Department of Transportation (WSDOT) and the Washington Asphalt Pavement Association (WAPA) who provided supporting documentation for the SR 5 case study in this thesis, namely Mrs. Karen Carlie, Mr. David Gent, and Mrs. Kim Schofield. Additionally, thank you to WAPA for awarding me a scholarship for the research contained in this paper.

Finally, many thanks to everyone in my CESI cohort, for offering academic support on top of their friendship, especially Abbey Murray, Kieran Basheer, and Ashlyn Aldridge. I also could not have made it through this program without my partner, Allison Burkhalter, who has provided her unwavering support for the last four years.

1 Introduction

With climate change's acceleration, anthropogenic greenhouse gas emissions are a well-discussed issue, and infrastructure decision-making now discusses the financial value of carbon emissions as well. President Biden's 2021 Bipartisan Infrastructure Law (BIL) specifically allocated billions of dollars towards carbon reduction efforts, a large share of which were tied to transportation infrastructure (Fact Sheet: Climate and Resilience in the Bipartisan Infrastructure Law, 2022). While the Trump administration has stepped back from federal carbon reduction measures, many other organizations and individual states remain committed to combatting climate change. The National Asphalt Pavement Association (NAPA) still promotes their 'Road Forward' initiative, which envisions an asphalt pavement industry with net zero carbon emissions (*The Road Forward*, 2025). 33 US states currently have climate action plans, and three emissions trading markets exist across the country (State Climate Policy Maps, n.d.). With a present interest in reducing carbon emissions, structures to value its financial impact must exist. Life cycle cost analysis (LCCA) is "an analysis technique that builds on the well-founded principles of economic analysis to evaluate the over-all-long-term economic efficiency between competing alternative investment options [...] and incorporates initial and discounted future agency, user, and other relevant costs over the life of alternative investments" (Federal Highway Administration, 1998). While existing LCCA frameworks provide a logical path to incorporate the cost of carbon, several issues remain. Primarily, methods of performing life cycle cost analysis on carbon emissions are largely unexplored. In addition, the cost of carbon itself is a contentious issue, with conflicting values across government reporting, academic research, and privatized markets. This thesis addresses the following research question:

How does incorporating the cost of carbon into life cycle cost analysis influence decision-making in the roadway construction industry?

This thesis addresses the research question by performing LCCA's as operationalized by RealCost 3.0 to determine life cycle costs for three asphalt pavement case studies. It then incorporates a separately determined unit cost of carbon into these life cycle costs to measure carbon's impacts on overall project costs, through both the embodied carbon of pavement construction and excess vehicle emissions resulting from work zone delays. Overall, this paper attempts to quantify the cost of carbon in relation to the life cycle costs of pavement construction. While these case studies do not reach statistical significance, they do provide insight into the relationship between these topics, as well as some guidance on where to begin future work.

2 Background

Life cycle cost analysis in the pavement sector is a well-established field of study. Keyword searching ("LCCA" AND "pavement") yields 323 records on the Engineering Village database. However, incorporating the cost of carbon into life cycle cost analysis is still a fairly new research topic. I refined my search to ("LCCA" AND "cost of carbon" AND "pavement"), which produced one paper (Ibrahim et al., 2024). This study performed life cycle cost analysis on asphalt pavements made partially from renewable materials and factored the social cost of

carbon (SCC) into its evaluation. Using a SCC of \$185/MTCO₂e, this paper considered the environmental savings attained by using a form of green asphalt over typical HMA mix designs (Ibrahim et al., 2024). The SCC used comes from a 2022 paper that suggests a mean cost of carbon estimate of \$185/MTCO₂e at a 2% discount rate (Rennert et al., 2022). While this article from Ibrahim does incorporate the cost of carbon into LCCA work, it does so in order to measure the environmental cost reductions of using a green asphalt mix, which is beyond the scope of this thesis.

I broadened my search to (life cycle cost analysis AND “cost of carbon” AND “building”), which produced 13 papers. The first of these articles applied varying social costs of carbon (\$55.1, \$86.4, \$377, \$77.2, and \$73.4/MT/CO₂e) to building construction LCCA studies, with SCC values based on five different climate scenarios (Pajgade et al., 2025). Study authors determined that “the discount rate, cost of carbon, average electricity consumption, and itemized rates have the most significant impact on total life cycle costs, with variations leading to approximately 5% – 6% changes in overall cost” (Pajgade et al., 2025). Though this paper applies different costs of carbon to construction LCCA’s, it considers a broad selection of variables beyond just the SCC.

One paper I found outside of this keyword searching method asks how incorporating the SCC into building construction LCCA’s may influence the decision to build a new structure or to renovate. This study applied two different values for the social cost of carbon: 242 EUR/MTCO₂e and 830 EUR/MTCO₂e (Nydahl et al., 2022). These values convert to \$274/MTCO₂e and \$939/MTCO₂e, respectively (*Euro Dollar Exchange Rate (EUR USD) - Historical Chart*, n.d.). Nydahl et al. (2022) ranked the building alternatives relative to one another, then applied these two cost of carbon rates, determining that while increasing the SCC increases the overall LCCA value, it does not impact an alternative’s ranking relative to the others.

The three papers reviewed here all incorporate the cost of carbon into life cycle cost analysis within the construction industry. However, all apply different variables, including a wide range for the cost of carbon itself. In addition, all use the social cost of carbon as their carbon pricing strategy, and do not consider financial market pricing mechanisms in their analysis. Moreover, there are few papers that combine these topics in the pavement sector.

3 Literature Review

3.1 Introduction

This literature review analyzes different carbon pricing strategies (emissions trading systems, carbon taxes, carbon offsets, and the social cost of carbon) in order to determine a representative range for the unit cost of carbon. From here, a singular value is identified for use in economic analysis. In addition, this section reviews different methods of discounting the future and selects a discount rate for use in economic analysis.

3.2 Emissions Trading System (ETS) Markets

3.2.1 Introduction

The ideas in section 3.2.1 are cited from the Center for Climate and Energy Solutions' explanatory article on emissions trading systems (*Cap and Trade Basics*, 2024), specifically cap-and-trade markets, citation below:

Cap and Trade Basics. (2024, May). Center for Climate and Energy Solutions.
<https://www.c2es.org/content/cap-and-trade-basics/>

One way to determine the cost of carbon is through different trading markets. These markets are known as emissions trading systems (ETS). ETS markets are based on a region placing a cap, or limit, on emissions over a certain period. The total permitted emissions are then apportioned to participating businesses through a set of allowances. One allowance equals one metric ton of greenhouse gas emissions (MTCO_{2e}), and these are distributed either for free or through auctions. Free allowances are often granted to utility companies, due to the fluctuating price of retail energy. This allowance distribution system aims to limit emissions of individual companies. Over-emitting entities are compelled to buy more allowances, while businesses that have reduced their emissions can sell off unused allowances.

Auction prices start at a floor price and rise to a settlement price through the bidding process that all participating businesses pay, per metric ton of CO₂ equivalent (MTCO_{2e}). I corrected all auction settlement prices for inflation using the U.S. Labor Bureau's Consumer Price Index (CPI), inflating to December 2024 USD (*CPI Inflation Calculator*, n.d.). This section addresses emissions trading programs in Washington, California, the American Northeast, and the European Union.

The figures and tables provided list all available auction results for each program, but comparative analysis is limited to 2023 and 2024, primarily because only recent carbon prices are relevant. While older values can highlight trends, they do not represent the current state of the market. In addition, Washington's Cap-and-Invest market began in 2023, so this interval captures all Washington values and only analyzes other markets since Washington Cap-and-Invest has existed.

3.2.2 Washington – Cap-and-Invest Program

The ideas in section 3.2.2 are cited from Washington's Cap-and-Invest Program webpage (*Washington's Cap-and-Invest Program*, n.d.) and the International Carbon Action Partnership's factsheet for this program (*USA - Washington Cap-and-Invest Program*, n.d.), citations below:

USA - Washington Cap-and-Invest Program. (n.d.). International Carbon Action Partnership. Retrieved February 20, 2025, from <https://icapcarbonaction.com/en/ets/usa-washington-cap-and-invest-program>

Washington's Cap-and-Invest Program. (n.d.). Department of Ecology - State of Washington. Retrieved February 20, 2025, from <https://ecology.wa.gov/Air-Climate/Climate-Commitment-Act/Cap-and-invest>

3.2.2.1 Description

On January 1, 2023, the Department of Ecology in Washington began its statewide Cap-and-Invest Program. Quarterly emissions auctions began February 2023, with 8 auctions having occurred as of December 2024.

3.2.2.2 Legislative Origin

This emissions allowance program was created out of the 2021 Climate Commitment Act (CCA), passed by the Washington State Legislature. The CCA identifies the need for a market-based solution to greenhouse gas reduction.

3.2.2.3 Markets Addressed

All companies that emit at least 25,000 MTCO₂e per year are included in this Cap-and-Invest Program. This amounts to around 150 participating businesses as of 2023, including industrial facilities, electricity generators and importers, fuel distributors, and natural gas suppliers. Waste-to-energy facilities will be onboarded in 2027, and railroads in 2031. In its current phase, this program addresses around 70% of statewide emissions.

3.2.2.4 ETS Goals

The greenhouse gas reduction goals of this trading system mirror those in state law, based on 1990 emissions levels: 45% reduction by 2030, 70% by 2040, and 95% by 2050. There is also a broader goal of reaching net-zero emissions by 2050. This ETS program divides its emissions targets into multiple compliance periods, depicted in Figure 1. In Period 1, the total cap reduces by 7% annually, with a target of 49 million MTCO₂e in 2026. The blue dashed line shows this cap reduction, while the red horizontal lines illustrate when the decade reduction goals (45%, 70%, 95%) should be met.

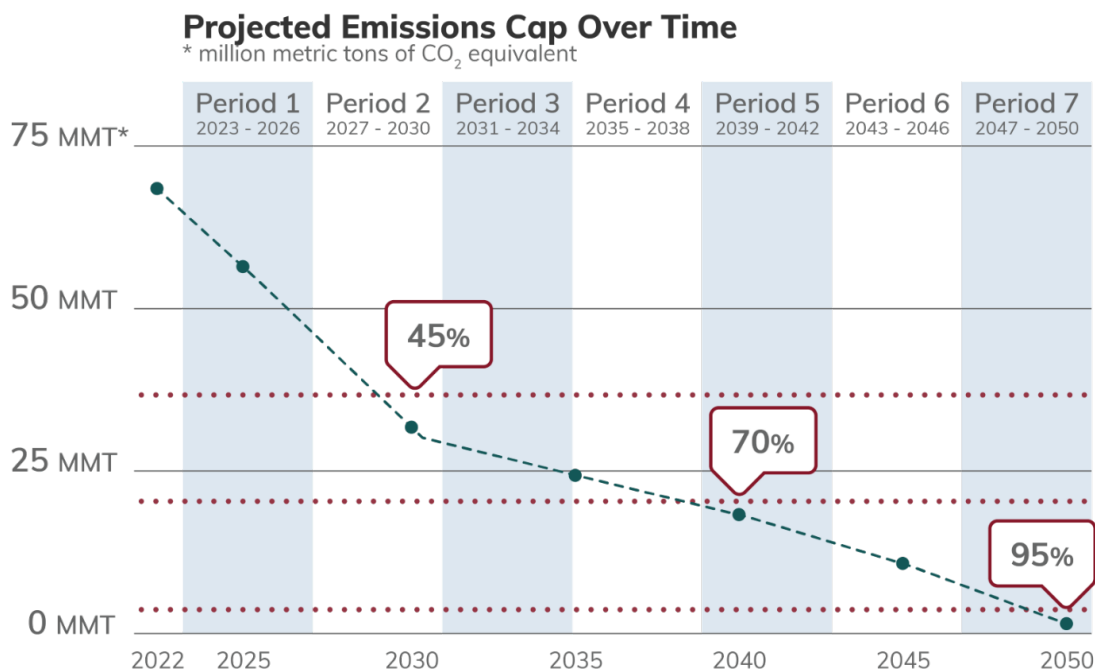


Figure 1 – Projected Emissions Cap for Washington’s ETS Market (*Washington’s Cap-and-Invest Program*, n.d.).

3.2.2.5 Auction Data

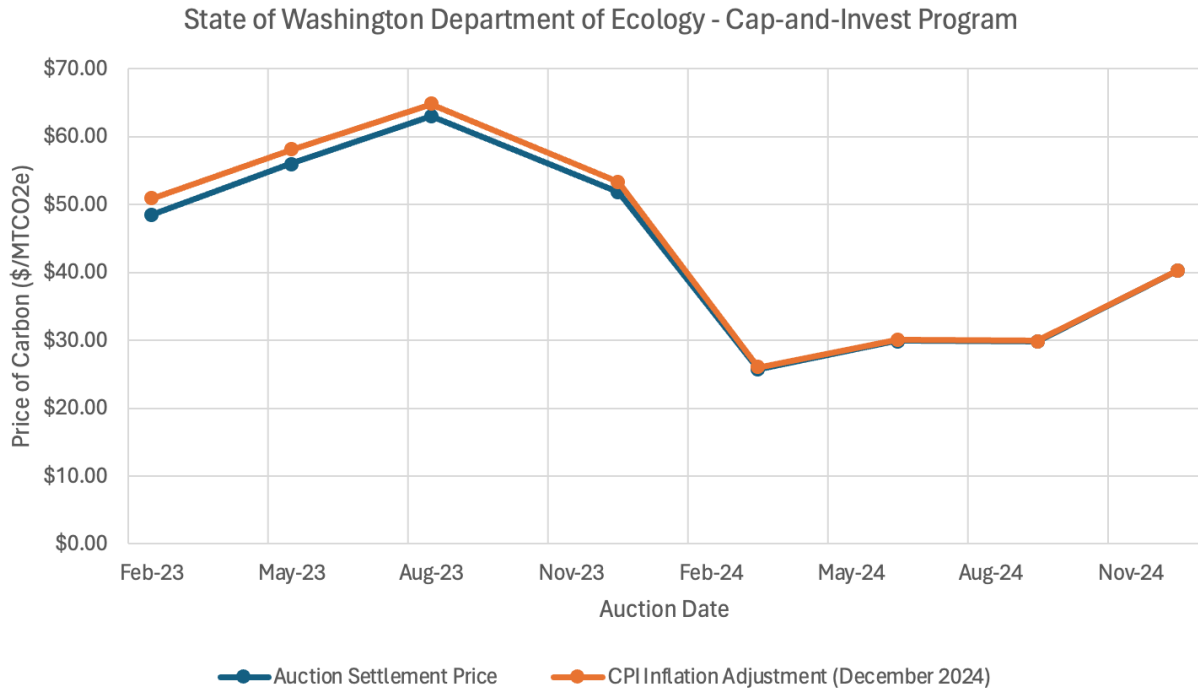


Figure 2 and Table 1 show the settlement price history of Washington’s ETS auctions, along with the CPI inflation correction to December 2024.

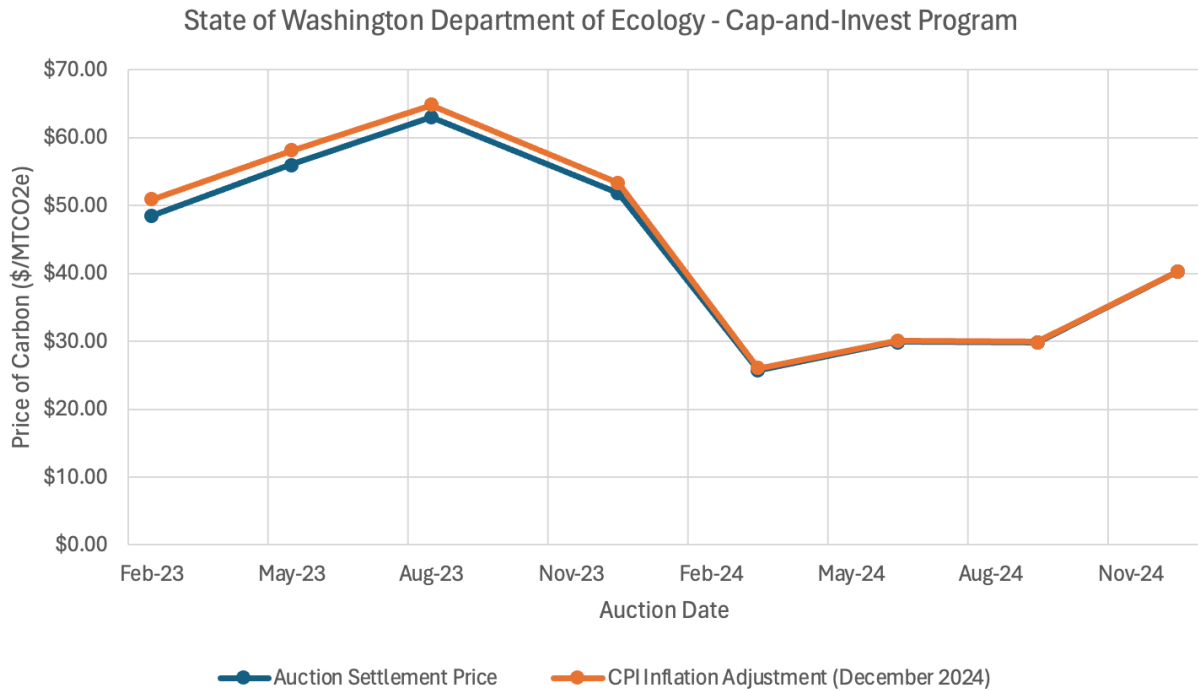


Figure 2 - Auction Results from Washington State’s Cap-and-Invest Program.

Table 1 - Settlement Prices for Washington State’s Cap-and-Invest Auctions

Auction Number	Auction Date	Allowance Settlement Price	CPI Inflation Adjustment (December 2024)
1	Feb-23	\$48.50	\$50.88
2	May-23	\$56.01	\$58.12
3	Aug-23	\$63.03	\$64.79
4	Dec-23	\$51.89	\$53.39
5	Mar-24	\$25.76	\$26.03
6	Jun-24	\$29.92	\$30.06
7	Sep-24	\$29.88	\$29.91
8	Dec-24	\$40.26	\$40.26

Over this two-year period, settlement prices ranged between \$26.06 and \$64.79 per MTCO₂e, with a mean value of \$44.18/MTCO₂e.

3.2.3 California – Cap-and-Trade Program

The ideas in section 3.2.3 are cited from California's Cap-and-Trade Program webpage (*Cap-and-Trade Program*, n.d.) and the International Carbon Action Partnership's factsheet for this program (*USA - California Cap-and-Trade Program*, n.d.), citations below:

Cap-and-Trade Program. (n.d.). California Air Resources Board. Retrieved February 20, 2025, from <https://ww2.arb.ca.gov/our-work/programs/cap-and-trade-program>

USA - California Cap-and-Trade Program. (n.d.). International Carbon Action Partnership. Retrieved February 20, 2025, from <https://icapcarbonaction.com/en/ets/usa-california-cap-and-trade-program>

3.2.3.1 Description

Developed by the state's Air Resources Board, California's Cap-and-Trade Program has run allowance auctions since November 2012. In 2013, it linked with Quebec's ETS market, and since then auctions have run jointly. To date, 49 auctions have taken place.

3.2.3.2 Legislative Origin

Passed in 2006, California Assembly Bill 32 mandated the state to return to 1990 levels of emissions by 2020. This legislation was the first of its kind in the United States and paved the way for the state's Cap-and-Trade Program to be implemented a few years later.

3.2.3.3 Markets Addressed

All companies that emit at least 25,000 MTCO₂e per year are included in this Cap-and-Trade Program. This amounts to around 400 participating businesses as of 2015, representing the following sectors: large industrial facilities, electricity generators and importers, and natural gas and fuel suppliers. As of 2021, this program addresses around 76% of the state's total emissions.

3.2.3.4 ETS Goals

This program delineates certain compliance periods through which it identifies greenhouse gas reduction goals, based on 1990 emissions levels. By 2030, it targets a 40% reduction, to reach a

200.5 million MTCO₂e cap. By 2045, it aims to reduce emissions by 85% and achieve carbon neutrality.

3.2.3.5 Auction Data

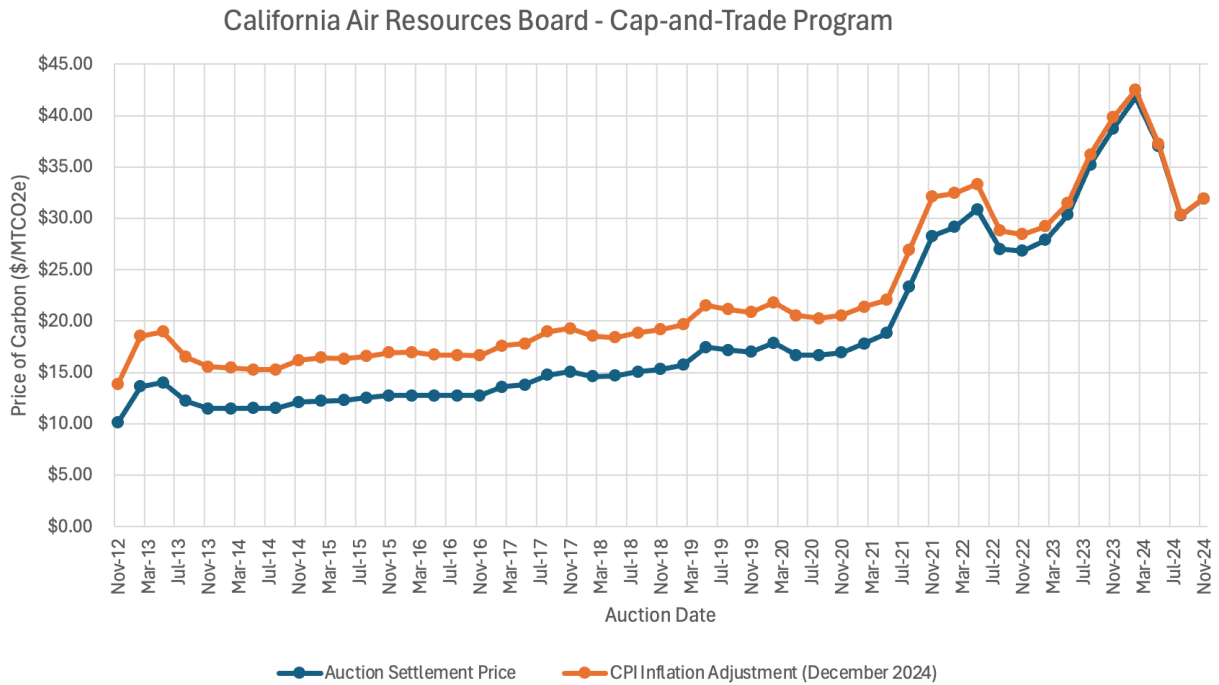


Figure 3 and Table 2 show the settlement price history of California’s ETS auctions, along with the CPI inflation correction to December 2024.

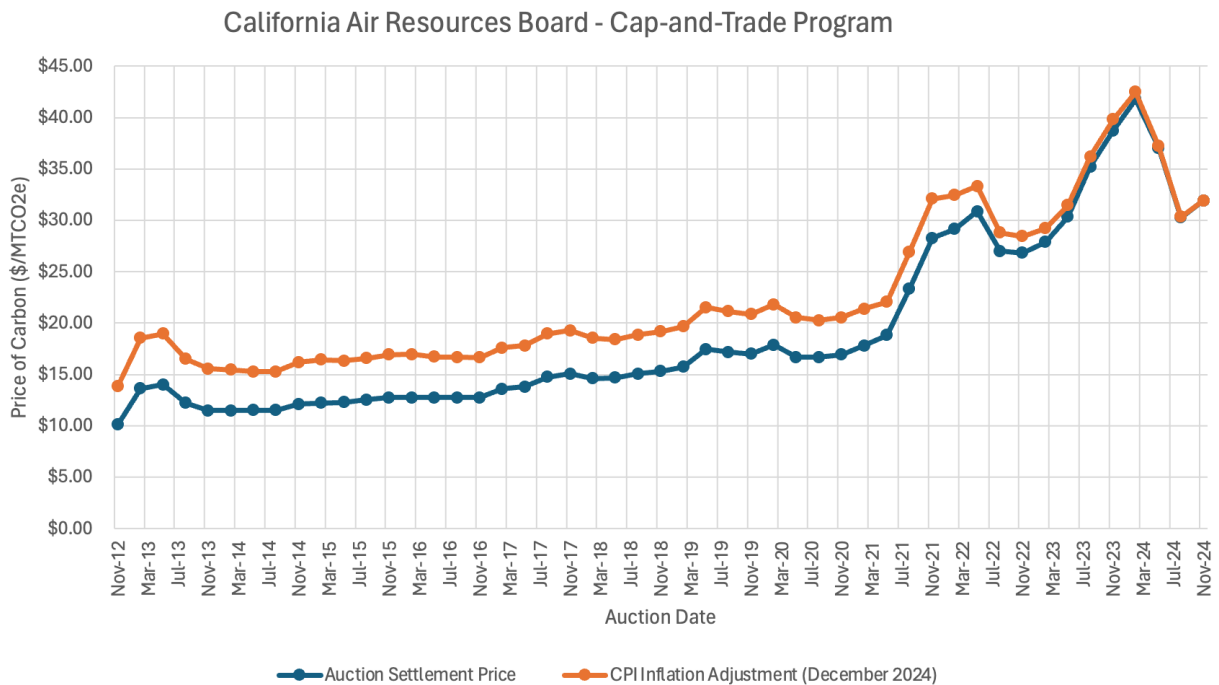


Figure 3 – Auction Results from California’s Cap-and-Trade Program.

Table 2 – Settlement Prices for California’s Cap-and-Trade Auctions

Auction Number	Auction Date	Current Auction Settlement Price	CPI Inflation Adjustment (December 2024)
1	Nov-12	\$10.09	\$13.83
2	Feb-13	\$13.62	\$18.51
3	May-13	\$14.00	\$18.97
4	Aug-13	\$12.22	\$16.49
5	Nov-13	\$11.48	\$15.55
6	Feb-14	\$11.48	\$15.43
7	May-14	\$11.50	\$15.26
8	Aug-14	\$11.50	\$15.26
9	Nov-14	\$12.10	\$16.17
10	Feb-15	\$12.21	\$16.42
11	May-15	\$12.29	\$16.31
12	Aug-15	\$12.52	\$16.58
13	Nov-15	\$12.73	\$16.93
14	Feb-16	\$12.73	\$16.94
15	May-16	\$12.73	\$16.72
16	Aug-16	\$12.73	\$16.68
17	Nov-16	\$12.73	\$16.65
18	Feb-17	\$13.57	\$17.58
19	May-17	\$13.80	\$17.80
20	Aug-17	\$14.75	\$18.96
21	Nov-17	\$15.06	\$19.27
22	Feb-18	\$14.61	\$18.52
23	May-18	\$14.65	\$18.38
24	Aug-18	\$15.05	\$18.84
25	Nov-18	\$15.31	\$19.17
26	Feb-19	\$15.73	\$19.64
27	May-19	\$17.45	\$21.51
28	Aug-19	\$17.16	\$21.11
29	Nov-19	\$17.00	\$20.86
30	Feb-20	\$17.87	\$21.80
31	May-20	\$16.68	\$20.53
32	Aug-20	\$16.68	\$20.25
33	Nov-20	\$16.93	\$20.53
34	Feb-21	\$17.80	\$21.36
35	May-21	\$18.80	\$22.04
36	Aug-21	\$23.30	\$26.88
37	Nov-21	\$28.26	\$32.09

Auction Number	Auction Date	Current Auction Settlement Price	CPI Inflation Adjustment (December 2024)
38	Feb-22	\$29.15	\$32.43
39	May-22	\$30.85	\$33.31
40	Aug-22	\$27.00	\$28.77
41	Nov-22	\$26.80	\$28.41
42	Feb-23	\$27.85	\$29.22
43	May-23	\$30.33	\$31.47
44	Aug-23	\$35.20	\$36.18
45	Nov-23	\$38.73	\$39.81
46	Feb-24	\$41.76	\$42.47
47	May-24	\$37.02	\$37.20
48	Aug-24	\$30.24	\$30.32
49	Nov-24	\$31.91	\$31.92

A gradual upward trend in pricing over the 2010’s is observed, with larger fluctuations occurring in the last five years. Through 2023 and 2024, which includes auctions 42 through 49, settlement prices ranged between \$29.22 and \$42.47/MTCO₂e, with a mean value of \$34.82/MTCO₂e.

3.2.4 Regional Greenhouse Gas Initiative – Carbon Allowance Market

The ideas in section 3.2.4 are cited from (unless otherwise noted) the Regional Greenhouse Gas Initiative’s webpage (*The Regional Greenhouse Gas Initiative*, n.d.) and the International Carbon Action Partnership’s factsheet for this program (*USA - Regional Greenhouse Gas Initiative (RGGI)*, n.d.), citations below:

The Regional Greenhouse Gas Initiative. (n.d.). RGGI, Inc. Retrieved February 20, 2025, from <https://www.rggi.org/>

USA - Regional Greenhouse Gas Initiative (RGGI). (n.d.). International Carbon Action Partnership. Retrieved February 20, 2025, from <https://icapcarbonaction.com/en/ets/usa-regional-greenhouse-gas-initiative-rggi>

3.2.4.1 Description

The Regional Greenhouse Gas Initiative (RGGI) runs a carbon allowance market representing the American Northeast. Participating states include Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, and Vermont. The RGGI has run ETS auctions since October 2008, and to date 66 auctions have occurred.

3.2.4.2 Legislative Origin

This program stems from a Memorandum of Understanding (MOU) signed in 2005 by the governors of participating states. This MOU called for emissions reductions throughout the American Northeast and thus led to the development of this mandatory market-based approach (*Regional Greenhouse Gas Initiative (RGGI)*, n.d.).

3.2.4.3 Markets Addressed

The RGGI Cap-and-Trade Program targets the power sector, specifically entities with annual energy production exceeding 25 MW. As of 2021, this program includes 228 facilities and addresses 14% of total emissions.

3.2.4.4 ETS Goals

The RGGI uses a declining cap basis for its total emissions, which means that over several control periods the total cap on emissions lowers in accordance with broader climate goals. Over nearly 20 years of operation, there have been six phases. In phase six, 2024 had a cap of 63 million MTCO_{2e}.

3.2.4.5 Auction Data

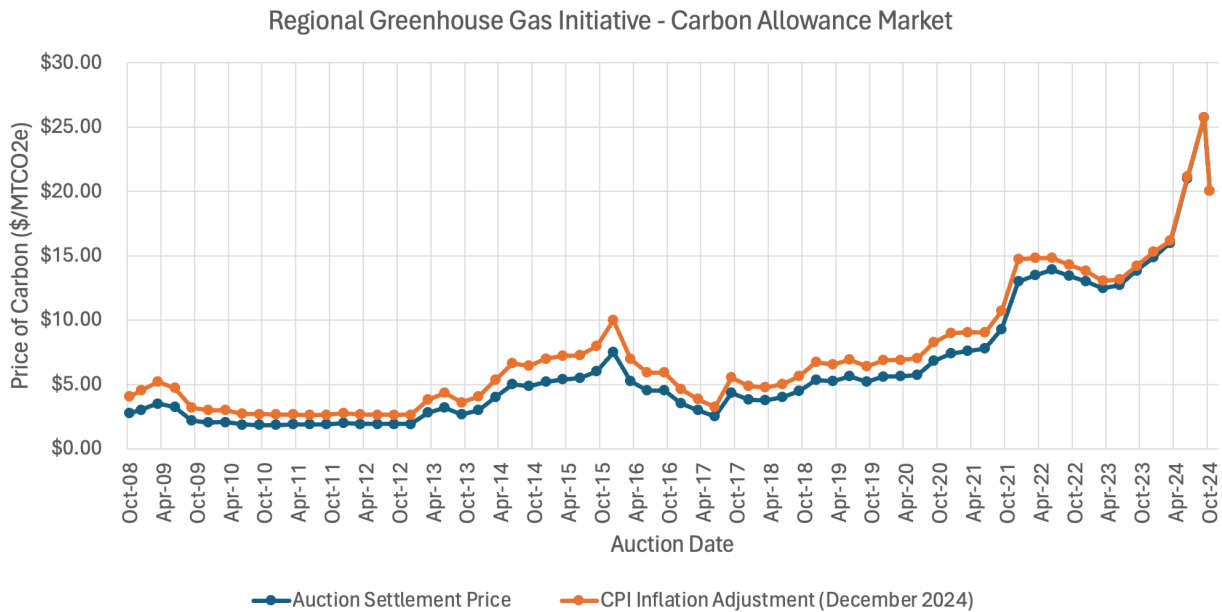


Figure 4 and Table 3 detail the settlement price history of the RGGI’s ETS auctions, along with the CPI inflation correction to December 2024. Note that for auctions one and two, no settlement price was listed in auction documents, so I based the CPI adjustment off the average price.

Regional Greenhouse Gas Initiative - Carbon Allowance Market

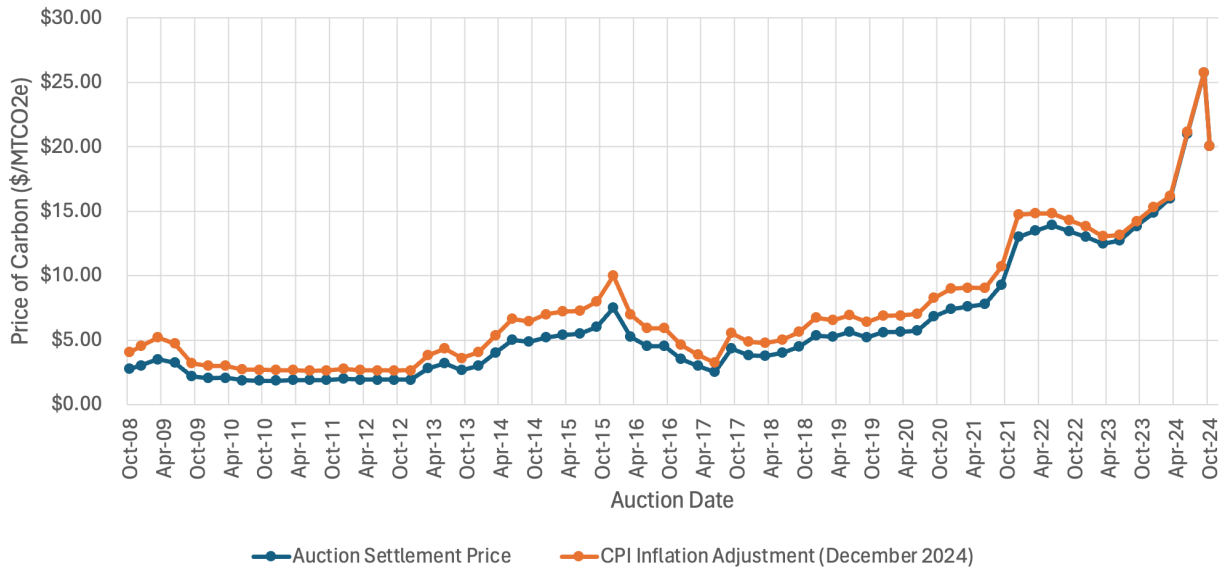


Figure 4 – Auction Results from the RGGI’s Allowance Market.

Table 3 – Settlement Prices for RGGI’s Carbon Allowance Market

Auction Number	Auction Date	Average (Mean)	Clearing Price	CPI Inflation Adjustment (December 2024)
1	Oct-08	\$2.77	n/a	\$4.04
2	Dec-08	\$3.03	n/a	\$4.55
3	Mar-09	\$3.24	\$3.51	\$5.21
4	Jun-09	\$2.83	\$3.23	\$4.73
5	Sep-09	\$2.30	\$2.19	\$3.20
6	Dec-09	\$2.12	\$2.05	\$3.00
7	Mar-10	\$2.07	\$2.07	\$3.00
8	Jun-10	\$2.01	\$1.88	\$2.72
9	Sep-10	\$1.92	\$1.86	\$2.69
10	Dec-10	\$2.38	\$1.86	\$2.68
11	Mar-11	\$1.97	\$1.89	\$2.67
12	Jun-11	\$1.99	\$1.89	\$2.64
13	Sep-11	\$2.05	\$1.89	\$2.63
14	Dec-11	\$1.99	\$1.99	\$2.78
15	Mar-12	\$2.00	\$1.93	\$2.66
16	Jun-12	\$1.98	\$1.93	\$2.65
17	Sep-12	\$2.02	\$1.93	\$2.63
18	Dec-12	\$1.98	\$1.93	\$2.65
19	Mar-13	\$2.69	\$2.80	\$3.80
20	Jun-13	\$3.08	\$3.21	\$4.34
21	Sep-13	\$2.79	\$2.67	\$3.60

Auction Number	Auction Date	Average (Mean)	Clearing Price	CPI Inflation Adjustment (December 2024)
22	Dec-13	\$2.87	\$3.00	\$4.06
23	Mar-14	\$3.76	\$4.00	\$5.34
24	Jun-14	\$4.95	\$5.02	\$6.65
25	Sep-14	\$4.58	\$4.88	\$6.47
26	Dec-14	\$4.77	\$5.21	\$7.00
27	Mar-15	\$4.78	\$5.41	\$7.23
28	Jun-15	\$4.82	\$5.50	\$7.27
29	Sep-15	\$5.73	\$6.02	\$7.98
30	Dec-15	\$7.03	\$7.50	\$10.01
31	Mar-16	\$4.41	\$5.25	\$6.96
32	Jun-16	\$3.96	\$4.53	\$5.93
33	Sep-16	\$4.10	\$4.54	\$5.93
34	Dec-16	\$3.40	\$3.55	\$4.64
35	Mar-17	\$2.96	\$3.00	\$3.88
36	Jun-17	\$2.57	\$2.53	\$3.26
37	Sep-17	\$4.13	\$4.35	\$5.56
38	Dec-17	\$3.63	\$3.80	\$4.86
39	Mar-18	\$3.56	\$3.79	\$4.79
40	Jun-18	\$3.80	\$4.02	\$5.03
41	Sep-18	\$4.28	\$4.50	\$5.63
42	Dec-18	\$5.21	\$5.35	\$6.72
43	Mar-19	\$5.03	\$5.27	\$6.54
44	Jun-19	\$5.42	\$5.62	\$6.92
45	Sep-19	\$4.87	\$5.20	\$6.39
46	Dec-19	\$5.33	\$5.61	\$6.89
47	Mar-20	\$5.18	\$5.65	\$6.91
48	Jun-20	\$5.34	\$5.75	\$7.04
49	Sep-20	\$6.67	\$6.82	\$8.27
50	Dec-20	\$7.11	\$7.41	\$8.98
51	Mar-21	\$8.12	\$7.60	\$9.06
52	Jun-21	\$7.72	\$7.79	\$9.05
53	Sep-21	\$9.08	\$9.30	\$10.70
54	Dec-21	\$12.47	\$13.00	\$14.72
55	Mar-22	\$11.77	\$13.50	\$14.82
56	Jun-22	\$12.38	\$13.90	\$14.81
57	Sep-22	\$11.77	\$13.45	\$14.30
58	Dec-22	\$11.58	\$12.99	\$13.81
59	Mar-23	\$11.28	\$12.50	\$13.07
60	Jun-23	\$11.92	\$12.73	\$13.17

Auction Number	Auction Date	Average (Mean)	Clearing Price	CPI Inflation Adjustment (December 2024)
61	Sep-23	\$12.81	\$13.85	\$14.20
62	Dec-23	\$13.53	\$14.88	\$15.31
63	Mar-24	\$15.91	\$16.00	\$16.17
64	Jun-24	\$18.99	\$21.03	\$21.13
65	Sep-24	\$21.84	\$25.75	\$25.77
66	Oct-24	\$19.19	\$20.05	\$20.05

Through 2023 and 2024, which includes auctions 59 through 66, settlement prices ranged between \$13.07 and \$25.77/MTCO_{2e}, with a mean value of \$17.36/MTCO_{2e}.

3.2.5 European Union – Emissions Trading System

The ideas in section 3.2.5 are cited from (unless otherwise noted) the European Commission’s ETS webpage (*EU Emissions Trading System (EU ETS)*, n.d.-a) and the International Carbon Action Partnership’s factsheet for this program (*EU Emissions Trading System (EU ETS)*, n.d.-b), citations below:

EU Emissions Trading System (EU ETS). (n.d.-a). European Commission. Retrieved February 20, 2025, from https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en

EU Emissions Trading System (EU ETS). (n.d.-b). International Carbon Action Partnership. Retrieved February 20, 2025, from <https://icapcarbonaction.com/en/ets/eu-emissions-trading-system-eu-ets>

3.2.5.1 Description

The European Union created its emissions trading system in 2005, with allowance auctions occurring since late 2012. This system operates as a cap-and-trade program, and includes all participating EU countries, along with Iceland, Liechtenstein, and Norway.

3.2.5.2 Legislative Origin

Emissions reduction targets are based on the European Climate Law, which defines reduction percentages from 1990 GHG levels.

3.2.5.3 Markets Addressed

This program includes over 11,000 businesses, including power plants, industrial factories, and aviation. As of 2021, this ETS market addresses around 38% of emissions across the EU.

3.2.5.4 ETS Goals

Though this ETS is soon being replaced with a new version (ETS2), the original model states goals of reducing emissions by 55% below 1990 levels by 2030 and reaching climate neutrality by 2050.

3.2.5.5 Auction Data

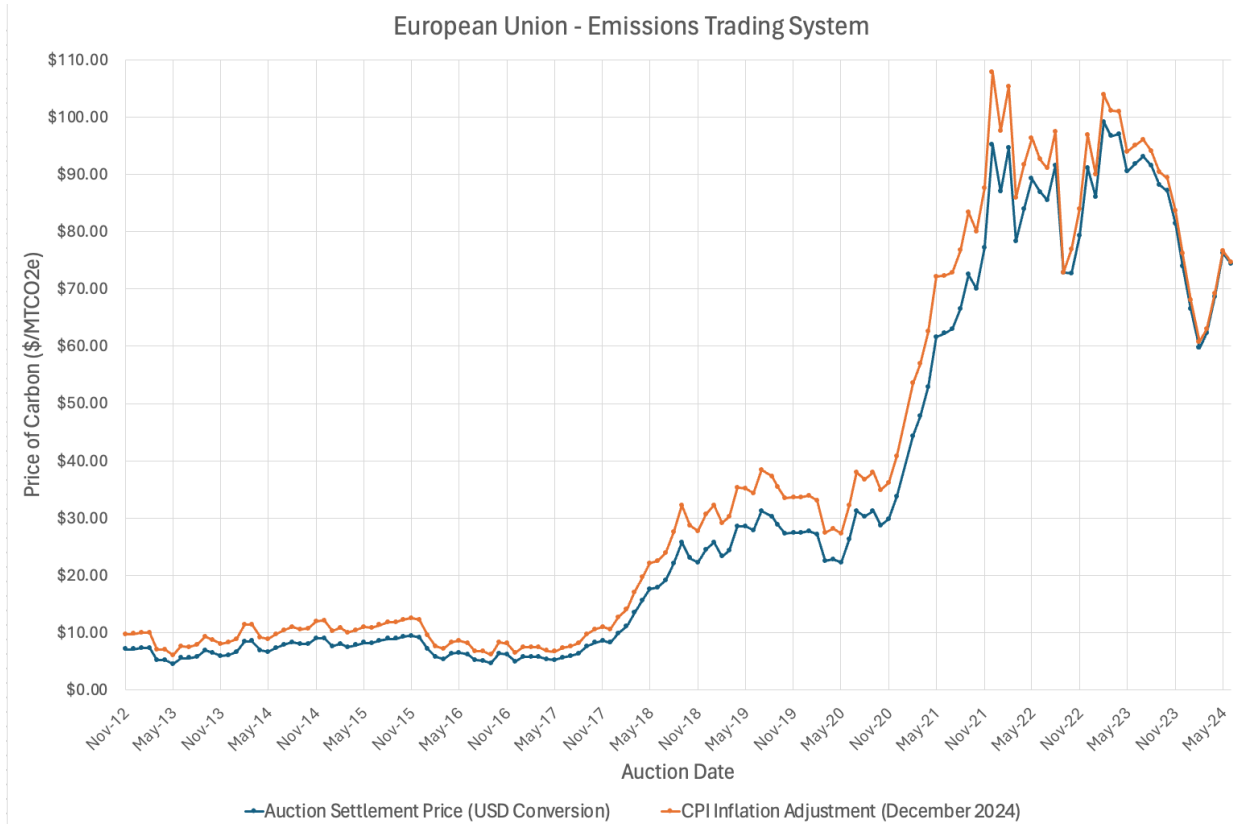


Figure 5 and Table 4 aggregate the monthly average clearance prices of these allowance auctions, converting to USD from Euros based on the annual average conversion rate (*Euro Dollar Exchange Rate (EUR USD) - Historical Chart, n.d.*), as well as a monthly CPI inflation correction (*CPI Inflation Calculator, n.d.*) to December 2024.

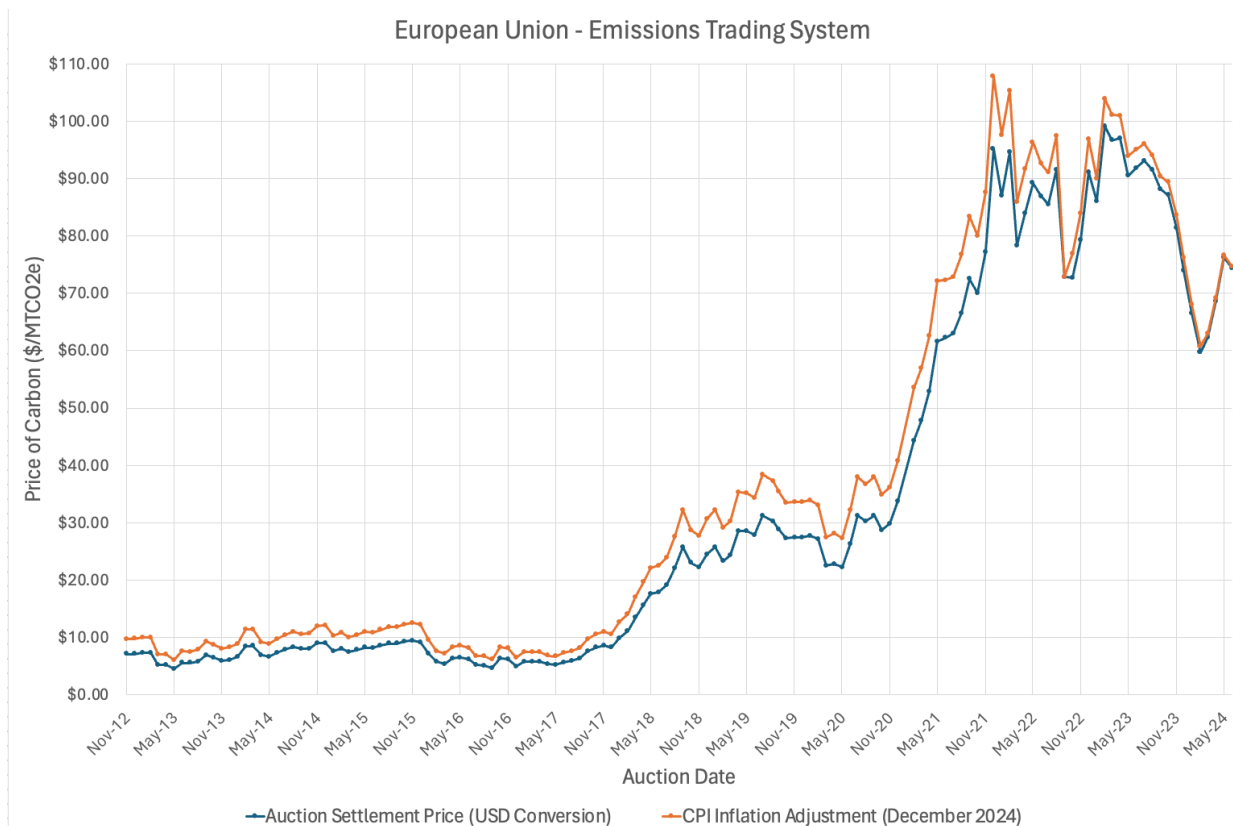


Figure 5 – Auction Results from the European Union’s Emissions Trading System.

Table 4 – Settlement Prices for the European Union’s Emissions Trading System

Auction Date	Average Auction Clearing Price	USD Conversion	CPI Inflation Adjustment (December 2024)
Nov-12	5.52 €	\$7.12	\$9.76
Dec-12	5.52 €	\$7.12	\$9.79
Jan-13	5.52 €	\$7.34	\$10.06
Feb-13	5.52 €	\$7.34	\$9.98
Mar-13	3.93 €	\$5.23	\$7.09
Apr-13	3.93 €	\$5.23	\$7.10
May-13	3.40 €	\$4.52	\$6.12
Jun-13	4.20 €	\$5.59	\$7.56
Jul-13	4.19 €	\$5.57	\$7.53
Aug-13	4.39 €	\$5.84	\$7.88
Sep-13	5.18 €	\$6.89	\$9.29
Oct-13	4.85 €	\$6.45	\$8.72
Nov-13	4.49 €	\$5.97	\$8.08
Dec-13	4.61 €	\$6.13	\$8.30
Jan-14	4.96 €	\$6.60	\$8.90
Feb-14	6.39 €	\$8.50	\$11.43
Mar-14	6.42 €	\$8.54	\$11.41

Auction Date	Average Auction Clearing Price	USD Conversion	CPI Inflation Adjustment (December 2024)
Apr-14	5.19 €	\$6.90	\$9.19
May-14	5.02 €	\$6.68	\$8.86
Jun-14	5.53 €	\$7.35	\$9.73
Jul-14	5.91 €	\$7.86	\$10.41
Aug-14	6.24 €	\$8.30	\$11.01
Sep-14	6.01 €	\$7.99	\$10.59
Oct-14	6.04 €	\$8.03	\$10.67
Nov-14	6.77 €	\$9.00	\$12.03
Dec-14	6.76 €	\$8.99	\$12.08
Jan-15	6.89 €	\$7.65	\$10.33
Feb-15	7.24 €	\$8.04	\$10.81
Mar-15	6.76 €	\$7.50	\$10.02
Apr-15	7.06 €	\$7.84	\$10.46
May-15	7.43 €	\$8.25	\$10.95
Jun-15	7.42 €	\$8.24	\$10.90
Jul-15	7.73 €	\$8.58	\$11.35
Aug-15	8.06 €	\$8.95	\$11.85
Sep-15	8.06 €	\$8.95	\$11.87
Oct-15	8.35 €	\$9.27	\$12.30
Nov-15	8.48 €	\$9.41	\$12.51
Dec-15	8.27 €	\$9.18	\$12.25
Jan-16	6.52 €	\$7.24	\$9.64
Feb-16	5.19 €	\$5.76	\$7.67
Mar-16	4.87 €	\$5.41	\$7.17
Apr-16	5.70 €	\$6.33	\$8.35
May-16	5.88 €	\$6.53	\$8.58
Jun-16	5.60 €	\$6.22	\$8.14
Jul-16	4.68 €	\$5.19	\$6.81
Aug-16	4.63 €	\$5.14	\$6.74
Sep-16	4.23 €	\$4.70	\$6.14
Oct-16	5.70 €	\$6.33	\$8.26
Nov-16	5.59 €	\$6.20	\$8.11
Dec-16	4.49 €	\$4.98	\$6.51
Jan-17	5.10 €	\$5.76	\$7.49
Feb-17	5.10 €	\$5.76	\$7.46
Mar-17	5.10 €	\$5.76	\$7.46
Apr-17	4.70 €	\$5.31	\$6.85
May-17	4.60 €	\$5.20	\$6.71
Jun-17	5.00 €	\$5.65	\$7.28

Auction Date	Average Auction Clearing Price	USD Conversion	CPI Inflation Adjustment (December 2024)
Jul-17	5.20 €	\$5.88	\$7.58
Aug-17	5.60 €	\$6.33	\$8.14
Sep-17	6.70 €	\$7.57	\$9.68
Oct-17	7.30 €	\$8.25	\$10.56
Nov-17	7.60 €	\$8.59	\$10.99
Dec-17	7.30 €	\$8.25	\$10.56
Jan-18	8.40 €	\$9.91	\$12.62
Feb-18	9.40 €	\$11.09	\$14.06
Mar-18	11.40 €	\$13.45	\$17.01
Apr-18	13.20 €	\$15.58	\$19.63
May-18	14.90 €	\$17.58	\$22.05
Jun-18	15.20 €	\$17.94	\$22.47
Jul-18	16.20 €	\$19.12	\$23.95
Aug-18	18.70 €	\$22.07	\$27.62
Sep-18	21.80 €	\$25.72	\$32.16
Oct-18	19.50 €	\$23.01	\$28.72
Nov-18	18.80 €	\$22.18	\$27.77
Dec-18	20.70 €	\$24.43	\$30.69
Jan-19	22.95 €	\$25.70	\$32.22
Feb-19	20.80 €	\$23.30	\$29.09
Mar-19	21.78 €	\$24.39	\$30.28
Apr-19	25.54 €	\$28.60	\$35.32
May-19	25.52 €	\$28.58	\$35.22
Jun-19	24.91 €	\$27.90	\$34.38
Jul-19	27.85 €	\$31.19	\$38.37
Aug-19	27.05 €	\$30.30	\$37.27
Sep-19	25.72 €	\$28.81	\$35.41
Oct-19	24.38 €	\$27.31	\$33.49
Nov-19	24.49 €	\$27.43	\$33.66
Dec-19	24.45 €	\$27.38	\$33.63
Jan-20	24.32 €	\$27.72	\$33.91
Feb-20	23.82 €	\$27.15	\$33.12
Mar-20	19.71 €	\$22.47	\$27.47
Apr-20	20.03 €	\$22.83	\$28.10
May-20	19.50 €	\$22.23	\$27.36
Jun-20	23.11 €	\$26.35	\$32.26
Jul-20	27.37 €	\$31.20	\$38.00
Aug-20	26.56 €	\$30.28	\$36.77
Sep-20	27.44 €	\$31.28	\$37.93

Auction Date	Average Auction Clearing Price	USD Conversion	CPI Inflation Adjustment (December 2024)
Oct-20	25.21 €	\$28.74	\$34.83
Nov-20	26.19 €	\$29.86	\$36.21
Dec-20	29.57 €	\$33.71	\$40.84
Feb-21	37.59 €	\$44.36	\$53.52
Mar-21	40.47 €	\$47.75	\$56.89
Apr-21	44.82 €	\$52.89	\$62.51
May-21	52.16 €	\$61.55	\$72.16
Jun-21	52.74 €	\$62.23	\$72.29
Jul-21	53.44 €	\$63.06	\$72.90
Aug-21	56.35 €	\$66.49	\$76.71
Sep-21	61.43 €	\$72.49	\$83.40
Oct-21	59.40 €	\$70.09	\$79.98
Nov-21	65.39 €	\$77.16	\$87.61
Dec-21	80.71 €	\$95.24	\$107.81
Jan-22	82.83 €	\$86.97	\$97.63
Feb-22	90.18 €	\$94.69	\$105.33
Mar-22	74.54 €	\$78.27	\$85.92
Apr-22	79.97 €	\$83.97	\$91.67
May-22	84.97 €	\$89.22	\$96.33
Jun-22	82.79 €	\$86.93	\$92.59
Jul-22	81.40 €	\$85.47	\$91.05
Aug-22	87.15 €	\$91.51	\$97.48
Sep-22	69.35 €	\$72.82	\$72.82
Oct-22	69.19 €	\$72.65	\$76.94
Nov-22	75.47 €	\$79.24	\$84.00
Dec-22	86.76 €	\$91.10	\$96.87
Jan-23	79.71 €	\$86.09	\$90.02
Feb-23	91.77 €	\$99.11	\$103.97
Mar-23	89.51 €	\$96.67	\$101.08
Apr-23	89.88 €	\$97.07	\$100.99
May-23	83.79 €	\$90.49	\$93.91
Jun-23	85.04 €	\$91.84	\$95.00
Jul-23	86.17 €	\$93.06	\$96.08
Aug-23	84.76 €	\$91.54	\$94.10
Sep-23	81.66 €	\$88.19	\$90.43
Oct-23	80.66 €	\$87.11	\$89.36
Nov-23	75.38 €	\$81.41	\$83.68
Dec-23	68.53 €	\$74.01	\$76.15
Jan-24	61.55 €	\$66.47	\$68.02

Auction Date	Average Auction Clearing Price	USD Conversion	CPI Inflation Adjustment (December 2024)
Feb-24	55.28 €	\$59.70	\$60.72
Mar-24	57.70 €	\$62.32	\$62.97
Apr-24	63.59 €	\$68.68	\$69.13
May-24	70.58 €	\$76.23	\$76.60
Jun-24	68.87 €	\$74.38	\$74.72

Through 2023 and 2024, which includes the last 18 auction months posted, average monthly settlement prices ranged between \$60.72 and \$103.97/MTCO_{2e}, with a mean value of \$84.83/MTCO_{2e}.

3.2.6 Comparison

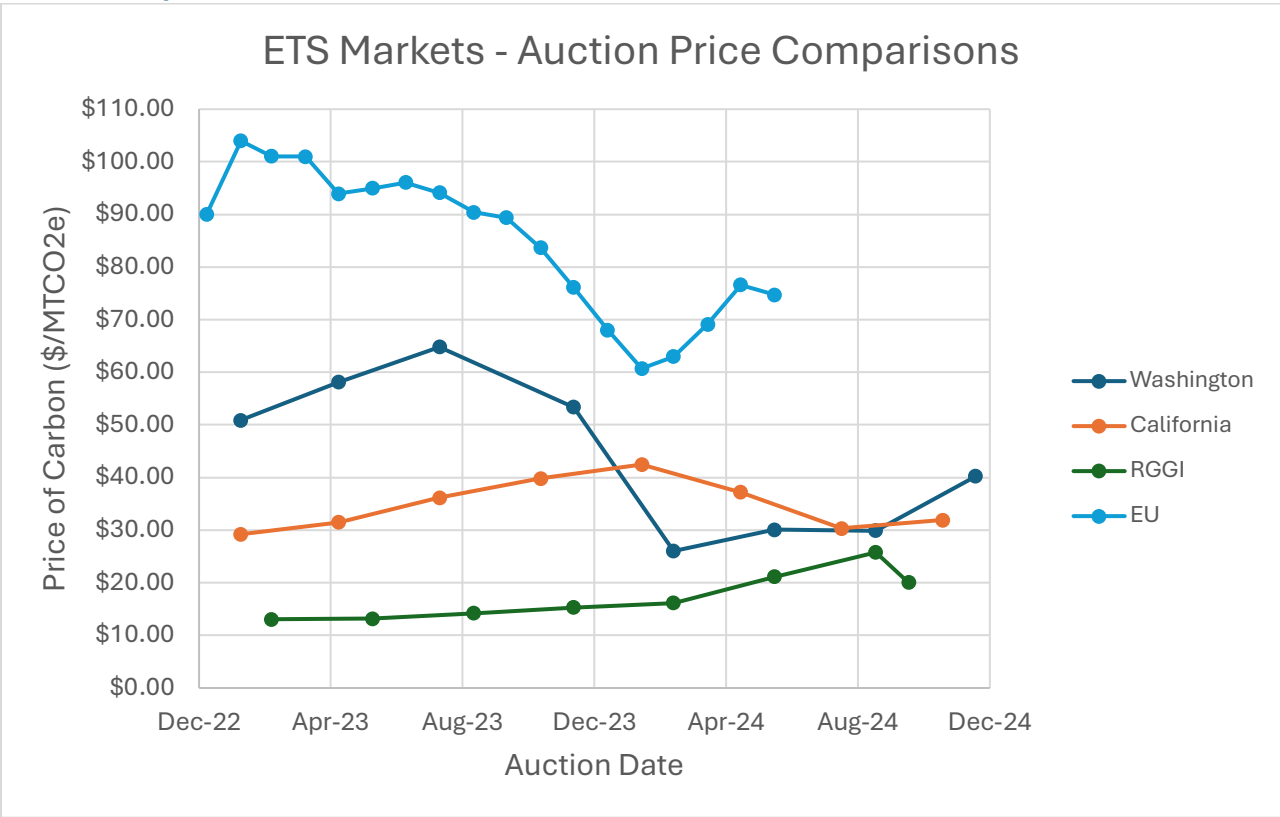


Figure 6 combines the past two years of data for all four ETS markets. Note that this comparison offers a visual representation of different carbon trading markets, direct comparison is unadvised, as all markets stem from different legislative initiatives that define different cap limits and emissions reduction goals. They all operate in different economies, whether regionally within the US or abroad in Europe, thus there are significant geographic and market differences to be considered.

Table 5 summarizes the ranges and averages of 2023 and 2024 prices for all four ETS markets. Note that the EU auction website does not provide settlement pricing data from the third or fourth quarter of 2024.

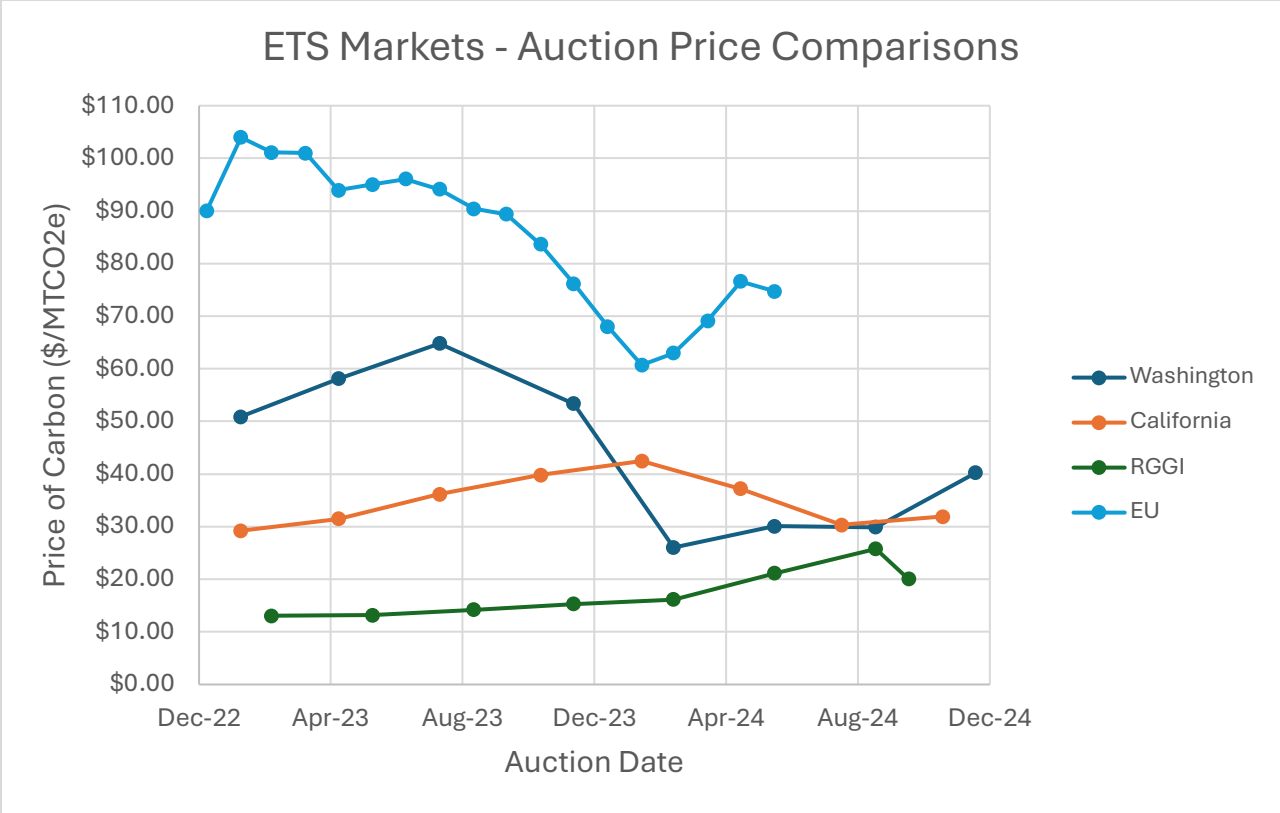


Figure 6 – Auction Price Comparisons for all ETS Markets Considered.

Table 5 – 2023 and 2024 Ranges and Averages of Auction Settlement Prices (\$/MTCO2e)

	Washington	California	RGGI	EU
Range	\$26.06 - \$64.79	\$29.22 - \$42.47	\$13.07 - \$25.77	\$60.72 - \$103.97
Average	\$44.18	\$34.82	\$17.36	\$84.83

The 2023 numbers show a wide disparity between all the markets considered, with the EU settlement prices being particularly high. However, 2024 sees a convergence between the three American markets, with the California and Washington allowance programs specifically meeting around \$30/MTCO2e in summer of that year.

3.3 Carbon Taxes

3.3.1 Introduction

The ideas in section 3.3.1 are cited from the Center for Climate and Energy Solutions’ article titled Carbon Tax Basics (*Carbon Tax Basics*, 2024), citation below:

Carbon Tax Basics. (2024, May). Center for Climate and Energy Solutions.
<https://www.c2es.org/content/carbon-tax-basics/>

While ETS markets see the unit cost of carbon fluctuate over the course of many different auctions, a carbon tax sets a fixed rate that entities must pay based on the quantity of their greenhouse gas emissions. Though these taxes do not set organizational limits for emissions like a cap-and-trade program, they collect revenue at a specific rate. Two main types of carbon taxes

exist: emissions-based and goods-based. While emissions taxes are levied on a company’s activity, a goods-based tax focuses on carbon-producing materials. Canada notably has a federal fuel charge, an example of a goods-based tax.

3.3.2 Compiling Global Carbon Taxes

The ideas in section 3.3.2 are cited from the World Bank Group’s Carbon Pricing Dashboard (*Carbon Pricing Dashboard*, 2024), citation below:

Carbon Pricing Dashboard. (2024). World Bank Group.
<https://carbonpricingdashboard.worldbank.org/>

While the US has several regional markets for pricing carbon, as seen in the ETS section above, there is not currently a federal carbon tax. However, many other countries have implemented federal carbon taxes over the last 35 years. The World Bank Group has created a Carbon Pricing Dashboard, which provides a map detailing carbon pricing initiatives across the globe. I filtered for carbon taxes specifically and input all countries with active data into Table 6, listing their current price (in USD), year implemented, and market coverage. The table is organized by low to high price per MTCO_{2e}. Note that LULUCF stands for land-use, land-use change, and forestry. While Portugal and Poland were included on this dashboard, no pricing information was given.

Table 6 – Carbon Taxes Implemented across the Globe

Country	Current Price (\$/MTCO _{2e})	Year Implemented	Market Coverage
Ukraine	\$0.77	2011	Electricity and heat, Industry, Mining and extractives, Buildings, Waste, LULUCF
Argentina	\$0.81	2018	Electricity and heat, Industry, Mining and extractives, Transport, Aviation, Agriculture, forestry and fishing fuel use
Japan	\$1.91	2012	Electricity and heat, Industry, Mining and extractives, Transport, Buildings
Estonia	\$2.15	2000	Electricity and heat, Industry
Mexico	\$4.31	2014	Electricity and heat, Industry, Mining and extractives, Transport, Aviation, Buildings, Agriculture, forestry and fishing fuel use
Chile	\$5.00	2017	Electricity and heat, Industry, Mining and extractives
Colombia	\$6.68	2017	Electricity and heat, Industry, Mining and extractives, Transport, Buildings, Agriculture, forestry and fishing fuel use
Taiwan (China)	\$9.12	2024	Electricity and heat, Industry, Mining and extractives, Transport, Aviation, Buildings, Agriculture, forestry and

Country	Current Price (\$/MTCO2e)	Year Implemented	Market Coverage
			fishing fuel use, Agricultural emissions, Waste, LULUCF
South Africa	\$10.09	2019	Electricity and heat, Industry, Mining and extractives, Aviation, Buildings, Agriculture, forestry and fishing fuel use, Waste
Albania	\$13.11	2008	Electricity and heat, Industry, Transport, Buildings, Agriculture, forestry and fishing fuel use
Spain	\$16.12	2014	Electricity and heat, Industry, Mining and extractives
Latvia	\$16.12	2004	Industry
United Kingdom	\$22.62	2013	Electricity and heat
Denmark	\$28.21	1992	Electricity and heat, Industry, Mining and extractives, Transport, Aviation, Buildings, Agriculture, forestry and fishing fuel use
Iceland	\$36.51	2010	Electricity and heat, Industry, Mining and extractives, Transport, Aviation, Buildings, Agriculture, forestry and fishing fuel use
Hungary	\$38.70	2023	Electricity and heat, Aviation
France	\$47.94	2014	Industry, Transport, Buildings, Agriculture, forestry and fishing fuel use
Canada	\$58.95	2019	Electricity and heat, Industry, Mining and extractives
Ireland	\$60.19	2010	Electricity and heat, Industry, Mining and extractives, Transport, Aviation, Buildings, Agriculture, forestry and fishing fuel use.
Netherlands	\$71.48	2021	Electricity and heat, Industry, Mining and extractives, Waste
Finland	\$99.99	1990	Industry, Mining and extractives, Transport, Buildings, Agriculture, forestry and fishing fuel use
Norway	\$107.78	1991	Electricity and heat, Industry, Mining and extractives, Transport, Aviation, Buildings, Agriculture, forestry and fishing fuel use, Waste
Sweden	\$127.26	1991	Electricity and heat, Industry, Mining and extractives, Transport, Aviation,

Country	Current Price (\$/MTCO2e)	Year Implemented	Market Coverage
			Buildings, Agriculture, forestry and fishing fuel use
Switzerland	\$132.12	2008	Electricity and heat, Industry, Mining and extractives, Buildings, Agriculture, forestry and fishing fuel use
Uruguay	\$167.17	2022	Electricity and heat, Industry, Mining and extractives, Transport, Aviation, Buildings, Agriculture, forestry and fishing fuel use
Portugal	Pricing not available	2015	Electricity and heat, Industry, Mining and extractives, Transport, Aviation, Buildings, Agriculture, forestry and fishing fuel use
Polan	Pricing not available	1990	Electricity and heat, Industry, Mining and extractives, Transport, Aviation, Buildings, Agriculture, forestry and fishing fuel use

The prices represented in this table range from \$0.77 to \$167.17 per MTCO2e, with a mean tax rate of \$43.40/MTCO2e. Norway, Sweden, and Finland, which have all had their taxes in existence since the early 1990’s, have high tax rates compared to the rest of the world (\$100+). Switzerland and Uruguay also surpass the \$100 mark.

3.4 Carbon Offsets

3.4.1 Introduction

Carbon offsets are a form of voluntary carbon credits that represent “a one-ton drop in greenhouse gas emissions tied to projects such as a wind farm or a tree-planting scheme. They’re bought by companies to compensate for the pollution they produce somewhere else in the world” (White, 2024). Organizations with sustainability goals first seek to reduce their emissions as much as possible but often supplement their efforts with this voluntary market. Buying and selling institutions collaborate through third party brokers. There is a joint group of organizations that act as verification sources for individual offset projects, to ensure the industry’s legitimacy (van Kooten & de Vries, 2013).

3.4.2 Publicly Available Carbon Offset Prices

I researched carbon offset companies in an attempt to document the financial state of this market. Table 7 represents the brokers and projects I found with publicly available prices.

Table 7 – Carbon Offset Projects and Associated Prices

Broker	Project Name	Cost (\$/MTCO _{2e})	Location	Description
CoolEffect	Seeing the Forest for the Trees	\$15.38	Mexico	Forestry management project that encourages residents to preserve and grow the biomass in their standing forests
CoolEffect	A Bright Idea	\$10.99	India	Replaces fossil fuel energy sources with direct current solar systems
CoolEffect	A Bearadise	\$18.68	Alaska	Maintaining old growth forests
CoolEffect	Beaut Down Under	\$43.95	Australia	Planted 30 million native trees and shrubs
CoolEffect	Breath of Fresh Air	\$16.48	Guatemala	Installs energy efficient wood cookstoves in homes
CoolEffect	Gas Buster	\$20.88	Chile	Clean destruction and disposal of ODS gasses
CoolEffect	Sea of Change	\$38.27	Myanmar	Plants mangroves to save shorelines and remove carbon
Native: A Public Benefit Corporation	From Waste to Fuel	\$18	Uganda, Kenya	Provides small family farms with a digester that generates biofuel for cooking and organic fertilizer for planting
CNaught	Impact	\$20	n/a	Contains full range of recommended offset project types.
CNaught	Impact Lite	\$16	n/a	Excludes tech-based carbon removal projects.
CNaught	Value	\$10	n/a	Supports emissions-avoidant projects, no carbon removal.
TerraPass	Personal Carbon Offsets	\$15.98	n/a	Personal offsets that go towards a portfolio of projects sponsored by TerraPass.

Prices for these offset projects ranged from \$10 to \$43.95 per MTCO_{2e}, with a mean value of \$20.38/MTCO_{2e}.

3.4.3 Limitations

Publicly available information on carbon offset prices is limited. Most offset companies do not list any projects, only inquiry forms for interested businesses. Those that do list projects do not provide pricing. I reached out to a company called One Tribe with a wide range of offset projects to request pricing data and was told that this was confidential information.

3.5 Social Cost of Carbon

3.5.1 Introduction

The Social Cost of Carbon (SCC) is a carbon pricing strategy explored in scientific literature. While other pricing mechanisms assign a market-based value to carbon, the SCC is a theoretical

valuation of carbon that considers a multitude of social factors, such as how climate change disproportionately impacts lower income and under-resourced communities. In financial terms, “the social cost of carbon (SCC) is an estimate of the cost, in dollars, of the damage done by each additional ton of carbon emissions. It also is an estimate of the benefit of any action taken to reduce a ton of carbon emissions” (Asdourian & Wessel, 2023). Economist Richard Tol published a thorough meta-analysis on the social cost of carbon (Tol, 2025). This section details his key graphs and findings.

3.5.2 A Meta-Analysis of the Social Cost of Carbon

The data in section 3.5.2 is cited from a 2025 paper by Richard Tol (Tol, 2025), citation below:

Tol, R. S. J. (2025). *Database for the meta-analysis of the social cost of carbon (v2025.1)*. <https://doi.org/https://doi.org/10.48550/arXiv.2402.09125>

Tol's meta-analysis compiles results from 446 papers, aggregating 14,152 estimates of the social cost of carbon. Figures Figure 7 and Figure 8 summarize Tol's findings.

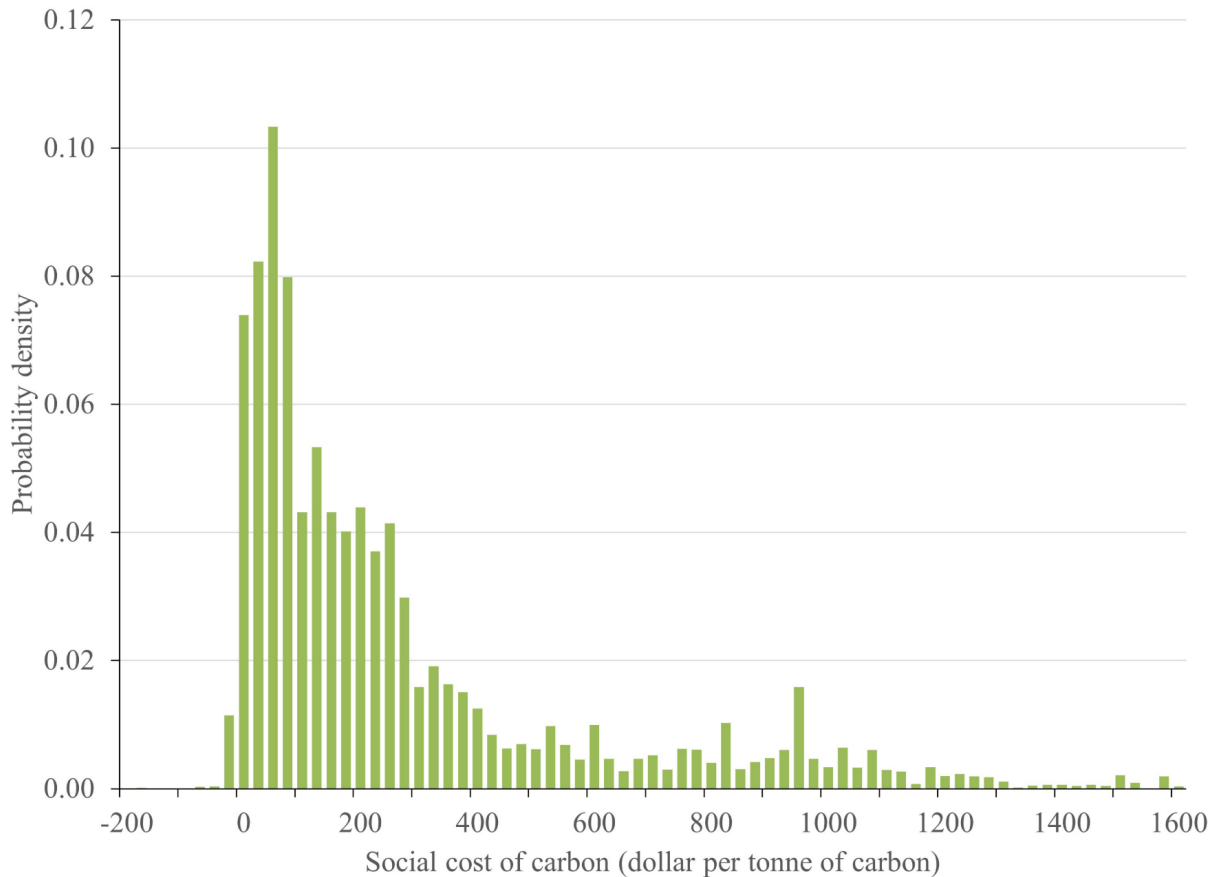


Figure 7 – Histogram Showing the Social Cost of Carbon (Tol, 2025).

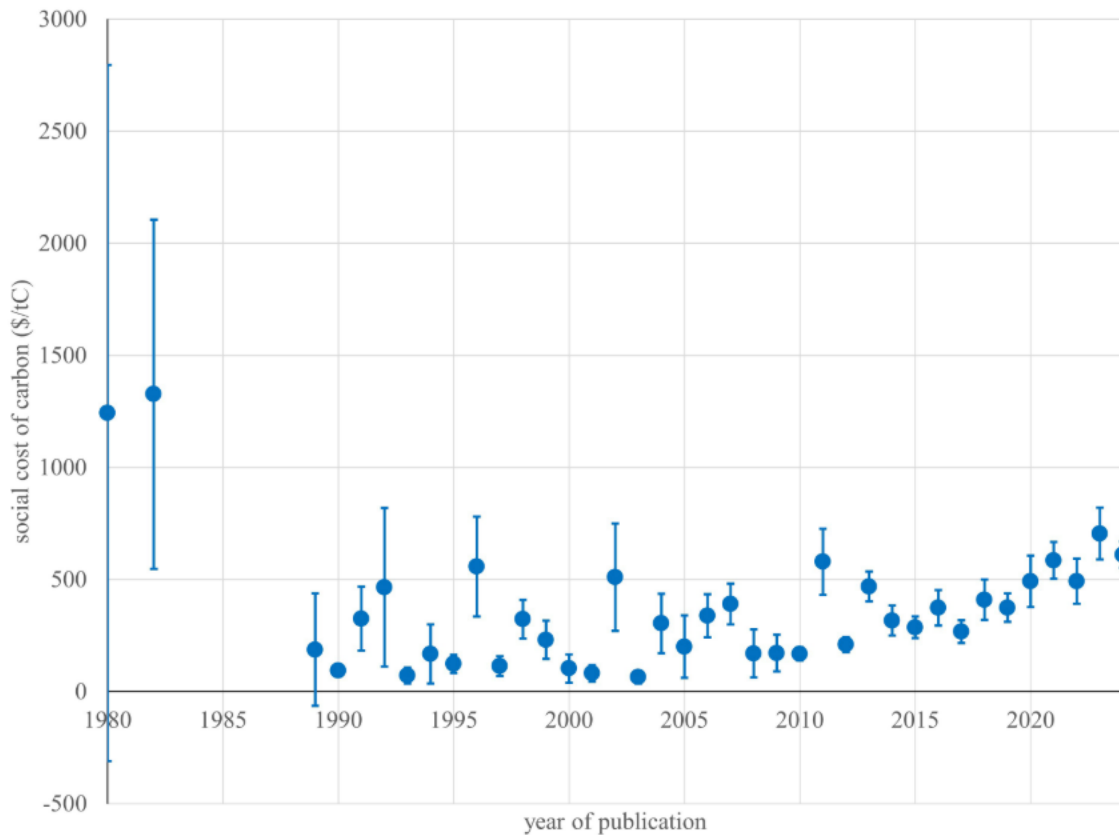


Figure 8 – The Average Social Cost of Carbon Based on Year of Publication (Tol, 2025).

From Figure 7, the mode of reported costs is between \$75 and \$100 per MTCO_{2e}, while the mean is significantly higher at \$402/MTCO_{2e}. Figure 8 shows high estimates of the SCC in the early 80's, with a lower correction in the 90's then a progressive increase in estimates over the last 30 years.

3.6 Discount Rate

3.6.1 Introduction

The discount rate is an accounting fixture that represents the time value of money, identifying the current value of future dollars (*Social Discount Rate*, n.d.). Generally, a high discount rate values the future less while a low discount rate values it more. In carbon terms, decreasing the discount rate increases the rate at which the SCC grows over time. Compared to the cost of carbon, much less information exists on how to select a discount rate. I chose to review the sources detailed in the sections below.

3.6.2 Interagency Working Group o Social Cost of Greenhouse Gases

The ideas in section 3.6.2 are cited from a 2021 Technical Support Document (TSD) published by an Interagency Working Group (IWG) on the social cost of greenhouse gases (U.S. Department of Energy, 2021), citation below:

U.S. Department of Energy (2021). *Technical Support Document: Social Cost of Carbon, Methane, and Nitrous Oxide*. United States Government.
<https://www.energy.gov/sites/default/files/2023-04/57.%20Social%20Cost%20of%20Carbon%202021.pdf>

This TSD was published as directed by President Biden’s 2021 Executive Order 13990, entitled “Protecting Public Health and the Environment and Restoring Science to Tackle the Climate Crisis”. This E.O. reinstated the IWG, which had been previously established during the Obama administration, then disbanded during the first Trump term. It tasked them with publishing updated SCC estimates along with an associated discount rate. Table 8 lists SCC estimates scaled over time (in 2020 USD) based on different discount rates.

Table 8 – Social Cost of Carbon (2020 USD/MTCO_{2e}) with Different Discount Rates (*United States Department of Energy, 2021*)

Year	Discount Rate			
	5%	3%	2.5%	High Impact ¹
2020	\$14	\$51	\$76	\$152
2025	\$17	\$56	\$83	\$169
2030	\$19	\$62	\$89	\$187
2035	\$22	\$67	\$96	\$206
2040	\$25	\$73	\$103	\$225
2045	\$28	\$79	\$110	\$242
2050	\$32	\$85	\$116	\$260

¹The high impact model uses a 3% discount rate and considers the 95th percentile of SCC estimates.

While this TSD examines all the discount rates listed above, it considers a 3% discount rate as its central value in carbon accounting. However, the IWG states that as climate science has developed, many jurisdictions have deemed a 3% discount rate to be “too high for intergenerational analysis”. Several examples of more effective discount rates are provided, including a 2020 New York rate of 2% and a 2019 Washington rate of 2.5%.

3.6.3 Literature

The ideas in section 3.6.3 are cited from a 2021 report published by Resources for the Future, a DC-based sustainability nonprofit, on the social cost of carbon and relevant discount rates (Rennert et al., 2021), citation below:

Rennert, K., Prest, B. C., Pizer, W. A., Newell, R. G., Anthoff, D., Kingdon, C., Rennels, L., Cooke, R., Raftery, A. E., Ševčíková, H., & Erickson, F. (2021). *The Social Cost of Carbon: Advances in Long-Term Probabilistic Projections of Population, GDP, Emissions, and Discount Rates*. <https://doi.org/10.1353/eca.2022.0003>

Referencing the IWG’s 3% discount rate estimate, Rennert et. al (2021) cites the “systemic decline in observed interest rates over at least the past two decades”, and states that 2% is a more reasonable discount rate when considering the SCC.

3.6.4 United States Federal Positioning

The Biden White House released an issue brief in early 2024 with a revision to the federal social discount rate. Citing the importance of long-termism in economic forecasting, this brief states that "according to a moving average of 10-year Treasury rates [...] the recommended annual discount rate is calculated to be 2 percent, compared to the dual rates of 3 and 7 percent" (The White House, 2024) that were previously established.

The Trump White House released an executive order (E.O.) titled "Unleashing American Energy" in early 2025 that disbanded the Interagency Working Group on the Social Cost of Greenhouse Gases (IWG) and withdrew all documents they produced, including the 2021 TSD. This E.O. states that "the calculation of the 'social cost of carbon' is marked by logical deficiencies, a poor basis in empirical science, politicization, and the absence of a foundation in legislation"(The White House, 2025), and that discount rates should be calculated per the 2003 OMB Circular A-4. This document states that "for regulatory analysis, you should provide estimates of net benefits using both 3 percent and 7 percent" (The White House, 2003).

3.7 Summary

This section reviewed different carbon pricing strategies and provided background on discount rate selection. The four ETS markets examined show the most consistent and stable form of carbon pricing. Based on the auction price comparisons performed in

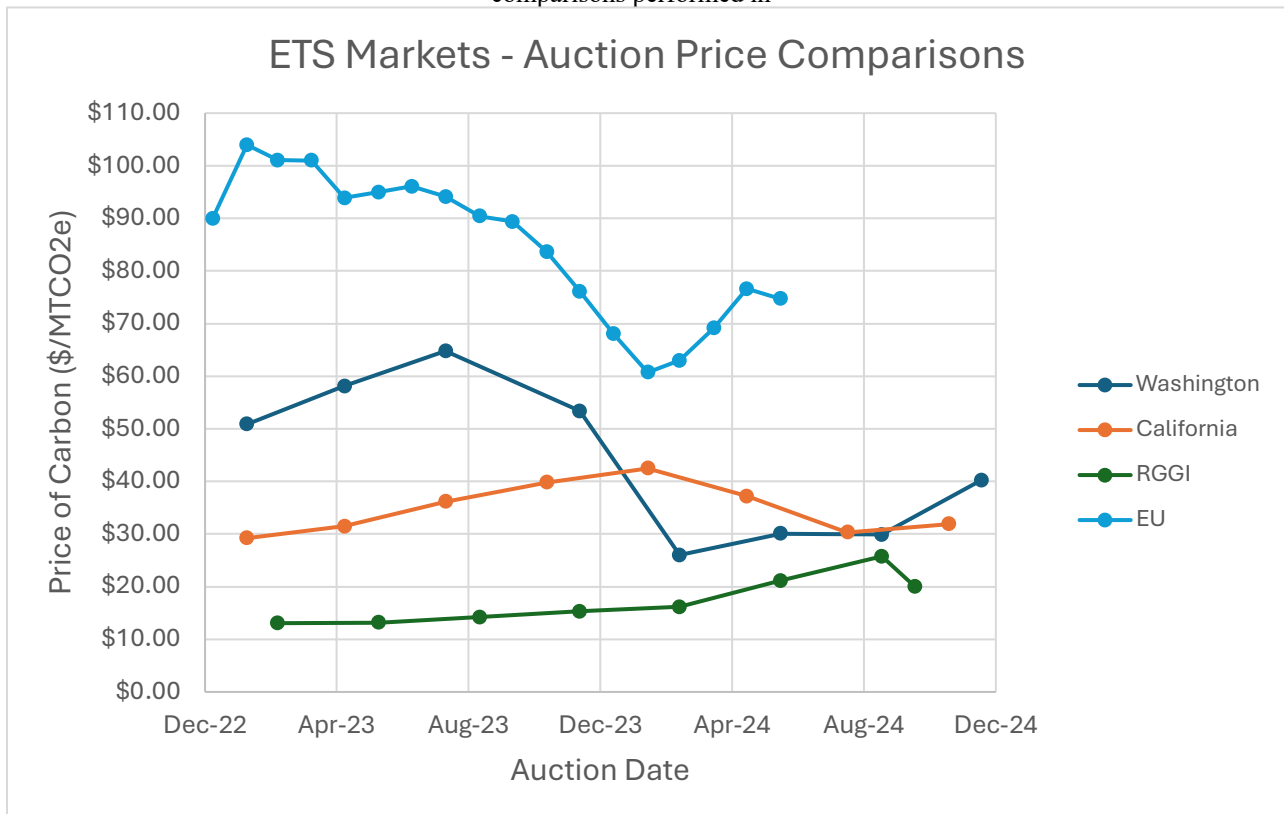


Figure 6 and Table 5, I decided to use \$35/MTCO_{2e} as the unit cost of carbon in subsequent life cycle cost analysis. Based on the work of Rennert et al. (2021) and the conclusions of the 2024 White House issue brief, I chose to apply a 2% discount rate to LCCA case studies.

If seeking to replicate this work, ensure data recency when deciding on a unit cost of carbon and discount rate. For the unit cost of carbon, add new ETS auction figures to existing data and reaggregate the results. Most of these markets publish new auction reports quarterly, so carbon costing estimates should be updated quarterly as well. For the discount rate, check for the most current federal reporting, while understanding that different administrations may view carbon-related economic analysis differently. Update discount rate estimates annually.

4 Life Cycle Cost Analysis

4.1 Introduction

Life Cycle Cost Analysis (LCCA) performed in this section adheres to the processes outlined in the WSDOT Pavement Policy, including input details (Pavement Policy, 2018). Any deviation from the inputs specified in this policy is noted as an assumption I made.

4.1.1 Project Selection

I chose three Washington state routes as representative case studies for this thesis. Primarily, I wanted to identify the differences in LCCA results between low and high-traffic highways. For the low-volume state routes, I selected SR 530 (Montague Creek Bridge to Seeman St Vic) and SR 8 (US 12 to US 101). These two HMA mill and fill projects were the subjects of life cycle assessment (LCA) work in Lum et. al 2024, so construction and EPD details were already collected. For the high-volume project, I selected a crack, seat, and overlay (CSOL) project on the Northbound side of SR 5, where paving occurred between S 260th St and the Duwamish River Bridge. I selected this project as it is on a major interstate that runs through a densely trafficked section of Seattle.

4.2 Methods

This section sets up the life cycle cost analysis case studies performed in RealCost 3.0, providing explanations of software inputs and external calculations used to find the cost of carbon for each project.

4.2.1 RealCost 3.0 Inputs

RealCost 3.0 is a macro-enabled Excel sheet where users provide input values through an organizing switchboard (Figure 9) and may obtain deterministic or probabilistic results.

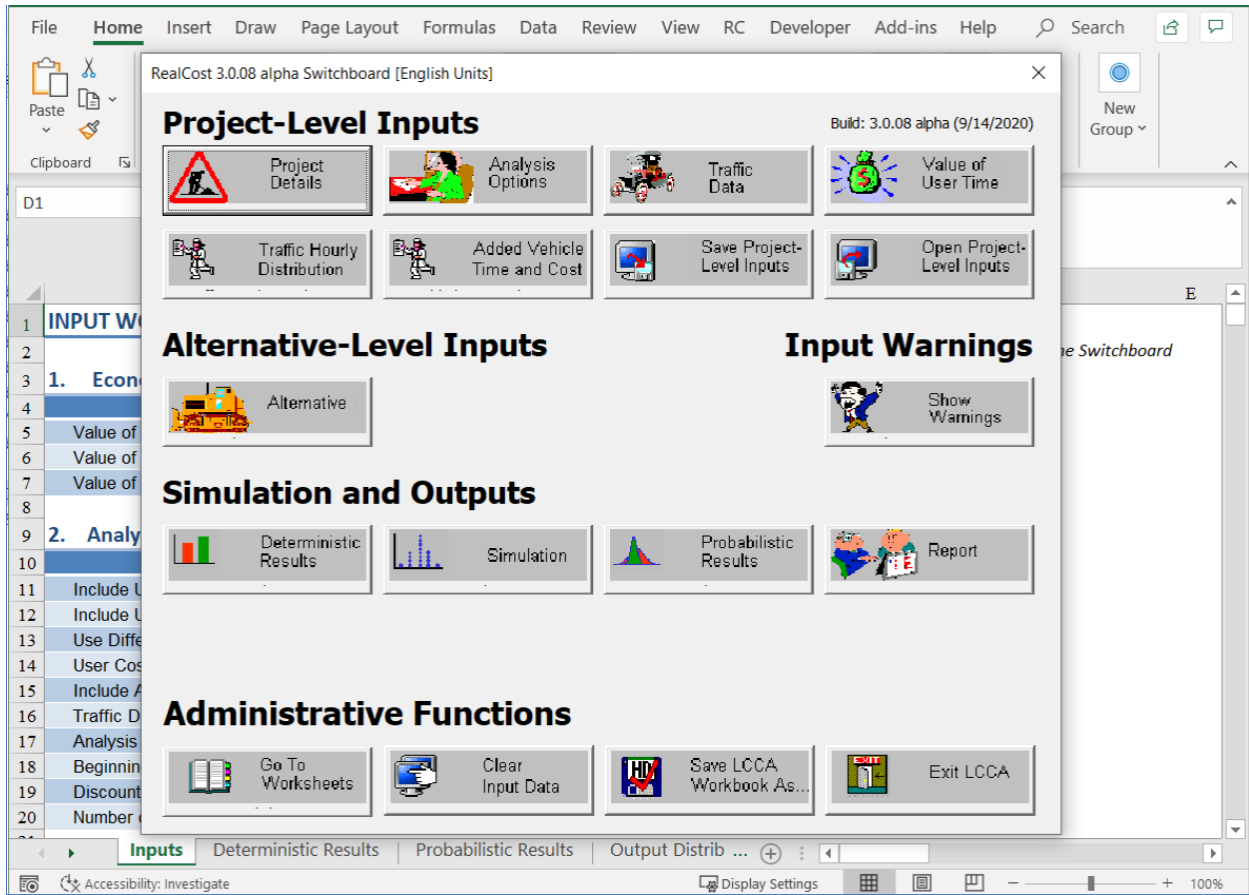


Figure 9 – RealCost 3.0 Switchboard (Federal Highway Administration, 2023).

This section is organized by switchboard tab, displaying inputs in a summary table with explanations and assumptions detailed after.

4.2.1.1 Project Details (Table 9)

Table 9 – Project Details

	SR 530	SR 8	SR 5
State Route	SR 530	SR 8	SR 5
Project Name	Montague Creek Bridge to Seeman Street Vic	US 12 to US 101	NB S 260 th St to Duwamish River Br
Region	Washington State	Washington State	Washington State
County	Snohomish County	Grays Harbor County	King County
Beginning Milepost	35.37	0	147.64
Ending Milepost	48.65	20.63	156.51

4.2.1.2 Analysis Options (Table 10)

Table 10 – Analysis Options

Analysis Units	English
Analysis Period (years)	50
Discount Rate (%)	2
Beginning of Analysis Period	2025
Include Agency Cost Remaining Value	Yes
Include User Costs in Analysis	Yes
User Cost Computation Method	Calculated
Traffic Direction	Both (SR 530 & SR 8), Inbound (SR 5)
Include User Cost Remaining Value	Yes
Number of Alternatives	2

Inputs for all case studies were the same in this window except for traffic direction. Note that I chose an analysis period of 50 years, stated by the WSDOT Pavement Policy as the required design period for all state highways (Pavement Policy, 2018).

4.2.1.3 Traffic Data (Table 11)

Table 11 – Traffic Data

	SR 530	SR 8	SR 5
AADT at Beginning of Analysis Period (total both directions)	3,395	20,343	67,490
Single Unit Trucks as Percentage of AADT (%)	0	5	3.03
Combination Trucks as Percentage of AADT (%)	14	5	4.4
Annual Growth Rate of Traffic (%)	0.75	0.8	0.85
Speed Limit Under Normal Operating Conditions (mph)	55	60	60

		SR 530	SR 8	SR 5
Lanes Open in Each Direction Under Normal Conditions		1	2	5
Free Flow Capacity Calculation	Number of Lanes in Each Direction	1	2	5
	Lane Width (ft)	12	12	11
	Proportion of Trucks and Buses (%)	14	10	7.43
	Upgrade (%)	0	0	0
	Upgrade Length (miles)	13.28	20.63	8.87
	Obstruction on Two Sides	No	No	No
	Distance to Obstruction / Shoulder Width (ft)	6	10	10
Free Flow Capacity (vphpl)		2,056	2,095	2,015
Queue Dissipation Capacity (vphpl)	Probability Distribution	Normal	Normal	Normal
	Mean	1818	1818	1818
	Standard Deviation	144	144	144
Maximum AADT (total for both directions)		6,790	40,686	134,979
Maximum Queue Length (miles)		5	5	5
Rural or Urban Hourly Traffic Distribution		Rural	Rural	Urban

I found vehicle type distributions and traffic growth rates on the WSDOT Traffic Count website (*Traffic Count Database System (TCDS)*, n.d.). Figures Figure 10, Figure 11, and Figure 12 display screenshots of each traffic station selected. For each case study, I selected a traffic count station that met the following criteria:

- Presented recent data
- Located within the project work zone
- Reported on passenger and commercial vehicle distributions

Record 1 of 1 Goto Record go								
Location ID	CS06026					MPO ID		
Type	SPOT					HPMS ID		
On NHS						On HPMS		
LRS ID						LRS Loc Pt.		
SF Group	SFG-05 (2025)					Route Type		
AF Group	AFA-011 (2025)					Route	530	
GF Group	GFG-05 (2025)					Active	Yes	
Class Dist Grp						Category		
Seas Class Grp	SCG-05 (2025)							
WIM Group								
QC Group	Short Count - Rural							
Funct'l Class						Milepost	43.74	
Located On	On SR 530, E/O Mine Rd Intersection; Swede Heaven Rd Intersection							
Loc On Alias								
More Detail								
STATION DATA								
Directions: 2-WAY EB WB ?								
AADT ?								
	Year	AADT	DHV-30	K %	D %	PA	BC	Src
	2023	3,395 ³		9	57	2,933 (86%)	462 (14%)	
	2022	3,312 ³		9	57	2,860 (86%)	452 (14%)	
	2021	3,380 ³	293	9	57	2,920 (86%)	460 (14%)	
	2020	3,038 ³	263	9	57	2,624 (86%)	414 (14%)	
	2019	3,331 ³	288	9	57	2,878 (86%)	453 (14%)	
1-5 of 38								

Figure 10 – WSDOT Traffic Count for SR 530 at Location ID CS06026 (*Traffic Count Database System (TCDS)*, n.d.).

For SR 530, I selected Location ID CS06026, which had data from 2023. This station had a 2-way AADT of 3,395 and a distribution of 86% PA (passenger vehicles) and 14% BC (commercial vehicles). As this section of highway is near lumber facilities, I allocated all commercial vehicles as combination trucks.

Record		1		of 1		Goto Record		go
Location ID	CS12712	MPO ID						
Type	SPOT	HPMS ID						
On NHS		On HPMS						
LRS ID		LRS Loc Pt.						
SF Group	SFS-R003W (2025)	Route Type						
AF Group	AFS-R003W (2025)	Route	008					
GF Group	GFS-R003W (2025)	Active	Yes					
Class Dist Grp		Category						
Seas Class Grp	SCS-R003W (2025)							
WIM Group								
QC Group	Short Count - Rural							
Funct'l Class		Milepost	0.29					
Located On	On SR 008, NE/O SR 12 On Ramp							
Loc On Alias								
More Detail ▶								
STATION DATA								
Directions: 2-WAY NE SW ?								
AADT ?								
	Year	AADT	DHV-30	K %	D %	PA	BC	Src
	2023	20,343 ³		8	56	18,361 (90%)	1,982 (10%)	
	2022	19,636 ³		8	56	17,721 (90%)	1,915 (10%)	
	2021	19,895	1,667	8	56	17,956 (90%)	1,939 (10%)	
	2020	17,840 ³	1,466	8	58	16,101 (90%)	1,739 (10%)	
	2019	19,639	1,614	8	58	17,728 (90%)	1,911 (10%)	
<< < > >> 1-5 of 37								

Figure 11 – WSDOT Traffic Count for SR 8 at Location ID CS12712 (*Traffic Count Database System (TCDS)*, n.d.).

For SR 8, I selected Location ID CS12712, which had data from 2023. This station had a 2-way AADT of 20,343 and a distribution of 90% PA (passenger vehicles) and 10% BC (commercial vehicles). Though this section of highway is rural, it neighbors Olympia and likely has a balanced share of commercial vehicles. Thus, I split commercial vehicle traffic evenly between single-unit and combination trucks.

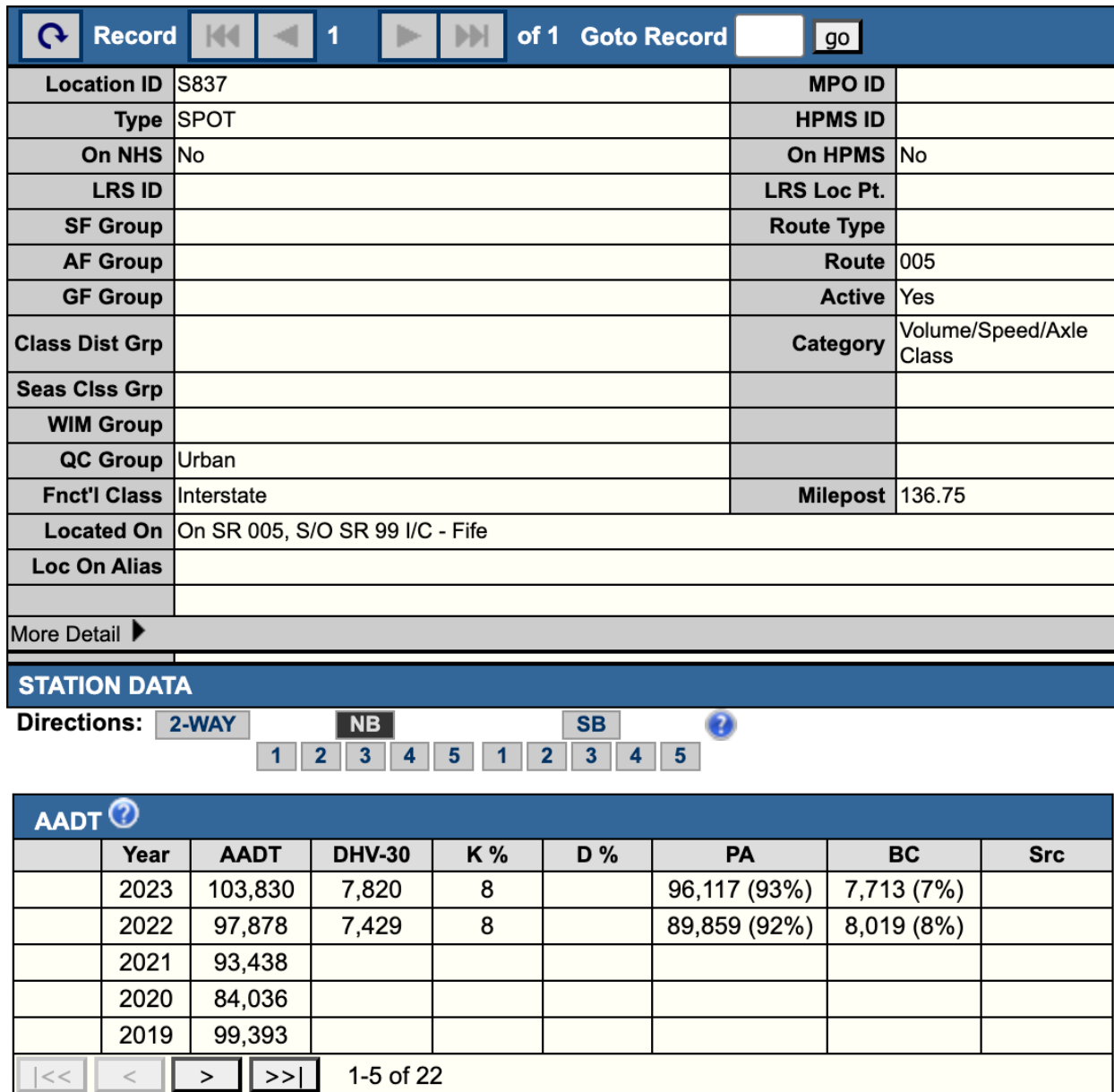


Figure 12 – WSDOT Traffic Count for Location ID S837 (*Traffic Count Database System (TCDS)*, n.d.).

For SR 5, I selected Location ID S837, which had data from 2023. Since no traffic stations within the project work zone contained vehicle distribution percentages, I selected the nearest station with this data present. Station S837 lies South of the work zone, West of Fife. This station had a one-way (Northbound) AADT of 103,830 and a distribution of 93% PA (passenger vehicles) and 7% BC (commercial vehicles). For the AADT, I assumed that in densely trafficked urban areas, commuters will often reschedule, reroute, or cancel their trips altogether to avoid excessive queueing. I based this idea on a Los Angeles highway closure study, which reported AADT reductions between 30.4% and 42.5%% (Taylor & Wachs, 2014). Thus, I chose to apply a 35% reduction to the initial AADT, which yielded a value of 67,490. I determined the trucking distributions based on Washington’s Spatial Data report for SR 5, which reports 3.03% single-unit trucks, 4.09% double-unit trucks, and 0.31% triple-unit trucks at the location tagged

“SOUTH OF MILEPOST 136.75: SR 99 ON RAMP; PERMANENT RECORDER S837” (Washington State Geospatial Open Data Portal, 2024). I combined double and triple-unit trucks to yield 4.4% combination trucks.

Table 12 displays the traffic growth rate for each station considered (Traffic Count Database System (TCDS), n.d.). I chose to average growth rates over the last 20 years in order to represent traffic growth over time instead of selecting data from a single year. I also considered the volatility in traffic numbers surrounding the COVID-19 pandemic in choosing to average more data points.

Table 12 – Traffic Growth Rates (Traffic Count Database System (TCDS), n.d.)

SR 530		SR 8		SR 5	
Year	Growth Rate (%)	Year	Growth Rate (%)	Year	Growth Rate (%)
2024	12	2023	4	2024	1
2023	3	2022	-1	2023	6
2022	-2	2021	12	2022	5
2021	11	2020	-9	2021	11
2020	-9	2019	5	2020	-15
2019	1	2018	0	2019	-1
2018	3	2017	2	2018	1
2017	-4	2016	3	2017	0
2016	3	2015	4	2016	2
2015	4	2014	2	2015	3
2014	2	2013	3	2014	1
2013	3	2012	-1	2009	1
2012	-1	2011	-3	2008	-2
2011	-9	2010	-1	2007	1
2010	1	2009	1	2006	-1
2009	4	2008	-2	2005	0
2008	-5	2007	2	2004	1
2007	1	2006	-1	2003	0
2006	1	2005	-3	2002	2
2005	-4	2004	-1	2001	1
Average – 0.75		Average – 0.8		Average – 0.85	

I located lane structure and traffic speed data in the Washington State Highway Log (SHL) (State Highway Log, 2024). The below information can be referenced with the SHL sample screenshot shown in Figure 13. For these inputs, I selected a representative value based on the most often repeated number within the work zone boundaries:

- Lanes Open in Each Direction Under Normal Conditions – This data falls under column header ‘NBR LNS’, where ‘D’ represents the decreasing mile marker side of the highway and ‘I’ represents the increasing side. WSDOT states that mile markers increase along the Northbound side of state routes, so for SR 5 I selected data under the ‘I’ column header. Note that the most often repeated number for SR 5 was 4, but since this does not account for the HOV lane, I input a total of five lanes into RealCost 3.0. Washington Asphalt

- Queue Dissipation Capacity – Table A5.4 of the WSDOT Pavement Policy states that this value should be input as a normal distribution with a mean of 1818 vphpl and a standard deviation of 144 vphpl (Pavement Policy, 2018). These figures are also located in Table 3.7 of the FHWA Bulletin (Federal Highway Administration, 1998).
- Maximum AADT – I chose to input this at double the initial AADT.
- Maximum Queue Length – I chose to set this at 5 miles to prevent excess queuing.
- Rural or Urban Hourly Traffic Distribution – SR 530 and SR 8 are both in rural areas, and SR 5 is in an urban area. This is also noted by the ‘QC Group’ category on the traffic count site, identified in Figure 10, Figure 11, and Figure 12.

4.2.1.4 Value of User Time (Table 13)

Table 13 details the value of user time. In a 1998 Interim Technical Bulletin produced by the Federal Highway Administration, Table 2.13 lists recommended values of time as a range in (August 1996) dollars per vehicle hour (Federal Highway Administration, 1998). I calculated the average of these ranges, then converted to December 2024 dollars using the CPI Inflation Calculator (*CPI Inflation Calculator*, n.d.).

Table 13 – Value of User Time

	FHWA Range (August 1996 USD)	Average (August 1996 USD)	CPI Inflation Adjustment (December 2024 USD)
Value of Time for Passenger Cars (\$/hour)	10 – 13	11.50	23.07
Value of Time for Single Unit Trucks (\$/hour)	17 – 20	18.50	37.12
Value of Time for Combination Trucks (\$/hour)	21 – 24	22.50	45.14

4.2.1.5 Traffic Hourly Distribution

The Traffic Hourly Distribution window provides a list of premade traffic distributions, with options including Week Day 1, Week End 1, Week Day 2, and Week End 2. For case studies SR 530 and SR 8, where work occurred on week days only, I selected Week Day 1. For the SR 5 case study, where work occurred over a series of weekends, I selected Week End 1.

4.2.1.6 Added Time and Vehicle Stopping Costs

The Added Time and Vehicle Stopping Costs switchboard tab requires inputs for a base and current transportation component CPI’s, producing an escalation factor that impacts the costs of a vehicle slowing down from a certain speed. I located the base transportation component CPI in the FHWA Interim Technical Bulletin, which lists a value of 142.8 for August 1996 (Federal Highway Administration, 1998). I obtained the current component value from the U.S. Bureau of Labor Statistics’ Consumer Price Index Database (*Consumer Price Index (CPI) Databases*, n.d.), by following these steps:

- On the databases window, select the ‘One Screen’ button in the ‘All Urban Consumers (Current Series)’ row. This creates a new pop-up window.
- Under ‘Select an Area’, select ‘U.S. city average’.

- Under ‘Select one or more items’, select ‘Transportation’.
- Under ‘Select Seasonal Adjustment’, select ‘Seasonally Adjusted’.
- Select ‘Get Data’, which then lists CPI factors by month and year. December 2024 lists 273.452 as the current component CPI factor.

Table 14 lists the CPI values as they are input into RealCost 3.0. Once this has been completed, select ‘Escalate’ to apply the CPI adjustment. This produces an escalation factor of 1.91. Select ‘Ok’ to exit out of this window.

Table 14 – Added Time and Vehicle Stopping Costs

Base Transportation Component CPI	142.8
Base Year	1996
Current Transportation Component CPI	273.452
Current Year	2024

4.2.1.7 Alternative-Level Inputs (Table 15)

The alternative-level inputs window contains details on the different construction activities to occur over a pavement’s life span. Since the goal of this project was not to compare different paving alternatives, I copied the same information across alternatives one and two. I filled out five activities for each case study, with activity one being the initial construction, and activities two through five being rehabilitation jobs. For SR 530 and SR 8, all paving activities are HMA mill and fills. Thus, activities one through five for these case studies had the same inputs. However, the initial construction for SR 5 was a crack, seat, and overlay, while subsequent rehab activities are HMA mill and fills.

Table 15 – Alternative-Level Inputs

	SR 530	SR 8	SR 5	
			CSOL	Mill and Fill
Agency Construction Cost (\$1000)	6,385	5,410	28,094.62	3,149.88
Activity Service Life (years)	15	15	15	15
Activity Structural Life (years)	50	50	50	50
Work Zone Length (miles)	13.28	20.63	8.87	8.87
Work Zone Capacity (vphpl)	670	1,340	1,370	1,370
No of Lanes Open in Each Direction During Work Zone	1	1	2	2
Work Zone Duration (days)	25	22	6.875	6.405
Work Zone Speed Limit (mph)	45	50	50	50

	SR 530	SR 8	SR 5	
			CSOL	Mill and Fill
Traffic Hourly Distribution	Week Day 1	Week Day 1	Week End 1	Week End 1
Work Zone Hours	Inbound (6-18) Outbound (6-18)	Inbound (0-6, 18-24) Outbound (0-6, 18-24)	Inbound (0-24)	Inbound (0-24)

I calculated table inputs above as follows:

- Agency Construction Cost – I identified SR 530 and SR 8 costs in Lum, et. al (2024), and SR 5 costs in the WSDOT Construction Contract Progress Payment Reporting webpage (*Construction Contract Progress Payment Reporting*, n.d.) under contract number 008992. This contract number contained 34 payment dates occurring between 05/16/2017 and 08/04/2020. I summed these values to calculate the total cost. Since the mill and fill activities for this case study are hypothetical, I chose to estimate their agency construction costs based on the figures from SR 8. Assuming a uniform mill and fill paving depth of 0.15 ft, I obtained a representative unit cost for SR 8 with the equation below:

$$\begin{aligned}
 \text{Unit Cost} &= \frac{\text{Initial Agency Construction Cost}}{\text{Paving Width} \times \text{Work Zone Length}} \\
 &= \frac{\$5,410,000}{4 \text{ lanes} \times \frac{12 \text{ ft}}{\text{lane}} \times 20.63 \text{ mi} \times \frac{5,280 \text{ ft}}{\text{mi}}} = \$1.03/\text{ft}^2
 \end{aligned}$$

From this unit cost, I calculated the SR 5 agency construction cost by factoring in its paving dimensions. Note that I included an extra 10 ft in roadway width to account for the shoulder, which was paved. The SR 8 width did not include the shoulder as it was not paved:

$$\begin{aligned}
 \text{Agency Construction Cost (SR 5)} &= \text{Unit Cost} \times \text{Paving Width} \times \text{Work Zone Length} \\
 &= \frac{\$1.03}{\text{ft}^2} \times \left(5 \text{ lanes} \times \frac{11 \text{ ft}}{\text{lane}} + 10 \text{ ft} \right) \times 8.87 \text{ mi} \times \frac{5,280 \text{ ft}}{\text{mi}} \\
 &= \$3,149,878.31
 \end{aligned}$$

- Activity Service Life – The WSDOT Pavement Type Selection document for the SR 5 case study states that rehabilitation activities are to occur at 15-year intervals (Pavement Type Selection - I-5 NB S 260th St to Duwamish River Bridge - Concrete Pavement Rehab, 2015). Figure 14 details the maintenance schedule for SR 5, with CSOL occurring in year 0 and mill and fill activities happening in years 15, 30, and 45. I chose to apply this 15-year interval to all three case studies.
- Activity Structural Life – The WSDOT Pavement Policy dictates that all state highways are designed to have a structural life of 50 years (Pavement Policy, 2018).

- Work Zone Length – I calculated these values based on the distance between starting and ending mile markers identified in the project descriptions.
- Work Zone Capacity – Table 3.8 of the FHWA Interim Technical Bulletin provides measured average work zone capacities based on directional lanes open during normal operations versus under work zone operations (Federal Highway Administration, 1998). For SR 530, I chose the figure with two lanes open normally and one open under work zone conditions, with a value of 1,340 vphpl. As SR 530 is a single lane highway with alternating lane closures to route traffic through (using a pilot vehicle), I had to simulate the work zone capacity beyond what Table 3.8 provided. Thus, I chose to divide the work zone capacity in half and obtained a value of 670 vphpl. For SR 8, I chose the two-to-one lane category with a capacity of 1,340 vphpl. The SR 5 project had five lanes open under normal conditions and two open during work zone hours, which corresponded to a work zone capacity of 1,370 vphpl.
- No of Lanes Open in Each Direction During Work Zone – For SR 530, I was unable to enter into RealCost 3.0 exactly what happened on the project. Thus, I chose to simulate the project conditions by keeping one lane open during work zone hours, but with half the capacity as seen above. For SR 8, one lane was closed at a time for paving, so I input a single lane in each direction as open in the work zone. For SR 5, WAPA Executive Director David Gent confirmed that this project left two lanes of traffic open at a time during work zone hours.
- Work Zone Duration – For SR 530 and SR 8, I chose 25 and 22 work days based on the number of paving days identified in Lum, et. al (2024). For the crack, seat, and overlay initial construction on SR 5, WAPA Executive Director David Gent confirmed that this project occurred over the course of three separate weekends, with continuous 55-hour closures running between 10 PM Friday and 5 AM Monday. Due to software constraints, I chose to represent the work zone hours in a single 24-hour closure, then calculate the number of days based on the total work hours that occurred. 55-hour closures over three weekends equals 165 total work hours. Dividing this by 24-hour work periods yields 6.875 workdays. I determined work zone duration for the HMA mill and fill portion of the SR 5 case study based on a unit duration estimate from the SR 8 numbers, calculated below:

$$\begin{aligned}
 \text{Unit Duration} &= \frac{\text{Construction Duration}}{\text{Paving Width} \times \text{Work Zone Length}} \\
 &= \frac{22 \text{ days} \times \frac{12 \text{ hours}}{\text{day}}}{4 \text{ lanes} \times \frac{12 \text{ ft}}{\text{lane}} \times 20.63 \text{ mi} \times \frac{5,280 \text{ ft}}{\text{mi}}} = 0.0000505 \text{ hr/ft}^2
 \end{aligned}$$

$$\begin{aligned}
 \text{Work Zone Duration (SR 5)} &= \text{Unit Duration} \times \text{Paving Width} \times \text{Work Zone Length} \\
 &= \frac{0.0000505 \text{ hr}}{\text{ft}^2} \times \left(5 \text{ lanes} \times \frac{11 \text{ ft}}{\text{lane}} + 10 \text{ ft} \right) \times 8.87 \text{ mi} \times \frac{5,280 \text{ ft}}{\text{mi}} \\
 &\times \frac{\text{day}}{24 \text{ hr}} = 6.405 \text{ days}
 \end{aligned}$$

Note that I include the 12-hour work day of SR 8 and the 24-hour work day of SR 5 in each equation, as ‘days’ here is subject to the work zone hours of each project.

- Work Zone Speed Limit – Exhibit 5-13 of the WSDOT Traffic Manual details speed limit requirements under variable regulatory work zone speed limit conditions. These speed limit reductions are recommended when “high operation speeds combined with high traffic volumes are anticipated” and the exhibit itself states that an existing speed limit of 60 mph should be reduced to 50 mph (Traffic Manual, 2021). For SR 8 and SR 5, where the normal operating speed limits are 60 mph, I selected a work zone speed limit of 50 mph. The normal speed limit on SR 530 is 55 mph, so I chose to apply the same 10 mph reduction and selected a work zone speed limit of 45 mph.
- Traffic Hourly Distribution – These inputs follow the selections made in the ‘Traffic Hourly Distribution’ section above.
- Work Zone Hours – Lum, et. al (2024) states that work on SR 530 occurred during the day between 6 AM and 6 PM, and on SR 8 at night between 6 PM and 6 AM. Thus, I selected work zone hours of 6-18 for SR 530, and 0-6 for the first period and 18-24 for the second period for SR 8. I set these numbers for both inbound and outbound directions of traffic. For SR 5, I calculated paving time as explained above in the Work Zone Duration bullet. Thus, I selected a 0–24-hour closure period, only in the inbound direction.

Activities	Year	Description
(2017) CSOL	0	<ul style="list-style-type: none"> • Crack and Seat the PCC pavement in Lanes 1 through 4 from milepost 149.71 to 151.19, and Lanes 1 through 5 from milepost 151.19 to 153.65 • Overlay of Lanes 1 through 5 and shoulders with 0.70 feet HMA • Transition at 500:1 from beginning and ending of CSOL and Bridge 005/516E to match existing profile by reconstructing lanes with a 1.08 feet of HMA over 0.75 feet of CSBC • Replace all guard rail • Adjust drainage and electrical features • Re-grade ditch
(2032) Inlay lanes	15	<ul style="list-style-type: none"> • Inlay lanes with 0.15 feet of HMA and fog sealing of the shoulders
(2047) Inlay lanes and shoulders	30	<ul style="list-style-type: none"> • Inlay lanes and shoulders with 0.15 feet of HMA
(2062) Inlay lanes	45	<ul style="list-style-type: none"> • Inlay lanes with 0.15 feet of HMA and fog sealing the shoulders

Figure 14 – Activity Schedule for SR 5 (*Pavement Type Selection – I-5 NB S 260th St to Duwamish River Bridge – Concrete Pavement Rehab, 2015*).

4.2.2 Agency Cost of Carbon

The cost of carbon attributed to the construction agency is based on the embodied carbon of the asphalt, quantified by the global warming potential (GWP). I obtained the GWP values for each mix design from associated Environmental Product Declarations (EPD). Agency carbon costs additionally depended on the following values:

- Net Present Value (NPV) Agency Cost (\$) – Locate in Table 1 of RealCost 3.0’s Deterministic Results tab.
- HMA Quantity (short tons) – For SR 530 and SR 8, locate in Lum, et. al (2024). For SR 5, locate in the WSDOT Bid Check Report (Bid Check Report, 2016).
- HMA GWP (kg CO2e/short ton) - For SR 530 and SR 8, locate in Lum, et. al (2024). For SR 5, locate in the Emerald Eco Label web tool (*AsphaltEPD - Find an EPD*, n.d.).
- Cost of Carbon - \$35/MTCO2e, value resultant from the Section 3 Literature Review.
- Discount Rate – 2%, value resultant from the Section 3 Literature Review.

4.2.2.1 HMA Quantities and GWP’s

Table 16 lists the HMA quantities and GWP’s as identified in relevant sources. Note that for the SR 5 case study, three different asphalt mixes were used for the initial CSOL construction, per the WSDOT Bid Check Report (Bid Check Report, 2016). See the sections below for these mixes’ EPD input data. For HMA Mill and Fill activities, however, only one mix design was used. Per construction plans for the initial CSOL activity, the top 0.15’ layer of pavement was paved with the 1/2” PG 70-22 mix, which is the depth targeted in a mill and fill operation. HMA mill and fill quantities for SR 5 are calculated below:

Table 16 – HMA Quantities and GWP’s

	SR 530	SR 8	SR 5			
			CSOL		Mill and Fill	
HMA Quantity (short tons)	24,451.96	28,851.93	3/8” PG 64-22	19,511	1/2” PG 70-22	33,106
			1/2” PG 64-22	68,710.3		
			1/2” PG 70-22	23,122		
HMA GWP (kg CO2e/short ton)	41.44	49.53	3/8” PG 64-22	52.1	1/2” PG 70-22	48.4
			1/2” PG 64-22	48.0		
			1/2” PG 70-22	48.4		

$$\begin{aligned}
 \text{HMA Quantity (ft}^3\text{)} &= \text{Mill and Fill Depth} \times \text{Project Length} \times \text{Roadway Width} \\
 &= 0.15 \text{ ft} \times 8.87 \text{ mi} \times \frac{5,280 \text{ ft}}{\text{mi}} \\
 &\times \left(5 \text{ lanes} \times \frac{11 \text{ ft}}{\text{lane}} + 1 \text{ shoulder} \times \frac{10 \text{ ft}}{\text{shoulder}} \right) = 456,627.6 \text{ ft}^3
 \end{aligned}$$

$$\begin{aligned}
 \text{HMA Quantity (short tons)} &= \text{HMA Quantity (ft}^3\text{)} \times \text{HMA density} \\
 &= 456,627.6 \text{ ft}^3 \times \frac{145 \text{ lb}}{\text{ft}^3} \times \frac{\text{short ton}}{2,000 \text{ lb}} = 33,106 \text{ short tons}
 \end{aligned}$$

Figure 15, Figure 16, and Figure 17 display the GWP values for each mix design as produced by the Emerald Eco Label tool. Inputs for this tool are described in the following sections.

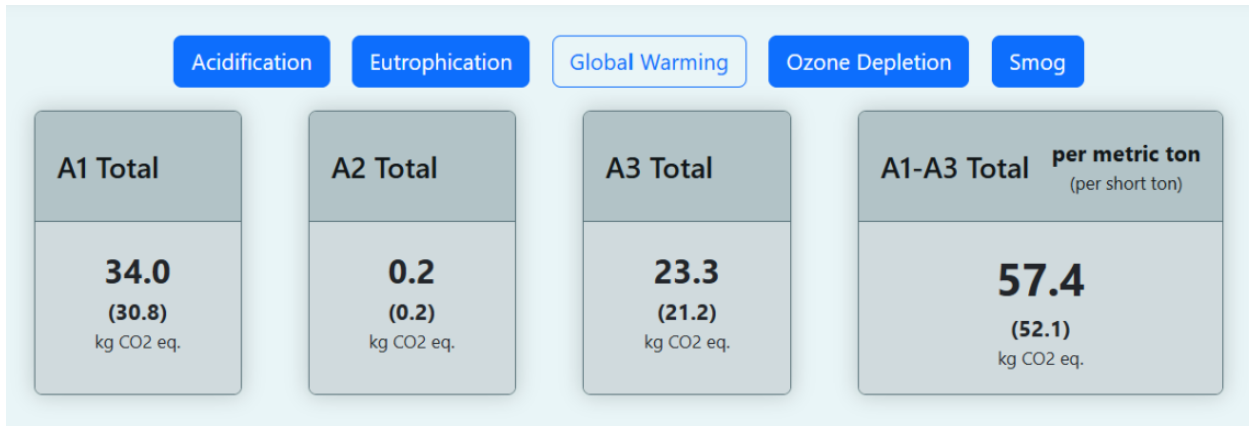


Figure 15 – Binder Content and GWP for 3/8” PG 64-22 Mix (*AsphaltEPD - Find an EPD*, n.d.).

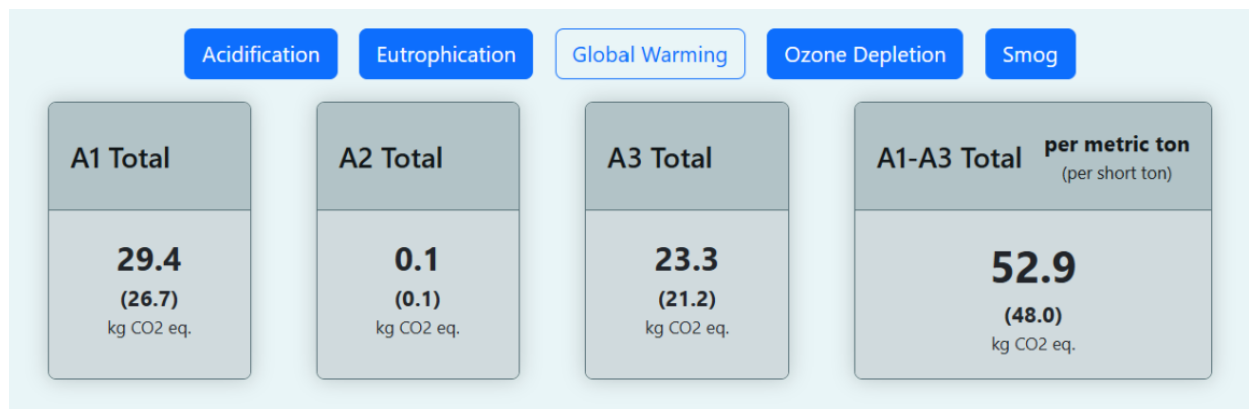


Figure 16 – Binder Content and GWP for 1/2” PG 64-22 Mix (*AsphaltEPD - Find an EPD*, n.d.).

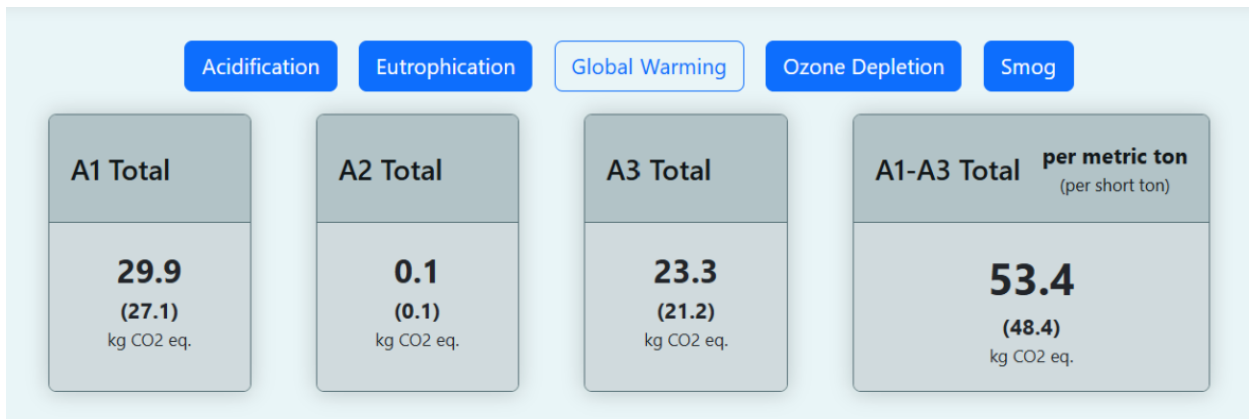


Figure 17 – Binder Content and GWP for 1/2” PG 70-22 Mix (*AsphaltEPD - Find an EPD*, n.d.).

4.2.2.2 Emerald Eco Label Inputs – HMA Plant

I generated EPD’s for the three SR 5 mix designs on Emerald Eco Label’s online tool (*AsphaltEPD - Find an EPD*, n.d.). I created these EPD’s by first making an asphalt plant within the tool, using figures for an average U.S. plant from the National Asphalt Pavement Association (NAPA) (Mukherjee, 2016), and located it at the ICON Materials plant’s address in Auburn, WA. Input factors are described below:

- Total Asphalt Mix Sold: 145,000 short tons/yr. This is based on the U.S. plant average as reported by NAPA.
- Total Water: 290,000 gal/yr. This is based on the U.S. plant average water use of 2 gal/short ton as reported by NAPA, then multiplied by the plant productivity of 145,000 short tons/yr.
- Grid Power: 48,400 kWh/yr. This is based on the U.S. plant average electricity use of 3.32 kWh/short ton as reported by NAPA, then multiplied by the plant productivity of 145,000 short tons/yr.
- Burner Fuel (Natural Gas): 40,469.5 mcf/yr. This is based on the energy content of natural gas burner fuel of 0.2791 mcf/short ton, then multiplied by the plant productivity of 145,000 short tons/year.
- Oil Heater (Natural Gas): 500 mcf/yr
- Equipment (Diesel): 14,500 gal/yr. This is based on the U.S. plant average equipment fuel use of 0.1 gal/short ton as reported by NAPA, then multiplied by the plant productivity of 145,000 short tons/yr.

4.2.2.3 Emerald Eco Label Inputs – HMA Mix Designs

Table 17 details the Emerald Eco Label inputs for each of the SR 5 mix designs. Input specifics are noted below:

- Minimum and Maximum Temperatures – I selected these values based on the optimum mixing temperature specified in the HMA mix reports. Both PG 64-22 mixes had an optimum mixing temperature of 310 °F, so I applied a range of 305-315 °F. The PG 70-22 mix design had an optimum mixing temperature of 338 °F, so I applied a range of 333-343 °F.
- Aggregate and Virgin Binder Percentages – I calculated these based on the quantity of recycled asphalt pavement (RAP) in each of the mixes (20%). I calculated virgin binder percentage by taking 80% of the total binder content, and aggregate percentage by taking 80% of the difference between total binder content and 100%. For reference, the total binder content of each mix design was 6.4%, 5.5%, and 5.6%, respectively.
- Trucking Distance – US Oil supplied the virgin binder, and the distance between their Tacoma facility and the Auburn ICON plant is 14 miles, so I set this as the trucking distance. I set aggregate and RAP trucking distances to 0.1 miles, as these materials were supplied on site.

Table 17 – Emerald Eco Label EPD Tool Inputs

	3/8” PG 64-22	1/2” PG 64-22	1/2” PG 70-22
Mix ID	MD160039 (3/8” PG 64-22)	MD160025 (1/2” PG 64-22)	MD160040 (1/2” PG 70-22)
Mix Specification Entity	WSDOT	WSDOT	WSDOT
Mix Specification	3/8-inch PG 64-22	1/2-inch PG 64-22	1/2-inch PG 70-22
Mix Design Method	Superpave	Superpave	Superpave
Upper PG Grade	64	64	70
Lower PG Grade	-22	-22	-22
Gradation Type	Dense Graded	Dense Graded	Dense Graded

	3/8" PG 64-22	1/2" PG 64-22	1/2" PG 70-22
Nominal Maximum Aggregate Size (inches)	0.375	0.5	0.5
Heat Processing	Hot Mix	Hot Mix	Hot Mix
Min Temp (Fahrenheit)	305	305	333
Max Temp (Fahrenheit)	315	315	343
Percent RAP by Mass	20	20	20
RAP is Processed Onsite	Yes	Yes	Yes
RAP Truck Distance (miles)	0.1	0.1	0.1
Aggregate Ingredient	Simulator Source – Natural Stone – Natural Stone	Simulator Source – Natural Stone – Natural Stone	Simulator Source – Natural Stone – Natural Stone
Aggregate Percent of Mix by Mass	74.88	75.6	75.52
Aggregate Truck Distance (miles)	0.1	0.1	0.1
Virgin Binder Ingredient	Simulator Source – Unmodified – Unmodified	Simulator Source – Unmodified – Unmodified	Simulator Source – Unmodified – Unmodified
Virgin Binder Percent of Mix by Mass	5.12	4.4	4.48
Virgin Binder Truck Distance (miles)	14	14	14

4.2.2.4 Cost of Carbon Calculations

I calculated the year zero cost of carbon for each case study’s HMA quantity using the equation below. Note that year zero is each project’s initial construction date:

$$\begin{aligned}
 &HMA \text{ Quantity (short tons)} \times HMA \text{ GWP} \left(\frac{kg \text{ CO}_2e}{short \text{ ton}} \right) \times 0.001 \left(\frac{tCO_2e}{kg \text{ CO}_2e} \right) \times 35 \left(\frac{\$}{tCO_2e} \right) \\
 &= \text{Year Zero Cost of Carbon (\$)}
 \end{aligned}$$

I forecasted these year zero costs forward to account for all the future maintenance activities, which occur at years 15, 30, and 45 within the 50-year analysis window. I calculated these costs using the below engineering economics formula:

$$\text{Year } n \text{ Cost of Carbon (\$)} = \text{Year Zero Cost of Carbon (\$)} \times \left(1 + \frac{\text{Discount Rate}}{100} \right)^{-n}$$

I then added all four costs together to obtain a total agency cost of carbon for each case study. Though SR 530 and SR 8 were mill and fill projects for both initial construction and subsequent pavement rehabs, SR 5 was initially a CSOL project in year zero. Thus, the HMA quantities for SR 5 are different in year zero than those for years 15, 30, and 45, and the costs of carbon are therefore calculated separately.

4.2.3 User Cost of Carbon

The user cost of carbon is attributed in this study to work zone delays. Lowered speed limits and lane closures cause drivers to spend more time operating their vehicles, which results in more emissions. The User Cost tab on RealCost 3.0 produces delay results, divided by vehicle and delay types. This section details the traffic demands and attributed delays of each work zone, along with the methods used to calculate the user cost of carbon for each case study. For full data tables, see Excel sheet titled ‘RealCost 3.0 Calculations’ submitted with this thesis.

4.2.3.1 Delay Types

RealCost 3.0 identifies four delay types used in its calculations in the User Cost tab. This section addresses each delay type and how the software calculates it.

4.2.3.1.1 Reduced Speed Delay

A reduced speed delay is “the additional time necessary to traverse the work zone at the lower posted speed; it depends on the upstream and work zone speed differential and length of the work zone” (Federal Highway Administration, 1998). RealCost 3.0 calculates reduced speed delays using the below equation:

$$\text{Reduced Speed Delay} = \frac{\text{Work Zone Length (mi)}}{\text{Work Zone Speed Limit (mph)}} - \frac{\text{Work Zone Length (mi)}}{\text{Normal Speed Limit (mph)}}$$

4.2.3.1.2 Speed Change Delay & Stopping Delay

A speed change delay is “the additional time necessary to decelerate from the upstream approach speed and then to accelerate back to the initial approach speed after traversing the work zone” (Federal Highway Administration, 1998). Speed change delays impact a project both when vehicles slow down to the work zone speed limit and when they slow down to stop for a queue. Stopping at a queue is identified as a Stopping Delay in the FHWA Bulletin document. These delay values are listed in a table on the Supplemental Data tab in RealCost 3.0. Values used specifically in these three case studies are listed in Table 18, specifically in units of hours per 1,000 stops. So, to calculate the speed change delay per vehicle between two non-zero speeds, the program subtracts the two values and divides the result by 1,000.

Table 18 – Speed Change Delays (hr/1000 stops)

Speed (mph)	Cars	Single-Unit Trucks	Combination Trucks
0	0.00	0.00	0.00
45	4.90	6.60	13.39
50	5.37	7.33	16.37
55	5.84	8.07	20.72
60	6.31	8.80	27.94

4.2.3.1.3 Queue Delay

A queue delay is “the additional time necessary to creep through the queue under forced-flow conditions” (Federal Highway Administration, 1998). RealCost 3.0 calculates queue delays using the below equation:

$$\text{Queue Delay} = \frac{\text{Queue Length (mi)}}{\text{Average Queue Speed (mph)}} - \frac{\text{Queue Length (mi)}}{\text{Normal Speed Limit (mph)}}$$

4.2.3.2 Traffic Demand Types

Each delay type is linked to a certain traffic demand type in RealCost 3.0’s calculations. Data tables on the User Cost tab list traffic demand and highway capacity (Step 1), then identify how many vehicles proceed through each section of the work zone (Step 2). Figure 18 depicts this work zone matrix based on rehab activity three of the SR 5 case study. Traffic demand types are explained individually below.

Step 1: from Hour	to	Step 1: to Hour	Step 1: Work Zone	Step 1: % AADT	Step 1: Demand	Step 1: Capacity	Step 1: Queue Rate	Number of Queued Vehicles	Step 2: Change Speed	Step 2: Traverse WZ	Step 2: Traverse Queue	Step 2: Stop for the Queue	Step 2: Slow Down for the WZ
0	-	1	Yes	0.6%	491	2740	(2249)	0	491	491	0	0	491
1	-	2	Yes	0.3%	299	2740	(2441)	0	299	299	0	0	299
2	-	3	Yes	0.3%	280	2740	(2460)	0	280	280	0	0	280
3	-	4	Yes	0.2%	209	2740	(2531)	0	209	209	0	0	209
4	-	5	Yes	0.4%	347	2740	(2393)	0	347	347	0	0	347
5	-	6	Yes	1.0%	858	2740	(1882)	0	858	858	0	0	858
6	-	7	Yes	3.2%	2795	2740	55	55	2795	2740	2740	2795	0
7	-	8	Yes	4.7%	4072	2740	1332	1387	4072	2740	2740	4072	0
8	-	9	Yes	3.7%	3234	2740	494	1881	3234	2740	2740	3234	0
9	-	10	Yes	2.9%	2488	2740	(252)	1629	2488	2740	2740	2488	0
10	-	11	Yes	2.2%	1881	2740	(859)	770	1881	2740	2740	1881	0
11	-	12	Yes	2.6%	2259	2740	(481)	289	2259	2740	2740	2259	0
12	-	13	Yes	2.8%	2436	2740	(304)	0	2436	2725	2606	2317	119
13	-	14	Yes	2.9%	2479	2740	(261)	0	2479	2479	0	0	2479
14	-	15	Yes	2.9%	2515	2740	(225)	0	2515	2515	0	0	2515
15	-	16	Yes	3.0%	2601	2740	(139)	0	2601	2601	0	0	2601
16	-	17	Yes	3.6%	3093	2740	353	353	3093	2740	2740	3093	0
17	-	18	Yes	3.4%	2958	2740	218	571	2958	2740	2740	2958	0
18	-	19	Yes	2.7%	2361	2740	(379)	192	2361	2740	2740	2361	0
19	-	20	Yes	1.9%	1629	2740	(1111)	0	1629	1821	473	281	1347
20	-	21	Yes	1.6%	1349	2740	(1391)	0	1349	1349	0	0	1349
21	-	22	Yes	1.3%	1145	2740	(1595)	0	1145	1145	0	0	1145
22	-	23	Yes	1.1%	960	2740	(1780)	0	960	960	0	0	960
23	-	24	Yes	0.8%	666	2740	(2074)	0	666	666	0	0	666
Daily Totals				49.9%	43406	65760			43406	43406	27739	27739	15667

Figure 18 – Work Zone Matrix from SR 5 Case Study.

4.2.3.2.1 Traverse the Work Zone

The ‘Traverse WZ’ category represents each hour’s traffic demand, capping the value at the highway’s capacity. Thus, under free-flow conditions (when there is no queue), ‘Traverse WZ’ equals ‘Demand’, and under forced-flow conditions (when there is a queue), ‘Traverse WZ’ equals ‘Capacity’. When the queue is dissipating, as traffic returns from forced to free-flow conditions, the ‘Traverse WZ’ value equals that hour’s demand plus the previous hour’s remaining queue. Since the sum of these two values is less than the capacity, the remaining queue is dissipated in this hour. All vehicles that traverse the work zone are subject to the reduced speed delay.

4.2.3.2.2 Traverse the Queue

The ‘Traverse Queue’ category is only populated under forced-flow conditions, or when a queue exists. When vehicles are actively queuing, this value equals the capacity. When the queue is dissipating, the number of vehicles traversing the queue equals the below equation:

$$\begin{aligned} & \text{Traverse Queue (hour } n) \\ &= \frac{\text{Capacity (hour } n) \times \text{Number of Queued Vehicles (hour } n - 1)}{|\text{Demand (hour } n) - \text{Capacity (hour } n)|} \end{aligned}$$

Vehicles that traverse the queue are subject to the queue delay. Since the queue delay changes hourly, based on the current queue length and speed, hour n ’s queue delay time corresponds to hour n ’s ‘Traverse Queue’ quantity.

4.2.3.2.3 Stop for the Queue

The ‘Stop for the Queue’ category is also only populated under forced-flow conditions. When a queue exists, all approaching vehicles must completely stop before traversing. While a day’s ‘Stop for the Queue’ total equals the ‘Traverse Queue’ total, hourly values of these two categories are not equivalent. Thus, RealCost 3.0 separates these two values, and vehicles stop for the queue are subject to the stopping delay. While a queue exists, the number of vehicles that stop for the queue is equal to that hour’s demand. When the queue is dissipating, this category is calculated by the below equation:

$$\begin{aligned} & \text{Stop for the Queue (hour } n) \\ &= \frac{\text{Demand (hour } n) \times \text{Number of Queued Vehicles (hour } n - 1)}{|\text{Demand (hour } n) - \text{Capacity (hour } n)|} \end{aligned}$$

4.2.3.2.4 Slow Down for the Work Zone

The ‘Slow Down for the WZ’ category equals demand under free-flow conditions and zero when a queue exists. When the queue is dissipating, this category equals the difference between that hour’s traffic demand and vehicles that have stopped for the queue. Vehicles that slow down for the work zone are subject to the speed change delay.

4.2.3.3 Cost of Carbon Calculations

4.2.3.3.1 Data Organization Notes

This section outlines data organization choices I made in formatting the attached RealCost 3.0 Calculations Excel file.

Multiple Rehab Numbers – Under a 50-year analysis window, four rehabilitation activities occurred for each case study. RealCost 3.0 presents user cost data for each rehab number separately, denoted in the yellow highlighted cell in the top left of the window. Each activity has different demands, which change over time based on the traffic growth rate input. Thus, I divided each case study’s data tables by rehab number.

Vehicle Types – Fuel consumption and vehicle emissions differ by vehicle type, so I calculated delays and the cost of carbon for each vehicle type separately. I accomplished this by applying the vehicle distribution percentages to each traffic demand type. Thus, each traffic demand type

has four separate columns: total vehicles, passenger cars, single-unit trucks (not applicable for SR 530), and combination trucks. I similarly split each delay type into three columns for each vehicle type. I summed delays separately to obtain a ‘Total Delay’ figure for each vehicle type.

Work Zone Duration – Since RealCost 3.0 reports delays in terms of hours per vehicle per day, I factored in the number of paving days outside the software. After summing all delays by vehicle type, I multiplied these values by the number of work days. Note the importance of grouping delays by rehab number, as on SR 5 the CSOL and mill and fill activities had different work zone durations.

4.2.3.3.2 Standard Values

This section outlines the constants I used in cost of carbon calculations.

Idling Fuel Consumption – In gallons per hour, a U.S. Department of Energy webpage reports idling fuel consumption statistics as 0.16 for a small sedan, 0.39 for a large sedan, 0.84 for a delivery truck, and 0.49 for a combination truck (*Idle Fuel Consumption for Selected Gasoline and Diesel Vehicles*, 2015). For passenger vehicles, I averaged the small and large sedan numbers to get a value of 0.275 gal/hr. For single-unit trucks, I selected the delivery truck statistic.

Vehicle Emissions – A US Environmental Protection Agency report identifies vehicle emissions as 8,887 gCO₂e/gallon of gasoline and 10,180 gCO₂e/gallon of diesel (*Greenhouse Gas Emissions from a Typical Passenger Vehicle*, 2025). These values convert to 0.00887 MTCO₂e/gal gasoline and 0.01018 MTCO₂e/gal diesel. I assigned the gasoline value to passenger cars and the diesel value to both truck types.

Unit Cost of Carbon – I chose a value of \$35/MTCO₂e based on the Section 3 Literature Review.

4.2.3.3.3 Calculation Methods

The total cost of carbon for each vehicle type and rehab number is calculated using the below equation:

$$\begin{aligned}
 & \textit{Total Cost of Carbon} (\$) \\
 &= \textit{Total Delay} (hr) \times \textit{Idling Fuel Consumption} \left(\frac{gal}{hr} \right) \\
 &\times \textit{Vehicle Emissions} \left(\frac{MTCO_2e}{gal} \right) \times \textit{Unit Cost of Carbon} \left(\frac{\$}{MTCO_2e} \right)
 \end{aligned}$$

4.3 Results

This section presents the results of each case study's RealCost 3.0 LCCA simulation, divided into agency and user costs.

4.3.1 SR 530 Results (Table 19 Table 20)

Table 19 – SR 530 Agency Costs

NPV Agency Cost (\$)	13,003,259
HMA Quantity (short tons)	24,451.96
HMA GWP (kg CO ₂ e/short ton)	41.44
Total HMA GWP (kg CO ₂ e)	1,013,289.22
Total HMA GWP (MTCO ₂ e)	1,013.28922
Discount Rate	0.02
Unit Cost of Carbon (\$/MTCO ₂ e)	35
HMA Cost of Carbon - year 0 (\$)	35,465.12
HMA Cost of Carbon - year 15 (\$)	26,351.11
HMA Cost of Carbon - year 30 (\$)	19,579.26
HMA Cost of Carbon - year 45 (\$)	14,547.68
HMA Cost of Carbon - total (\$)	95,943.17
Total Agency Cost (\$)	13,099,202.17

Table 20 – SR 530 User Costs

NPV User Cost (\$)	200,584
Idling Fuel Consumption - car (gal/hr)	0.275
Idling Fuel Consumption - combo truck (gal/hr)	0.49
Vehicle Emissions - gasoline (MTCO ₂ e/gal)	0.00889
Vehicle Emissions - diesel (MTCO ₂ e/gal)	0.01018
Unit Cost of Carbon (\$/MTCO ₂ e)	35
Reduced Speed Delay (hr/v)	0.053657
Speed Change Delay - cars (hr/v)	0.00094
Speed Change Delay - combo trucks (hr/v)	0.00733
Work Zone Duration - Mill and Fill (days)	25
Total Delay - cars (hr)	13,052.7778
Total Delay - combo trucks (hr)	2,376.96833
Cost of Carbon - cars (\$)	1,116.88
Cost of Carbon - combo trucks (\$)	414.99
Cost of Carbon - total (\$)	1,531.87
Total User Cost (\$)	202,115.87

4.3.2 SR 8 Results (Table 21 Table 22)

Table 21 – SR 8 Agency Costs

NPV Agency Cost (\$)	11,017,640
HMA Quantity (short tons)	28,851.93
HMA GWP (kg CO ₂ e/short ton)	49.53
Total HMA GWP (kg CO ₂ e)	1,429,036.09
Total HMA GWP (MTCO ₂ e)	1,429.03609
Discount Rate	0.02
Unit Cost of Carbon (\$/MTCO ₂ e)	35
HMA Cost of Carbon - year 0 (\$)	50,016.26
HMA Cost of Carbon - year 15 (\$)	37,162.82
HMA Cost of Carbon - year 30 (\$)	27,612.52
HMA Cost of Carbon - year 45 (\$)	20,516.51
HMA Cost of Carbon - total (\$)	135,308.12
Total Agency Cost (\$)	11,152,948.12

Table 22 – SR 8 User Costs

NPV User Cost (\$)	569,809
Idling Fuel Consumption - car (gal/hr)	0.275
Idling Fuel Consumption - single unit truck (gal/hr)	0.84
Idling Fuel Consumption - combo truck (gal/hr)	0.49
Vehicle Emissions - gasoline (MTCO ₂ e/gal)	0.00889
Vehicle Emissions - diesel (MTCO ₂ e/gal)	0.01018
Unit Cost of Carbon (\$/MTCO ₂ e)	35
Reduced Speed Delay (hr/v)	0.068767
Speed Change Delay - cars (hr/v)	0.00094
Speed Change Delay - single unit trucks (hr/v)	0.00147
Speed Change Delay - combo trucks (hr/v)	0.01157
Work Zone Duration - Mill and Fill (days)	22
Total Delay - cars (hr)	41,885.9604
Total Delay - single unit trucks (hr)	2,348.72528
Total Delay - combo trucks (hr)	2,686.46928
Cost of Carbon - cars (\$)	3,584.02
Cost of Carbon - single unit trucks (\$)	702.95
Cost of Carbon - combo trucks (\$)	469.02
Cost of Carbon - total (\$)	4,756.00
Total User Cost (\$)	574,565

4.3.3 SR 5 Results (Table 23 Table 24)

Table 23 – SR 5 Agency Costs

NPV Agency Cost (\$)	31,359,572
HMA GWP - 3/8" PG 64-22 (kg CO ₂ e/short ton)	52.1
HMA GWP - 1/2" PG 64-22 (kg CO ₂ e/short ton)	48.0
HMA GWP - 1/2" PG 70-22 (kg CO ₂ e/short ton)	48.4
Discount Rate	0.02
Unit Cost of Carbon (\$/MTCO ₂ e)	35
<i>CSOL</i>	
HMA Quantity - 3/8" PG 64-22 (short tons)	19,511
HMA Quantity - 1/2" PG 64-22 (short tons)	68,710.3
HMA Quantity - 1/2" PG 70-22 (short tons)	23,122
Total HMA GWP (kg CO ₂ e)	5,433,722.3
Total HMA GWP (MTCO ₂ e)	5,433.72
HMA Cost of Carbon - year 0 (\$)	190,180.281
<i>Mill and Fill</i>	
HMA Quantity - 1/2" PG 70-22 (short tons)	33,106
Total HMA GWP (kg CO ₂ e)	1,602,330.4
Total HMA GWP (MTCO ₂ e)	1,602.33
HMA Cost of Carbon - year 15 (\$)	41,669.43
HMA Cost of Carbon - year 30 (\$)	30,961.00
HMA Cost of Carbon - year 45 (\$)	23,004.48
<i>Total</i>	
HMA Cost of Carbon - total (\$)	285,815.19
Total Agency Cost (\$)	31,645,387.19

Table 24 – SR 5 User Costs

NPV User Cost (\$)	1,758,716
Idling Fuel Consumption - car (gal/hr)	0.275
Idling Fuel Consumption - single unit truck (gal/hr)	0.84
Idling Fuel Consumption - combo truck (gal/hr)	0.49
Vehicle Emissions - gasoline (MTCO ₂ e/gal)	0.00889
Vehicle Emissions - diesel (MTCO ₂ e/gal)	0.01018
Unit Cost of Carbon (\$/MTCO ₂ e)	35
Reduced Speed Delay (hr/v)	0.029567
Speed Change Delay (60-50) - cars (hr/v)	0.00094
Speed Change Delay (60-50) - single unit trucks (hr/v)	0.00147
Speed Change Delay (60-50) - combo trucks (hr/v)	0.01157
Speed Change Delay (60-0) - cars (hr/v)	0.00631
Speed Change Delay (60-0) - single unit trucks (hr/v)	0.0088

Speed Change Delay (60-0) - combo trucks (hr/v)	0.02794
Work Zone Duration - CSOL (days)	6.875
Work Zone Duration - Mill and Fill (days)	6.405
Total Delay - cars (hr)	320,314.15
Total Delay - single unit trucks (hr)	10,534.90
Total Delay - combo trucks (hr)	16,054.49
Cost of Carbon - cars (\$)	27,408.08
Cost of Carbon - single unit trucks (\$)	3,153.01
Cost of Carbon - combo trucks (\$)	2,802.91
Cost of Carbon - total (\$)	33,364
Total User Cost (\$)	1,792,080

4.3.4 Combined Graphs

Figure 19 presents the total costs of each case study divided into four categories: agency cost net present value (NPV), agency cost of carbon, user cost NPV, and user cost of carbon.

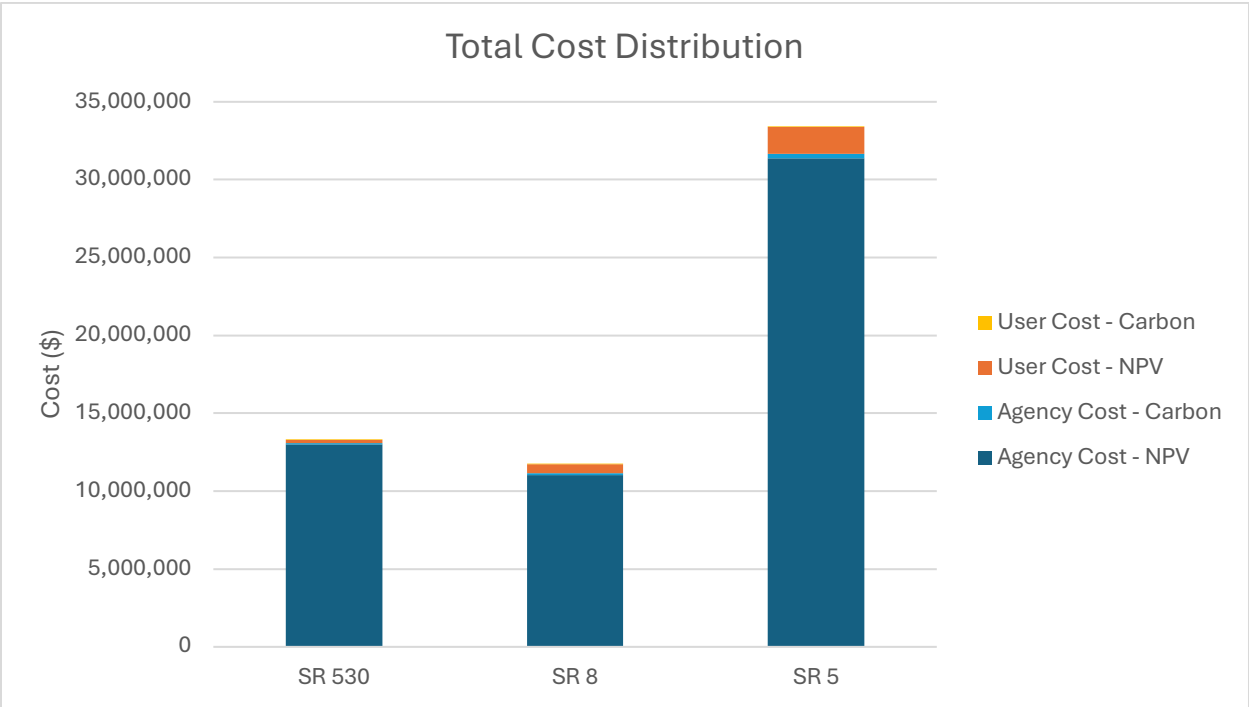


Figure 19 – Total Cost Distribution.

4.4 Discussion

This section addresses the distribution of project costs, the impacts of varying the unit cost of carbon, the influence of traffic modeling decisions, the decision to use RealCost 3.0’s deterministic results, and the limitations of the software and methods used.

4.4.1 Agency Costs Dominate

Comparison between case studies is only reasonable after controlling for paving area. Thus, Figure 20 and Figure 21 display the per lane-mile cost distributions, with Figure 21 only showing the costs of carbon.

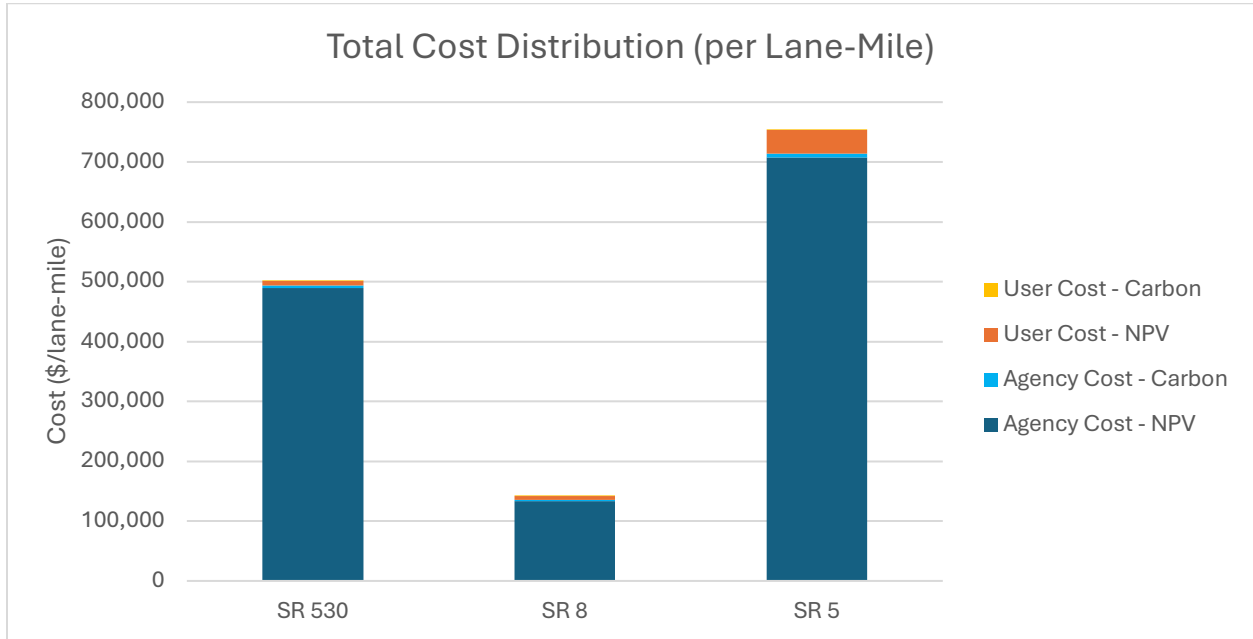


Figure 20 – Total Cost Distribution (per Lane-Mile).

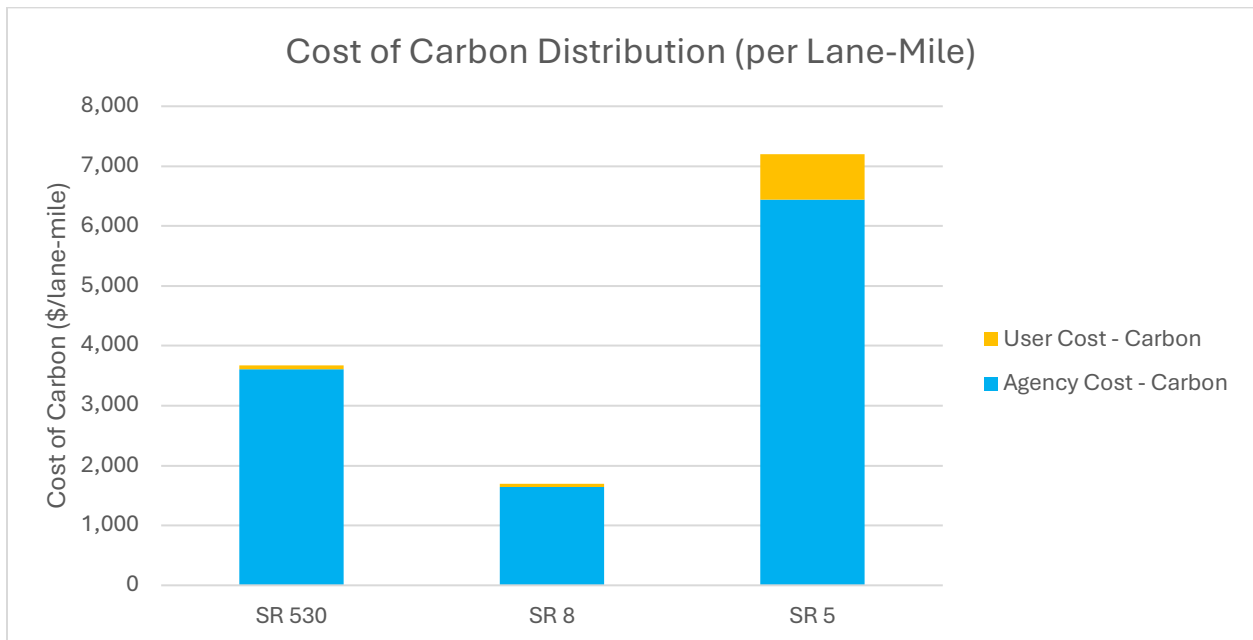


Figure 21 – Cost of Carbon Distribution (per Lane-Mile).

For both the LCCA-determined NPV costs and the costs of carbon, agency costs dominate. Note that while overall costs for SR 530 and SR 8 case studies are relatively close, the per lane-mile costs for SR 530 are nearly double those of SR 8. This is because SR 530 paved two lanes and

SR 8 paved four. Note that user costs for SR 5 were likely reduced as a result of truncating the AADT, which is addressed in the methods section and the traffic modeling discussion point below.

Figure 22Figure 23 show the same cost distributions as above, but as a percentage of the total project value.

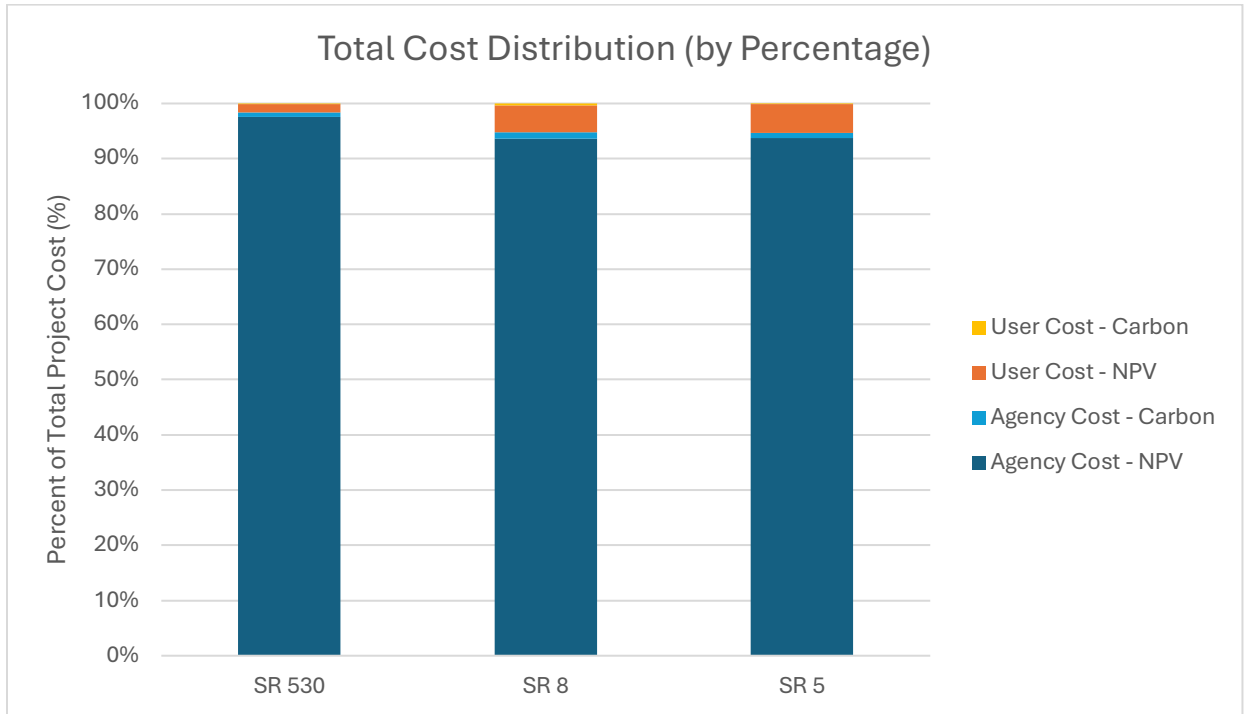


Figure 22 – Total Cost Distribution as a Percentage of Total Project Value.

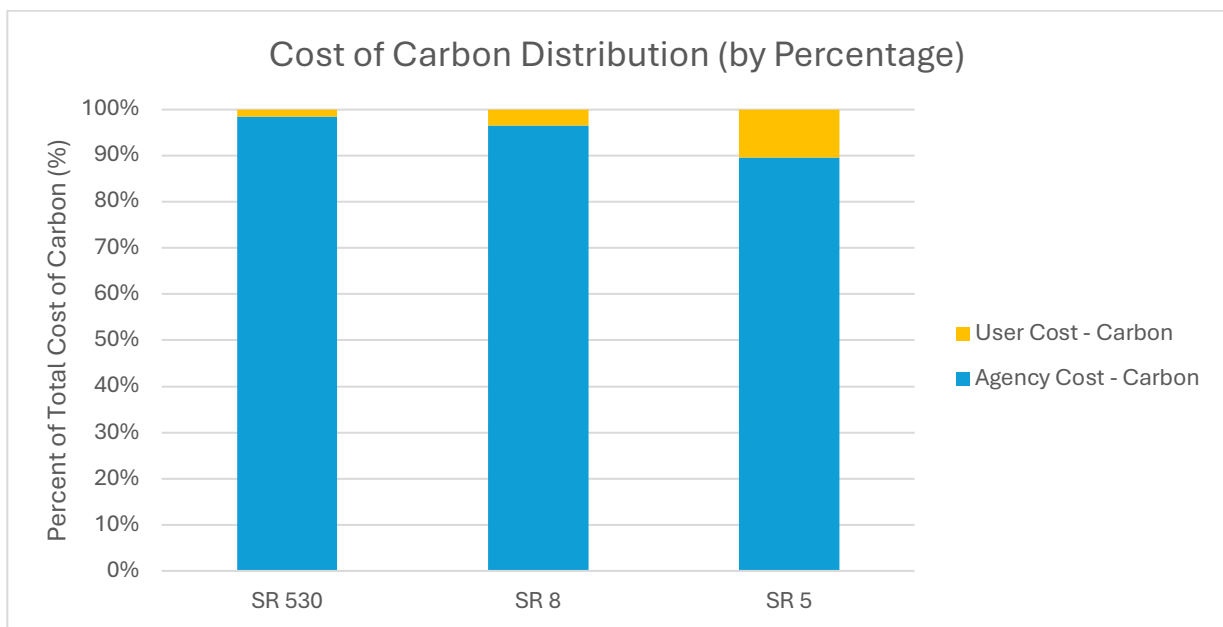


Figure 23 – Cost of Carbon Distribution as a Percentage of Total Project Value.

For all three case studies, total agency costs accounted for well over 90% of the total project value. For SR 530 and SR 8, agency cost of carbon was over 95% of total carbon cost. For SR 5, agency cost of carbon was nearly 90% of total carbon cost.

4.4.2 The Cost of Carbon is Relatively Insignificant at a \$35/MTCO_{2e} Unit Cost

At a \$35/MTCO_{2e} unit cost, the cost of carbon only accounts for about 1% of each case study’s total value and thus would likely not influence decision-making. Table 25 shows these contribution percentages, including individual agency and user figures along with a combined number.

Table 25 – Cost of Carbon as a Percentage of a Project’s Value

	SR 530	SR 8	SR 5
NPV Agency Cost (\$)	13,003,259	11,017,640	31,359,572
Agency Cost of Carbon (\$)	95,943.17	135,308.12	285,815.19
Agency Percentage (%)	0.74	1.23	0.91
NPV User Cost (\$)	200,584	569,809	1,758,716
User Cost of Carbon (\$)	1,531.87	4,756.00	33,364
User Percentage (%)	0.76	0.83	1.90
NPV Total Cost (\$)	13,203,843	11,587,449	33,118,288
Total Cost of Carbon (\$)	97,475.04	140,064.12	319,179.19
Total Percentage (%)	0.74	1.21	0.96

4.4.3 The Unit Cost of Carbon Must be \$300 – \$500/MTCO_{2e} to be 10% of Project Value

Figure 24 plots each case study’s cost of carbon as a percentage of total project value, based on a changing unit cost of carbon. This figure identifies several key points: the \$35/MTCO_{2e} used in RealCost 3.0 analysis, the \$75 – \$100/MTCO_{2e} SCC mode from Tol (2025), and the \$402/MTCO_{2e} SCC mean from Tol (2025). I truncated analysis at \$1,600/MTCO_{2e}, which was the upper limit of SCC estimates in Tol (2025).

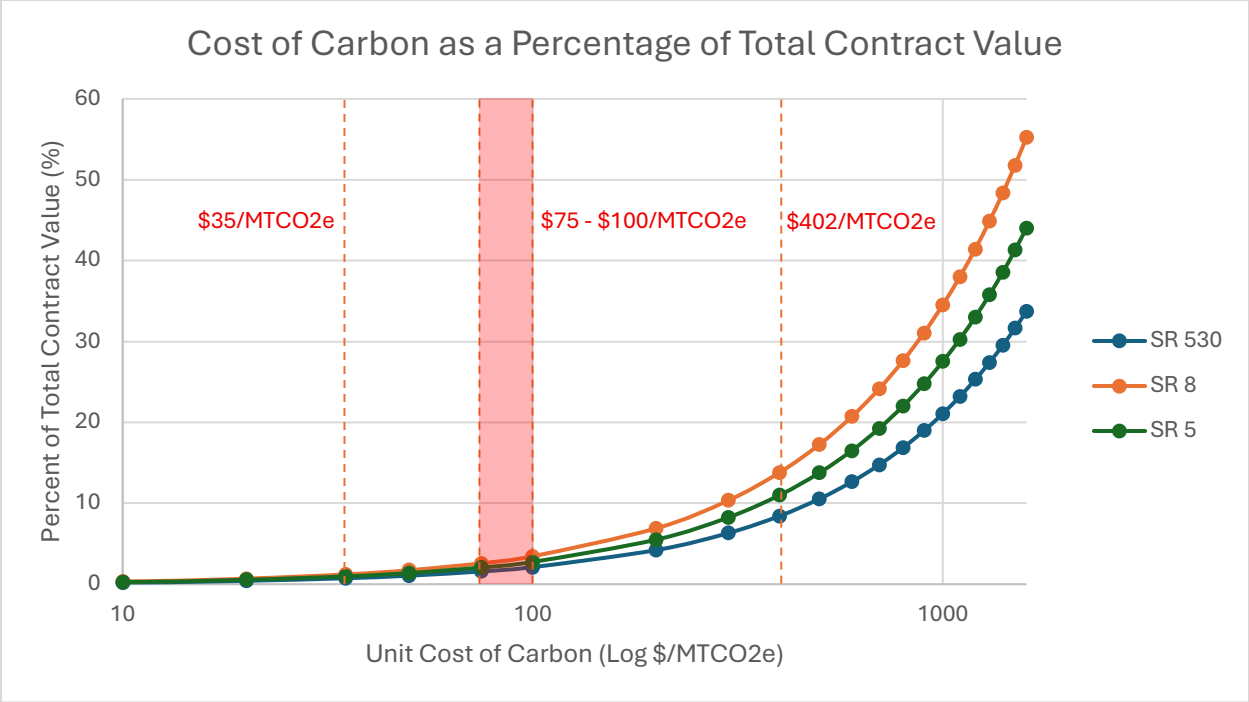


Figure 24 – Carbon’s Percent of a Case Study’s Total Value Based on the Unit Cost of Carbon.

Table 26 details what the unit cost of carbon must be to have each case study’s total cost of carbon reach 10% of its total value, which I identified as representing a significant contribution to project costs.

Table 26 – Required Unit Cost of Carbon to Reach 10% of Project Value

Case Study	Unit Cost of Carbon (\$)
SR 530	475
SR 8	290
SR 5	365

The unit cost of carbon needs to be significantly higher than the \$35/MTCO2e used in this thesis’ RealCost 3.0 analysis in order for it to noticeably impact decision-making on any of these case studies.

4.4.4 Traffic Modeling Choices are Influential in High-Traffic Environments

On this project, I used traffic data from a variety of WSDOT sources to set up case studies in RealCost 3.0. I also made several assumptions where information was missing or unclear. These methods are representative of the nature of traffic modeling, where data is inexact and distributions are designed to reflect the general traffic patterns of a certain roadway. RealCost 3.0 is a simplistic model that is especially limited in high traffic environments, the impacts of which show up in these two ways:

- SR 5 AADT Reduction – With the specified growth rate, the actual initial AADT of this case study caused software processing errors by the third rehab activity. I made the assumption that under high-traffic conditions in a work zone with multiple lane closures, many parties will delay, reroute, or cancel their trips altogether to avoid extreme traffic. This logic is based on the Los Angeles highway closure study examined in the methods

section above (Taylor & Wachs, 2014). Reducing the initial AADT by 35% allowed the software to run properly, but RealCost 3.0 does not account for where that extra traffic volume will go. In reality, the vehicles that reroute their trips are still producing emissions that contribute to the work zone's induced cost of carbon. These vehicles are just not counted in the software's analysis.

- Max Queue Length – I set the RealCost 3.0 input 'Max Queue Length' at 5 miles, in order to prevent excessive queuing delays from skewing the case study's data. Note that this figure only impacted the SR 5 case study, as SR 530 and SR 8 did not experience any queues throughout the analysis window. Rehab activity 1 had only two hours' worth of queuing where the queue length never surpassed 0.5 miles. By rehab activity four however, over half of the 24-hour work zone window was blocked with a queue, and the majority of these hours' queue lengths hit the maximum of 5 miles. I then altered the maximum queue length to study impacts on user costs and delays. Decreasing the max queue length decreased the queue delays and user costs, while increasing it caused the opposite effect. No other delay types were impacted by changing the max queue length, and traffic distributions were unaffected. Thus, the assumption of a 5-mile max queue length was an influential decision, but only in the high-traffic environment of SR 5.

4.4.5 Deterministic Modeling is Adequately Representative of this Project's Data

RealCost 3.0 allows for deterministic and probabilistic analysis in its LCCA methods. While deterministic results display the direct calculated net present values for agency and user costs, probabilistic analysis performs a Monte Carlo simulation that accounts for uncertainty in the data. Traffic modeling is not exact, so probabilistic analysis reflects the distribution of this data better. However, the data sources used in this project all provided exact values, so any variability used in the software would have been fabricated. While traffic distributions for these case studies likely exist, the point of this project was to examine how the cost of carbon impacts construction high and low-traffic highways, not to model traffic exactly. Thus, deterministic analysis was an effective method for the purposes of this thesis, but using probabilistic methods would offer a good follow-up.

4.4.6 Limitations

While incorporating the cost of carbon into RealCost 3.0 analysis provides insight into these specific case studies, further pavement industry generalizations are inaccurate. The following limitations are present in this thesis' analysis:

- I made many assumptions in setting up each RealCost 3.0 case study, all of which are fully explained in the methods section of this report.
- RealCost 3.0 is limited as an LCCA model. The software does not account for traffic on roads surrounding the project highway, which prevents results from capturing the full impact of a work zone.
- I only analyzed three case studies, which is not enough to amount to statistical significance.

5 Conclusions

The research question posed at the beginning of this thesis was: *How does the cost of carbon influence roadway construction decisions?* I addressed this question by identifying a unit cost of

carbon and discount rate, then incorporated these values into three asphalt pavement case studies through life cycle cost analysis. I obtained the following conclusions from these three case studies:

- **The cost of carbon is insignificant in pavement LCCA's at \$35/MTCO_{2e}.** The assigned unit cost of carbon caused an increase in 50-year life cycle costs of about 1%. The unit cost of carbon would have to be valued at a high range of SCC estimates (\$300-\$500/MTCO_{2e}) in order to contribute significantly (10%) to pavement life cycle costs. Thus, if a project's intention is to influence financial decisions such that carbon emissions are reduced, the social cost of carbon must be considered.
- **The cost of embodied carbon is significantly larger than the cost of carbon associated with traffic delays.** For SR 530, it is 63 times greater. For SR 8, it is 28 times greater. For SR 5, it is 9 times greater. For the two low-traffic case studies, the discrepancy is much higher as there were limited user delays. Considering the high volume of traffic and significant queue delays on SR 5, the smaller gap between the two figures makes sense. Note that these ratios are heavily influenced by traffic modeling decisions.
- **The case study nature of this work limits generalizing the results.** The results of this thesis apply to three specific case studies. They are meant to test the viability of my methods and to give a general idea of what results may be significant. Based on the limited number of case studies, results should not be generalized to the pavement industry or carbon markets in general. However, the convincing nature of the results in both high and low traffic situations makes it seem likely that they will apply to most other cases.
- **The unit cost of carbon varies widely depending on pricing strategy and location.** The social cost of carbon has the widest range (up to \$1,600/MTCO_{2e}) and highest average (\$402/MTCO_{2e}) (Tol, 2025). Carbon tax prices vary between from \$0.77 to \$167.17 per MTCO_{2e}, with a mean rate of \$43.40/MTCO_{2e}. Carbon taxes are significantly higher in Scandinavian countries than they are in other parts of the world (*Carbon Pricing Dashboard*, 2024). Carbon offset prices vary between \$10 to \$43.95 per MTCO_{2e}, with a mean rate of \$20.38/MTCO_{2e}. Auction prices in American ETS markets converge around \$30/MTCO_{2e}, but the European Union's market sells carbon allowances for nearly three times that amount on average.

5.1 Future Work Considerations

This thesis takes preliminary steps in incorporating the cost of carbon into LCCA structures, but further research must be done before results can be analyzed in detail. The following methods should be incorporated into future work:

- Perform a probabilistic analysis based on a full distribution of traffic data, instead of deterministic values.
- Incorporate more case studies from different regions with different traffic distributions.
- Update the HMA GWP's to include all life cycle stages, not just A1-A3.
- Use a range of unit costs of carbon from different pricing strategies to determine a similar range of impacts on project costs. Currently, the low end is represented by carbon markets (around \$35/MTCO_{2e}), and the high end is represented by the social cost of carbon (around \$400/MTCO_{2e}).

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